Boundary Influences In High Frequency, Shallow Water Acoustics

Edited by

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CD-Rom
Preface

As the interest of the military moves to shallow water, so the tasks demanded of acoustics increases both in scope and complexity. Acoustical interactions with the sea surface and seabed provide both limitations to activities and opportunities for exploitation. Engineering requirements are pushing, as never before, the need to understand the physics of these interactions. Presentations of recent results from ONR sponsored SAX04, SWAMSI and other MCM programmes, will set the current level of knowledge and provide guidance for future efforts.

This book and the enclosed CD–Rom are the proceedings of a conference organized and held at the Department of Physics, University of Bath, UK 5th-9th September, 2005

CD-Rom included
This volume contains a CD-Rom which in addition to an electronically searchable version of the proceeding, has full colour versions of figures which are printed in black and white in the book.

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Nicholas G. Pace and Philippe Blondel
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Section 1

SAX04 sound speed, attenuation, seabed properties
SAX04 OVERVIEW

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SAX04 (for sediment acoustics experiment–2004) was conducted in shallow water near
the coast of northwestern Florida, USA during September-November 2004. This major
sediment acoustics experiment extended work carried out during SAX99, conducted at a
site nearby. Investigators from several institutions in addition to the Applied Physics
Laboratory at the University of Washington (APL-UW) participated in SAX04, and
some of this work is described in other conference papers. The surficial sediment at the
experiment site is normally composed of fine-to-medium sand, leading to critical angle
of about 30°. However, in September 2004 a major hurricane affected the site, leading to
a complex environment with mud patches throughout the area and initially a thin layer
of mud in most other regions. An important focus of this work is to better understand
scattering from objects that are proud or buried in the seafloor; for buried targets the
primary interest is when the incident grazing angle is below the critical angle. Sediment
sound speed dispersion and scattering from sediments were two other important topics
investigated during SAX04. Divers deployed a 27-m rail system on the bottom for
synthetic aperture sonar measurements for target detection; the rail system was also used
for sediment backscatter and forward scatter studies. A research initiative on sediment
ripple formation, evolution, and decay was recently begun by the U.S. Office of Naval
Research, and investigators from this program also carried out studies at the SAX04 site.
An overview will be given for the SAX04 measurement program, outlining the scope of
the acoustic and environmental measurements made.

1 Introduction

SAX04 was conducted from the beginning of September to the middle of November
2004 in shallow water about 1 km from shore on the Florida Panhandle near Fort Walton
Beach, Florida, USA (Fig. 1). The site is about 100 km WNW of Panama City, Florida
with coordinates 30° 23.24′ N, 86° 38.64′ W. SAX04 was located close to the site for
SAX99 [1-3], and was designed to build on advances from SAX99 and to pursue
questions that remained.

The goals and strategy for SAX04 are best understood in the context of SAX99
results. SAX99 measurements at 11-50 kHz on sound penetrating into sand sediments at
angles below the nominal critical grazing angle of about 30° showed conclusively that
the dominant mechanism for subcritical penetration at the SAX99 site was scattering
from sediment ripples [4]. These measurements were made using a buried array, the
ripple wavelength was about 50 cm, and the RMS ripple height was about 1 cm. At the
same time that work was underway at the SAX99 site, synthetic aperture sonar (SAS)
detections of buried targets were made by investigators from the Naval Surface Warfare Center – Panama City (NSWC-PC) [known at that time as the Coastal Systems Station, or CSS] at a shallow water site offshore from Panama City. These measurements were made using a towed source at 20 kHz, the average ripple wavelength at the site was about 70 cm, and the ripple height was not measured. Our modeling of penetration measurements at the SAX99 site showed that the longer average ripple wavelength at the Panama City site would significantly reduce sound penetration at subcritical grazing angles for the 20 kHz SAS system used. Yet, the SAS measurements showed dramatic detections on cylindrical targets at grazing angles as low as 4° and at target depths as great as 50 cm [5].

These results in part led to a measurement program on subcritical penetration due to ripple scattering using a test pool at NSWC-PC [6,7]. This work is continuing and will be described in a separate conference paper by J. L. Lopes and co-workers. The test pool work has confirmed subcritical detection of buried targets via ripple scattering. With spherical targets the detection levels are in accord with modeling predictions as well as with expectations based on SAX99 results. For finite length cylindrical targets, detailed modeling of detection levels has not yet been obtained.

Since the SAS target detection measurements were made in the fall of 1999, techniques have been developed to infer RMS ripple height from the high-frequency (180 kHz) SAS images of the ripple field [8]. Use of this approach has yielded an RMS ripple height of about 2 cm for the 70 cm wavelength ripples at the site of the SAS measurements off Panama City. In general, increased ripple height leads to increased subcritical penetration, but nevertheless, neither test pool results to date nor simple
modeling would appear to predict the high signal-to-noise levels obtained for the 1999 SAS detections on buried cylindrical targets.

The strategy for SAX04 was designed to improve our understanding of subcritical target detections in several ways. A set of targets was buried at the site well before the experiment, ensuring that the burial disturbance would have time to heal, and ensuring that conditions would be nearly the same for target detection measurements and sediment characterization. A 27-m rail system [9] was deployed at the site for controlled SAS measurements on buried targets. (Results from this system are described in a separate conference paper by K. L. Williams et al.) The frequency range for SAS buried target detection measurements was extended down to 2 kHz. Thus, both evanescent wave detection at the low end of the frequency range and detection via ripple scattering at higher frequencies would be accessible by the instrumentation.

The importance of ripple scattering to subcritical penetration, shown in SAX99, contributed to the origin of a new research initiative by the U.S. Office of Naval Research on the formation, evolution, and decay of sediment ripples. One of the goals of this work is to develop better predictive capability on properties of sediment ripples when direct measurements are lacking. Investigators from this “Ripples Research Initiative” carried out measurements during the course of SAX04.

There are several other important SAX99 topics that warrant mention since they affected the scope of the SAX04 measurement program. Strong evidence of sound speed dispersion was obtained with a variety of measurements during SAX99, and using measured sediment properties the dispersion was shown to be consistent with Biot’s model for sediment acoustics [10]. However, there were few measurements made at the lowest frequencies (100 Hz to a few kHz) and their absolute uncertainties were not adequately determined. These low frequency data actually suggest more dispersion than is readily obtained with Biot’s model using the measured sediment properties. For SAX04 a major effort was made to cover the frequency region below 10 kHz. While SAX99 sound speed measurements generally showed dispersion consistent with Biot’s model, the frequency dependence of sediment attenuation was not in as good agreement with Biot’s model predictions, especially at high frequencies above about 50 kHz [10]. Attenuation was found to scale closely with the first power of frequency, leading to a divergence with Biot model predictions at higher frequencies (and to a result more in accord with a model proposed by Buckingham [10]). Following the analysis of SAX99 data, one possible reason given for the divergence was increased scattering from structures within the sand, such as shell hash, as the frequency increased. However, subsequent laboratory measurements with glass bead sediments showed similar scaling of attenuation with frequency with no such structures in the sediment [11]. Further attenuation measurements were planned for SAX04, including the lower frequency region where a clearer Biot model dependence might be obtained.

Backscattering from sediments was also extensively studied during SAX99 [12]. Scattering from surface roughness was found to be the dominant backscattering mechanism for frequencies up to about 50 kHz. The backscattering level is about 2 dB lower when modeled using a Biot sediment model compared to a fluid sediment model, and the measured backscattering levels were in closer agreement with Biot model predictions at frequencies less than 50 kHz. However, observed spatial variations in the statistical parameters describing the roughness limited the precision of model
predictions, making it difficult to use backscattering to conclusively choose between these models. This led to a goal of more extensive area coverage for roughness measurements in SAX04, both to better understand the spatial non-stationarity of roughness and to improve the precision of backscatter model predictions.

In addition, forward scattering measurements from the sediment to determine the reflection coefficient were added to the experimental program to give yet another independent measurement to compare with Biot and fluid model predictions. Also, there are some advantages for using reflection versus backscattering for such a test. With backscattering one needs the roughness spectrum averaged over the scattering patch, and without the roughness measured directly in the actual region of scattering, one needs (when making model predictions) to assign uncertainties on the range of roughness that could have been present. The observed spatial non-stationarity of roughness leads to significant uncertainties. For reflection, the goal is to obtain the flat surface reflection coefficient by averaging out the effects of roughness. Thus, when determining the experimental reflection coefficient, one must assign uncertainties related to the magnitude of incomplete cancellation of random scattering effects, after accounting for any deterministic bias due to scattering. It appears likely that when there are uncertainties in the roughness spectrum, the reflection measurements will lead to a more stringent test of competing sediment acoustics models than backscattering strength.

2 Overview of SAX04

During 4-9 May 2004 two sets of targets were buried at the SAX04 site using the R/V Savannah. One set was flush buried and the other set was buried at a depth of 30 cm to the tops of the targets. The targets included mine-like shapes, spheres, clutter-like objects (scuba tank, hollow cement pipe), and smaller scientific targets. The site chosen has a water depth of 17 m.

The R/V Seward Johnson and the R/V Pelican were the primary vessels used for the SAX04 and Ripples Program measurements. The R/V Seward Johnson was in a 4-point moor from 25 September until early November, except for brief periods dictated by weather. The 4-point moor allowed power and signal cables to be run from equipment on the bottom to the ship. The R/V Pelican remained mobile and supported some of the SAX04 equipment deployments and most of the Ripples Program measurements.

Work began with a multibeam survey of the site by Larry Mayer’s group from the University of New Hampshire, and was completed on 3 Sept. 2004. Then Tom Herbers and his group from the Naval Postgraduate School deployed a Datawell wave buoy and other wave measuring equipment at 9 sites over a wide area, completing work on 5 Sept. At this point a series of hurricanes and tropical storms began to affect Florida. Hurricane Ivan was a very intense storm that made landfall just over 100 km to the west of the SAX04 site, which brought its highest wave field to shore near the site. Offshore buoys recorded significant wave heights up to 15 m, but since wave breaking in shallow water will generally limit wave heights to about half the water depth, the wave heights at the SAX04 site would have been limited by shallow water effects, placing the site in the surf zone. The Datawell wave buoy survived the event but was damaged; it was replaced and gathered wave data for the remainder of the experiment period.
The effects of the Hurricane Ivan wave event were dramatic. The nearshore topography is characterized by a series of sand ridges and swales, and it appears that mud permanently resides in the swales during normal conditions. The effect of the hurricane was to produce mud patches throughout the area (Fig. 2) of variable size, ranging down to just a few meters. The mud normally found in the swales would have been one source of mud for the patches. Another (and likely more important) source would have been backwash of lagoonal sediments [13]. Note also in Fig. 2 that sediment ripples are evident in the top panel.

It appears that the top half to one meter of sediment had been suspended during the wave event. A layer of shell hash was re-deposited first, followed by a half to one meter of very clean sand, and then the surface of the sand was covered by mud patches and initially by a thin layer of mud in most other regions. The underwater visibility was extremely poor following the hurricane, complicating diving activity and underwater construction of the SAS rail system and other structures. The visibility gradually improved over the succeeding weeks, and the mud covering on the bottom reduced in scope, but even modest wave activity caused re-suspension of mud, reducing visibility once again. Visibility, while sufficient for diving activity during much of SAX04, limited the use of stereo photography for roughness determination to near the end of the experiment period.

Figure 2: Sidescan images (provided by P. Traykovski, WHOI) taken at 900 kHz at depths of 17.6 m (top) and 10.6 m (bottom). The dark mud patches in the top panel, where the depth is close to that for the SAX04 site, have 5-10 m horizontal scales. The lower panel shows an inshore region where the patch sizes were smaller.
The Hurricane Ivan wave event significantly affected the buried target field. Some targets were left only partially buried, others were left buried but moved, and others were lost altogether. A third set of targets was deployed on the sediment surface during SAX04, as originally planned, and one additional spherical target was buried by divers. In spite of the effects from H. Ivan, a number of interesting target detection measurements were made.

The situation encountered following H. Ivan was unexpected, with some regions on the seafloor consisting of mud overlying sand ripples. An example is shown in Fig. 3, obtained with a system known as IMP2 [14] that measures sediment conductivity. The formation factor (shown in Fig. 3) is the ratio of the conductivity of seawater to that of a given medium. The top panel in Fig. 3 shows sharply peaked, high amplitude ripples soon after H. Ivan in a region with little mud. The bottom panel shows lower amplitude ripples later in SAX04 in a region with overlying mud. Note that especially in the top panel the ripple wavelength is highly irregular. While the seafloor structure is complex, the effect of scattering by ripples on subcritical penetration is not necessarily affected, since 10-20 kHz sound can easily penetrate the overlying mud. In fact, the mud may act to preserve the ripples and thus maintain the ripple profile. There is also some evidence that the mud-sand interface may be smoother than the water-mud interface or an exposed water-sand interface [15], presumably because the mud-sand interface is more protected from biological activity. This may lead to reduced backscatter from the bottom, and thus increased signal-to-noise ratios for buried target detections. However, in some cases sand inclusions within the mud may significantly increase backscatter from the bottom, giving decreased signal-to-noise ratios. Further work will be needed to better understand these competing effects.

Figure 3: Formation factor (color) for two IMP2 measurements. There are no data in the dark blue regions, the top light blue region is water, the lighter blue region is mud with some sand inclusions, and the orange region is sand. Data for the top panel were taken about 5 days after
While the effects of H. Ivan did change the seafloor topography, these changes opened up a host of new and interesting research questions. A brief mention of the measurements made during the experiment period is contained in the following section.

## 3 Summary of SAX04 Measurements

Several papers in these proceedings describe the wide range of measurements made during SAX04. (For simplicity only the lead author of each paper will be cited.) Many of the measurements made with the 27-m rail system are described in a paper by Kevin Williams. These include SAS imaging of proud and buried targets, as well as backscattering and forward scattering from sediments, including the determination of the sediment reflection coefficient. Bistatic scattering measurements from targets made with the rail system are described in a paper by Steve Kargl. A paper by Darrell Jackson treats bistatic scattering measurements from sediment ripples, also made using the rail system.

Marcia Isakson from the Applied Research Laboratories, University of Texas describes a separate effort using a source mounted on an ROV plus a vertical line array receiver to obtain the sediment reflection coefficient. In both of these determinations of the sediment reflection coefficient, it is important to recognize that the sediment interface may not be perfectly flat, and a large number of measurements are required in order that the effects of scattering from the interface irregularities can be averaged out.

Our understanding of seafloor scattering can often be improved by manipulating the seafloor to enhance certain effects. Mike Richardson from NRL-SSC describes SAX04 measurements of this type. Fundamental studies of subcritical penetration were made during SAX99 using a buried array. Similar measurements were made during SAX04, and a comparison of results from the two experiments is given in a paper Todd Hefner (APL-UW).

SAS measurements are preferred for buried target detection at subcritical grazing angles, because the resulting small patch sizes minimize reverberation from the seafloor. However, small reverberation patch sizes may also lead to non-Gaussian statistics, which needs to be better understood. A paper by Tony Lyons from the Applied Research Laboratory, The Pennsylvania State University describes a statistical analysis of SAS reverberation data taken during SAX04.

Measurements of sediment sound speed dispersion and attenuation have had a high priority in the SAX04 measurement program. In two papers John Osler and Paul Hines from Defence Research and Development Canada describe complementary approaches for determining sound speed dispersion in the 1-10 kHz band. Mike Zimmer from Naval Research Laboratory, Stennis Space Center (NRL-SSC) describes multiple systems used to measure sediment sound speed and attenuation from 1 to 400 kHz. Finally, a paper by Kevin Briggs, also from NRL-SSC, presents spatial and temporal variations in the sediment sound speed and attenuation at 400 kHz.

Characterization of the sediment properties is a very challenging task in itself, and only a portion of the SAX04 work in this area is represented in papers at this conference. A paper by Todd Hefner (APL-UW) presents results of bottom roughness measurements made during SAX04 using a diver-deployed stereo imaging system. A paper by Allan Reed (NRL-SSC) describes microcomputed tomography analysis of SAX04 sands to obtain information on pore structure and grain contacts. A paper by Mike Buckingham
from the Scripps Institution of Oceanography discusses a novel method for inversion of geoacoustic parameters using a light aircraft as the sound source combined with receivers in the water column and in the sediment. Finally, DJ Tang discusses a novel method for obtaining the sediment sound speed using small boat noise.

Work by investigators from the Ripples Research Initiative is not comprehensively described at this conference. However, a paper by Alex Hay from Dalhousie University presents findings on ripple decay made during SAX04.

At the very end of SAX04 on 13 November 2004 a group from NSWC-PC headed by John Piper carried out a SAS survey of the SAX04 target field site. The survey was done using the R/V Mr. Offshore with the SAS system mounted on a towbody. Two SAS images of the same patch of seafloor are shown in Fig. 4. The image in the left panel is at 180 kHz and shows the ripple field, which had an average wavelength of 42 cm at the time of these measurements. The image on the right is at low frequency (over about the 8–25 kHz band) and shows quite clearly a buried fluid-filled focusing sphere [7] at a depth of 5–10 cm to the top of the sphere. (The NSWC-PC “broadband” system would normally transmit over a frequency band of 8–55 kHz, but a component malfunction led to a reduction in total bandwidth.)

![Figure 4: SAS images of the same patch on the seafloor at high frequency (165–195 kHz, left) and at low frequency (about 8–25 kHz, right). The (subcritical) grazing angle was 18° at the sediment surface above a buried sphere, which was detected only at low frequency. The color scale is in dB with arbitrary reference level. (SAS images provided by J. E. Piper, NSWC-PC.)](image)

The signal-to-noise ratio for the target detection in Fig. 4 was 22.4 dB. It is also of note that the grazing angle of 18° was well below the critical angle of 30°. This is therefore a good example of a subcritical buried target detection via scattering from sediment ripples. The same target was detected on 5 separate passes with grazing angles in the 17°–21° range and single-to-noise ratios in the 20–25 dB range. In future work,
modeling of these detections will be undertaken in order to further verify our understanding of these detections.

4 Discussion

The papers presented at this conference that are related to SAX04 represent just the beginning of the results that will ultimately flow from this work. We expect in the future to prepare a special journal issue similar to [3] where a more comprehensive presentation of results will be given.

The initial results in the conference papers indicate that several of the basic research questions motivating SAX04 should be addressed more fully in the special issue. For example, more and better low frequency sound speed and attenuation measurements as well as reflection measurements allow testing of sediment propagation models. Transmissions to buried sensors allow further examination of penetration mechanisms. Finally, backscattering and bistatic scattering from sediments will be used to quantify the role of interface roughness. The additional environmental complexity due to Hurricane Ivan has led to new questions and will motivate new models. Backscattering from the sediment is a particularly interesting topic in that regard. Initial results indicate that volume heterogeneity may play a dominating role in scattering at some frequencies.

From an application standpoint, answers to these basic research questions will be used to understand SAS results from SAX04. In particular, the ability to quantitatively predict the successful buried target detections of SAX04 is a long-term goal that will rely on our basic understanding of sediment acoustics.

Acknowledgements

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References


INVERTING FOR SANDY SEDIMENT SOUND SPEED IN VERY SHALLOW WATER USING BOAT NOISE

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Outboard motor noise was recorded on a single hydrophone in very shallow water for the purpose of understanding wave propagation in very shallow water and estimating sediment sound speed. The experiment was conducted near shore in water depth between 2 and 10 meters, and the sediment consisted of uniform sand. The lone hydrophone was moored 2 m above the bottom at 6 m depth. A small boat traveling at constant speed was used as the sound source, and ran both parallel and perpendicular to shore. Thus, both the range-independent waveguide case and the wedge shaped waveguide case could be investigated. The source tracks were recorded by using a GPS recorder on the boat. Water depth in the entire area was measured, as was the sound speed profile at the receiver. The processed data sets resulted in interference patterns in range-frequency plots. Aided by numerical simulations, sediment sound speed can be estimated over the frequency range of 500 – 4500 Hz.

1 Introduction

Very shallow water near a shoreline provides a natural laboratory for studying sound propagation in a range-dependent environment. In many such areas, the water depth gradually decreases toward the beach, forming an ideal environment for the investigation of propagation in a wedge-shaped waveguide. Several advantages come to mind of conducting underwater acoustics measurements in these regions: (1) easy assess to the near-shore bottom makes it possible to acquire extensive geoacoustic parameters, critical to modeling sound propagation in shallow water; (2) logistical convenience allows for replication of experiments if necessary, a luxury not easily achievable in most underwater acoustics experiments; finally and more importantly, (3) because the water depth is very shallow, the waveguide supports relatively few modes even in the kilohertz range of frequency, hence results from these waveguides can be used to mimic lower frequency (100s of Hertz) sound propagation in typical littoral waters (~ 100 m depth).

In the past, there has been extensive theoretical and numerical work on such wedge problems. The benchmark problems of 1990 [1] offer an overview of the importance of the wedge problem as well as theoretical and numerical efforts devoted to it. Laboratory measurements have also been conducted to study the wedge problem [2]. However, there is a dearth of field data investigating the natural wedge problem. In this paper, results are reported from an experiment conducted in very shallow water with a sandy bottom. A
small boat with outboard motor noise over a usable band of 300 – 4500 Hz was used as the sound source and moved both parallel and perpendicular to shore. A single hydrophone was moored to record the boat sound from different ranges. The goals of this work are twofold: (1) to study the forward problem to understand propagation of sound from a broadband noise source in a wedge environment, and (2) to investigate the possibility of inverting sound speed dispersion in sandy sediments from the simple measurements.

2 Measurements

As part of SAX04 (Sediment Acoustics eXperiment 2004), a set of shallow water propagation measurements was made at a site off the coast of Fort Walton Beach, Florida on 29 October 2004. Extensive in situ sediment characterization measurements were made at the main SAX04 site at around 17 m water depth, including sediment sound speed, density, and attenuation coefficient. The work reported here was done, however, in water depths between 2 m and 10 m. A workboat (a Boston Whaler) was launched from the R/V Seward Johnson as the broadband sound source. Prior to acoustic measurements, 10 waypoints along a straight track perpendicular to shore were laid out and marked between 2 m and 10 m water depths. The locations of these points were recorded using a GPS unit. At these points water depths were measured to within 2 cm accuracy using both a marked line and a Sea Bird CTD unit. At 6 m water depth along this track, an autonomously recording Bioprobe (Bioacoustics Probe by Greeneridge Sciences, Inc.) unit with sampling frequency 12 kHz was moored 2 m above the bottom during the experiment. At the receiver location, a CTD cast indicated that the sound speed was constant throughout the water column ($c_1 = 1534.11 \text{ m/s} \pm 0.11\text{m/s}$).

The acoustics experiment consisted of two types of source boat runs. For the first type the boat steamed at a constant speed (approximately 8 knots) at constant water depth (6 m). It started from roughly 250 m away from the receiver, passed by it, and ended at about 250 m from it. Then a return run was made to finish at the starting point. These measurements provided data of sound propagation in a range-independent waveguide. For the second type the boat ran perpendicular to shore, starting at 2 m water depth, passing by within 5 m of the receiver, and ending at 10 m water depth. Then the boat ran the same course back to the starting point at 2 m water depth. This type of run was repeated 3 times. These measurements provided data for studying up- and down-slope propagation in a wedge. Figure 1 shows the measured water depth along the course of the second type of measurements, with the receiver at zero range denoted by a dark dot. Note that the bottom topography forms a wedge with almost constant slope.

Time-frequency analysis was performed on the data sets for each run and the results were then converted to the range-frequency domain using corresponding GPS track records. The usable frequency band is between 300 Hz and 4500 Hz. The reason for the lower frequency bound is that the outboard motor has a limited ability to create large bubbles that generate low-frequency sound. Fig. 2 shows results for three different propagation scenarios: (a) range-independent, (b) up-slope, and (c) down slope. The interferences pattern in (a) with straight-line striations is the result of modal interference, a phenomenon well documented [3] and related to the waveguide invariant beta. For a
waveguide with constant water sound speed such as the one in question, the striations are expected to be straight lines for the range-independent case [4,5].

For range-dependent cases, we need to first clarify the two different cases: up-slope and down slope. When the boat was moving between 2 m and 6 m depth in our experiment, the result was down-slope propagation with a moving source and fixed receiver; similarly, between 6 m and 10 m, it was up-slope. These cases can be converted to the more normal picture of a fixed source and a moving receiver using reciprocity to swap the source and receiver positions. Then when the boat was moving between 2 m and 6 m depth, the result is up-slope propagation, and when between 6 m and 10 m depth, the result is down-slope propagation. The striations are curved downward for the up-slope case and upward for the down-slope case, as shown in Fig. 2.

3 Model
To understand the striation patterns for the three cases, we proceed by starting from an ideal waveguide with pressure-released boundaries. Then the results will be extended to a penetrable bottom using Weston’s effective depth [6]. We also approximate the bottom slope as constant, although the final approximate results can also be derived independent of this assumption. The striations in a range-frequency plot are the result of interferences between pairs of modes and can be found by following curves of local intensity maxima in the plot [3-5]. To leading order, it is the phase difference between pairs of modes that
Figure 2. Range-frequency plots for (a) constant water depth, (b) up-slope (2 m and 6 m), and (c) down-slope (6 m and 10 m). The color scale is 120-165 dB re 1 µPa²/Hz. The circles are model results.
dictates the shape of the striations. Between modes $m$ and $n$, the phase difference is

$$\phi_{mn}(r, f) = \int_0^r \left[k_m(r') - k_n(r')\right] dr',$$  

(1)

where $f$ is the frequency and $k_m(r)$ is the horizontal wavenumber for mode $m$. Let $f_{mn}(r)$ denote a striation contour in range-frequency space for the mode pair $(m, n)$. By setting the total variation of $\phi_{mn}(r)$ to zero, the derivative of $f_{mn}(r)$ is found to be related to the ratio of the partial derivatives of the phase difference with respect to range and frequency, and this ratio is approximately independent of mode numbers [4,5]. For an ideal waveguide with constant slope the depth $H(r)$ is expressed as $H(r) = H_0 (1-ar)$. We find that

$$\frac{df_{mn}}{dr} = f_{mn} \left. \frac{d\phi_{mn}}{df} \right|_{r=\text{in}} = f_{mn} \frac{H_0}{r H(r)} [1 - \frac{H_0}{H(r)} \frac{k_m^0 - k_n^0}{k_m(r) - k_n(r)}].$$  

(2)

In (2), $r$ is range (which may be negative) measured from the reference point of depth $H_0$, and $k_m(r) = \sqrt{k_i^2 + (m_\pi/H(r))^2}$, with $k_i$ the wavenumber in water. The superscript 0 indicates that the wavenumber is at the reference depth. Equation (2) is an exact expression, but cannot be integrated analytically to obtain the striation curves. A common approximation is made [3] that to leading order the wavenumber of each mode is the same as the wavenumber of the medium. This approximation leads to the simple expression for the derivative and an explicit striation curve:

$$\frac{df_{mn}}{dr} = f_{mn} \frac{H_0}{r H(r)} f_{mn} = c_{mn}(\frac{r}{1-ar}),$$  

(3)

where $c_{mn}$ is a constant dependent on pairs of modes. The above expressions are for a pressure-released bottom. To extend them to a penetrable bottom, we use Weston’s effective depth [6], which has been successfully used by Buckingham [7] for studying shallow water ambient noise. The effective depth is the actual depth plus the added depth $\Delta H = \frac{c_2^2}{2c_s^2} \rho \sin \theta \sin k \Delta \theta$, where $c_2$ is the bottom sound speed and $\theta$ the critical angle. The added depth is inversely proportional to frequency and for the experiment conditions it is insignificant for frequencies above 500 Hz. In Fig. 2, subplots (b) and (c), frequency-range relation in (3) with different constants is plotted on the data. Note that the model is in excellent agreement with the data for both the up- and down-slope cases.

4 Sediment Dispersion

When modeled as a Biot medium, sandy sediment sound speed has a unique frequency-dependency or dispersion. Experimental data taken in the same area in SAX99 suggest that such dispersion may have been measured [8], but further confirmation is needed, especially at lower frequencies. It is relatively easy and more reliable to measure sound speed at high frequencies; data obtained below 1000 Hz have large uncertainties. However, the predicted dispersion by the Biot model has the largest effect around 1000 Hz. Assuming that measured sound speed at higher frequencies is dependable, the main difference between a non-dispersive bottom and a dispersive one is that below 1000 Hz, sound speed for the non-dispersive case is about 100 m/s greater than that of the
dispersive case [8]. It is the intention of this section to discuss the possibility of inverting for the frequency dependence of sediment sound speed using the experiment data. There are two assumptions made in our following discussion: (1) the sediment is a homogeneous half space, and (2) the sediment parameters measured nearby at deeper water are the same in the shallow water.

Parabolic Equation (PE) simulations are performed for two cases for the upslope wedge between 2 m and 6 m water depth. The first case includes dispersion as given in Fig. 3 [8]; for the second case, the sediment sound speed is a constant corresponding to the value for the dispersive case at 4000 Hz. Environmental parameters measured at 17-20 m depth in the same region are used as the PE input. Fig. 4 shows the simulations for the two cases along with data.

![Figure 3. Sediment sound speed dispersion as predicted by Biot model [8].](image)

Between the two simulations, we find that there are more striations in the non-dispersive case than the dispersive case, because the former has higher sediment sound speed than the latter, hence supporting more modes, hence more mode pairs. Comparing the models to data, the overall pattern favors the dispersive model when one observes (a) the number of striations and (b) a lack of striation in both data and the dispersive model at the upper right hand corner (lower frequency and shallower water). When a waveguide becomes shallow in a wedge, at some depth the guide can support only one mode for a given frequency, higher modes have been cut off. Then, the striation should cease to exist. The frequency \( f_2 \) at which the second mode is cut off is [9]

\[
f_2 = \frac{1.5c_1c_2}{2H(r)\sqrt{c_2^2 - c_1^2}}
\]

In the model sub-plots of Fig. (4), the blue curve is the cut-off frequency versus range calculated from (4) using the corresponding sediment sound speed. The blue curve in the data sub-plot is the same as the one in the dispersive model. As expected, the non-dispersive model has a lower cut-off frequency. It is noticeable that above the cut-off frequencies, there are still striations, although diminishing. This is because mode cut-off is a gradual process, not a sudden truncation [9]. Again we find that the changing nature of the striation patterns in the data compare well with the dispersive model. It should be
Figure 4. Comparison between model and data: (a) non-dispersive model, (b) dispersive model, (c) data. The blue curve in each case is the line where the second mode is cut off.
pointed out that the discussion of dispersion is not yet fully quantitative and is incomplete. The next steps are to understand the detailed behavior of the striations and to study the sensitivity of using such data for inversion.

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LOW-FREQUENCY SEDIMENT SOUND SPEED MEASURED USING A LIGHT AIRCRAFT AS AN ACOUSTIC SOURCE

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A technique, recently developed for estimating the speed of sound in marine sediments, is based on the Doppler shift of the engine and propeller harmonics from a light aircraft flying at low-level over the sea. A series of experiments has been conducted in two locations: the Pacific Ocean, north of Scripps pier, La Jolla, southern California and, as part of the ONR-supported SAX04, in the northern Gulf of Mexico, off Destin, Florida. In these experiments, the aircraft harmonics are detected at a sensor station comprising a microphone about 1 m above the sea surface, an autonomous vertical array of hydrophones spanning the water column, and several hydrophones buried to a depth of approximately 1 m in the sediment. Usually, the aircraft is detectable on all the sensors. On the sub-surface sensors the nominal detection range is 600 m, although this may be reduced in noisier environments such as that encountered during SAX04. Inversions of the Doppler-shifted harmonics, based on a newly developed theoretical model of acoustic propagation in a multi-layer waveguide, return the sound speed and attenuation in the sediment. The correlations that are known to exist between the sound speed and the remaining geoacoustic parameters are then used to estimate the shear speed, the shear attenuation, the porosity, the density and the mean grain size of the sediment.

1 Introduction

In unconsolidated marine sediments, the dispersion curves, expressing the sound speed and attenuation as functions of frequency, are fairly well established, at least at frequencies above a few kiloHertz, from the in-situ measurements of several investigators, notably Hamilton[1] and Richardson[2]. Basically, their in-situ techniques consist of a time-of-flight measurement over a known distance. At lower frequencies, below 1 kHz or so, a time-of-flight technique becomes impractical because of the excessively long travel path that is required. Accordingly, few good quality measurements exist of the dispersion curves in marine sediments in the lower-frequency regime.

In a pair of classic papers on dispersion in saturated, unconsolidated, porous media, Biot[3,4] developed a theory, based on the relative flow of pore fluid past the mineral frame, which predicts dispersion curves similar to those for an isotropic viscous fluid[5]: below a threshold frequency the sound speed asymptotes to Wood’s value[6] and the attenuation scales as the square of frequency; and above the threshold frequency the sound speed asymptotes to a constant, greater than Wood’s value, and the attenuation scales as the square-root of frequency. More recently, as an alternative to Biot’s approach, Buckingham[7] has developed a theory in which grain-to-grain interactions
govern the shape of the dispersion curves in unconsolidated marine sediments. The grain-
to-grain theory predicts weak dispersion in the sound speed, of the order of 1% per
decade of frequency, and an attenuation that scales essentially as the first power of
frequency. As with the Biot theory, the expressions for the dispersion curves from the
intergranular theory are physically reasonable in the sense that they satisfy the Kramers-
Kronig relations.

The principal differences between the predictions of the two theories occur at lower
frequencies, below a few kHz, in the very region where experimental data are so scarce
(see Fig. 1). In an attempt to provide reliable measurements of the low-frequency sound
speed and attenuation in marine sediments, a technique has been developed, as described
below, in which the sound from a light aircraft, flying at low-level over shallow water, is
inverted to yield the geoacoustic parameters of the sea bed.

2 Aircraft sound

Small, propeller-driven aircraft, which are readily available at modest cost, have
application as sound sources in ocean-acoustics experiments. The sound from such an
aircraft is produced mainly by the propeller and to a lesser extent the engine, both of
which produce a series of harmonics over the frequency band from about 50 Hz
(depending on the speed of the engine and the number of propeller blades) upwards. An
example of a spectrum from a Diamond Star DA40 (single four-cylinder, four-stroke
engine with a 3-blade propeller), measured with the aircraft stationary on the ground and
the engine running at 2000 rpm, is shown in Fig. 2. The harmonics are clearly visible as
prominent peaks in the spectrum, in this case extending up to at least 2 kHz. Below 1
kHz, the propeller and engine harmonics are interspersed, whereas at higher frequencies
the harmonics are due mainly to the propeller with only a minor contribution from the
engine.

When an aircraft is in flight, the spectrum of the sound received on the ground or
beneath the sea surface retains much the same harmonic structure as seen in the static
measurements, although frequency components above about 800 Hz are heavily
attenuated. Additionally, as a result of the relatively high Mach number, typically in the
region of 0.18, a significant Doppler shift occurs, which is observed as an up-shift
(down-shift) in the frequency of each harmonic ahead of (behind) the aircraft. These Doppler shifts provide the means by which the sound speeds in the multi-layer environment (air-water-sediment) are obtained.

Figure 2. Harmonics in the spectrum of the sound from a static Diamond Star DA40.

3 Doppler frequencies, arrival angles and normal modes

Consider an aircraft flying horizontally at uniform speed $V$ on a track that passes directly over a ground-based microphone. Assuming an isotropic atmosphere with sound speed $c$, then the Doppler-shifted frequency $f$ of a harmonic with unshifted frequency $f_0$ is given by the expression

$$f = \frac{f_0}{1 - \beta \cos \theta},$$

(1)

where $\beta = V/c$ is the Mach number and $\theta$ is the angle of elevation. Clearly, the maximum [$f_{\text{max}} = f_0/(1-\beta)$] and minimum [$f_{\text{min}} = f_0/(1+\beta)$] shifted frequencies occur, respectively, when $\theta = 0$ (aircraft far out on approach) and $\theta = \pi$ (aircraft far out on departure). At intermediate ranges, the Doppler-shifted frequency lies somewhere in the interval between $f_{\text{min}}$ and $f_{\text{max}}$ depending on the elevation angle, $\theta$. It follows that, by measuring the shifted frequency of a harmonic, the arrival angle of the associated ray can be inferred. That is to say, a point measurement of the Doppler-shifted frequency yields the direction of the source.

The idea of linking frequency with directionality may be extended to the more complicated air-sea-sediment environment. In this situation, sound rays from an aircraft that are steeper than the critical grazing angle of the air-sea interface ($\approx 13^\circ$) will penetrate into the channel, where they will excite normal modes. Bearing in mind that each normal mode may be represented in terms of a pair of upward- and downward-propagating eigenrays with a unique grazing angle, it is apparent from Snell’s law that a given normal mode will be excited by a ray incident on the sea surface from a specific direction. For a particular normal mode, excited by a particular aeroplane harmonic, the direction of the eigenrays is fixed, hence the direction of the associated airborne ray is
also fixed, from which it follows that each mode propagates at a unique characteristic frequency.

Taking the argument one step further, the frequency of each mode depends not only on the angle of incidence of the airborne ray but also on the properties of the channel, including the bottom boundary conditions, which are governed by the geo-acoustic parameters of the sediment. This suggests that the time series of the sound from an aircraft overflight, as measured at a point receiver in the channel, contains information about the properties of the sea bed.

By performing a high-resolution FFT on the acoustic signature of an overflight, as detected on a hydrophone in the water column, a spectrum such as that shown in Fig. 3 is obtained. In this case, the recording was made on 20 October 2003 in the shallow channel (14.4 m depth) north of Scripps pier, with a near-bottom hydrophone. The aircraft was a Diamond Star DA40 flying straight and level at a nominal altitude of 66 m, speed of 60 m/s and engine turning over at 2400 rpm.

Note that the abscissa in Fig. 3 spans a narrow frequency band just 20 Hz wide, extending from 70 to 90 Hz. Only the first engine harmonic falls within this range, with unshifted frequency $f_0 = 79$ Hz. The two prominent peaks at frequencies of approximately 82 Hz and 76 Hz are the up- and down-shifted first mode and, similarly, the two inner peaks at approximately 81 Hz and 79 Hz are the second mode. Each mode appears as two peaks in the spectrum because the time series is non-stationary, running from far
out on approach, through CPA to far out on departure, and thus includes both up-shifted and down-shifted signatures. Obviously, if the airborne source were somehow made motionless in the sky, there would be no Doppler shifting and all the modal peaks in Fig. 3 would collapse onto the unshifted frequency, $f_0$.

4 Flying experiments

The Doppler-shifted frequencies of the modal peaks which appear in high-resolution spectra such as that in Fig. 3 form the basis of an inversion technique for estimating the speed of sound in the sediment. From an acoustic propagation model of a moving, airborne source in a three-layer air-sea-sediment waveguide, a theoretical spectrum is computed and compared with the spectral data. By adjusting the bottom parameters appropriately, the best match between the modelled output and the measured spectrum is determined. This yields the sound speed in the bottom directly. Bottom attenuation is obtained from the spatial gradient of the modal amplitudes with the aircraft on approach or departure. The remaining sediment properties, including shear speed and attenuation, porosity, density and mean grain size, are obtained from the correlations that are known to exist between the geo-acoustic parameters of the bottom[2,10,11].

Figure 4. Spectrograms from the Scripps site showing Doppler-shifted harmonics from a Diamond Star DA40 as it overflies the sensor station. The grey scale is in dB re: $1 \mu Pa^2$.

Flying experiments aimed at recovering sediment properties have been performed in two locations: 1) over the past two years at the site mentioned earlier, north of Scripps pier, where the bottom is a fine sand with mean grain diameter of approximately 125
micron; and 2) in the northern Gulf of Mexico, off Fort Walton Beach, near Destin, Florida, during October 2004, as part of the ONR-sponsored SAX04 initiative. Of the two, the SAX04 site was somewhat noisier, due partly to the presence of the R/V Seward Johnson and also the considerably rougher seas in the aftermath of hurricane Ivan. The bottom at the SAX04 site is a medium sand with mean grain size of approximately 400 micron[8].

The acoustic sensors used in the experiments have been in a constant state of evolution. In the latest configuration, they consist of a microphone about 1 m above the sea surface, a fully autonomous vertical array of 11 non-uniformly spaced hydrophones spanning the water column, and several hydrophones and shear sensors buried in the sediment to a depth of less than 1 m. The bottom-moored vertical array has an on-board recording capability and the data can be down-loaded remotely over an RF link. For power conservation, a separate RF link allows the array to be switched on and off remotely.

Fig. 4 shows spectrograms of the acoustic signature of a Diamond Star DA40 in air, water and sediment as it flies over the sensor station at the Scripps site. In this particular example, the water-column phone was at the bottom of the vertical array, near the sea bed, and the buried phone was approximately 0.5 m deep in the sediment. Note the Doppler down-shift in the harmonics as the aircraft flies through the closest point of approach (CPA) and, most importantly, the fact that the down-shift is far greater in air than in water or sediment. In fact, the difference frequency in a harmonic on either side of CPA scales with the sound speed in the local medium, which provides the essential basis for the geo-acoustic inversions.

The Doppler-shifted harmonics shown in the air and water spectrograms of Fig. 4 resemble those observed by Ferguson[12] above and below the sea surface as a turboprop aircraft flew overhead at a speed of 250 knots (125 m/s). Prior to our flying experiments at the Scripps site, no observations of the sound from an aircraft in a marine sediment are known to the authors. Provided the ambient noise levels are not too high, which is usually the case at the Scripps site, where the sea state is typically 1 or less, the Diamond Star aircraft can be detected beneath the sea surface for approximately 10 seconds either side of CPA, which translates into a detection range of about 600 m.

5 Geo-acoustic inversion estimates, Scripps site

The high resolution spectra of individual harmonics, from either the engine or the propeller, such as that shown in Fig. 3, yield the Doppler-shifted frequencies of several modal peaks. To obtain the sound speed in the sediment, these frequencies are compared with the modal frequencies predicted by a wavenumber-integral model of the acoustic field from a moving, airborne source in a three-layer air-water-sediment waveguide. The computation may be performed in several different ways, as discussed in detail by Giddens[13].

Taking the first engine harmonic, with unshifted frequency $f_o \approx 79$ Hz, the average compressional wave speed found for the sandy sediment at the Scripps site from a dozen or so overflights of the Diamond Star on 20 October 2003 is 1650±30 m/s. As the sound
speed in the water column was 1515 m/s, obtained from a Sea Bird temperature profiler, this equates to a sound speed ratio of 1.0891 and a critical grazing angle of 23.3°. From the gradient of the modal amplitudes in the first engine harmonic, the average sediment attenuation is estimated to be 0.018±0.015 dB/m. The errors cited here on the sound speed and attenuation are the standard deviations of the values obtained from the set of overflights.

Buckingham[7,14] has derived a set of relationships connecting the speed of sound in a sediment to the remaining geoacoustic parameters. From these expressions, using a compressional speed of 1650 m/s, the following estimated values are obtained for the Scripps sediment, valid at the frequency $f_o = 79$ Hz of the first engine harmonic: shear speed = 95.81 m/s; shear attenuation = 34.23 dB/m; compressional attenuation = 0.01 dB/m; porosity = 0.3999; density = 2040 kg/m$^3$; and mean grain diameter = 121 micron.

Note that the computed compressional attenuation (0.01 dB/m) represents the intrinsic attenuation due to the irreversible conversion of acoustic energy into heat, whereas the measured value (0.018 dB/m) is the effective attenuation, which in addition to the intrinsic attenuation includes additional sources of loss such as scattering from shell fragments. The computed intrinsic value is therefore expected to be less than or equal to the effective measured value, which is in fact the case here. Note that the two attenuation values differ by less than the error on the measured attenuation, so it is possible that they are essentially equal. This would not be unreasonable, since at such a low frequency, corresponding to a wavelength of the order of 20 m, it seems unlikely that scattering would be a major dissipation mechanism.

6 Concluding remarks

The values cited above for the physical parameters (grain size, etc.), as obtained from the inversion of aircraft sound, are consistent with the known properties of the fine sand sediment at the Scripps site. As for the wave speeds and attenuations, little is known of the wave properties of sediments at such a low frequency, making comparisons with previous observations difficult. However, when the aircraft inversions are taken in conjunction with the higher-frequency measurements of Hamilton[15,16], it would seem to indicate that frequency dispersion in the compressional speed is extremely weak and that the compressional attenuation scales essentially as the first power of frequency. Such conclusions, however, are tentative, since more data are needed to fill the gap between the low frequencies of the aircraft measurements, in the region of 100 Hz, and the tens of kiloHertz of more conventional techniques.

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SPATIAL AND TEMPORAL VARIATIONS IN SEDIMENT COMPRESSIONAL WAVE SPEED AND ATTENUATION MEASURED AT 400 KHZ FOR SAX04

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Diver cores were collected from various locations within the SAX04 site from 21 September to 3 November 2004 and compressional wave speed and attenuation were measured every centimeter at 400 kHz. Although measured values of sound speed and attenuation fall within established ranges for archived data from similar medium quartz sands, fluctuations in measured values were observed in the data that can be explained by the pattern of storm events during the experiment. Three significant storm events occurred during the period in which cores were collected: a category-4 hurricane, a tropical storm, and an early-winter cold front. Following these events values of sound speed initially increased, but then later decreased; values of sound attenuation did not show this pattern, but were generally lower (mean = 92.1 dB/m) than values measured five years ago at the SAX99 site nearby (mean = 177.5 dB/m). Values of sediment sound speed measured at the SAX04 (mean velocity ratio = 1.162) were generally greater than those measured at the SAX99 site (mean velocity ratio = 1.155). Values of coefficient of variation for sediment sound speed were lower for SAX04 measurements (0.55%) than SAX99 measurements (0.70%). Lower values of sound attenuation measured at the SAX04 site was probably due to a lack or absence of shell fragments that may have been segregated by the sediment resuspension and settling during and after storms. The roles of sediment transport, grain size, grain sorting, porosity, and density in controlling sediment compressional wave speed and attenuation at the SAX04 site are discussed.

1 Introduction

Sediment compressional wave speed and attenuation are important parameters required in assessing acoustic scattering from the sea floor [1,2]. The contrast between the sound speed within the sediment and the sound speed in the overlying water is the chief characteristic determining the fate of acoustic energy reaching the sea floor. The magnitude of the attenuation of the acoustic energy within the sediment determines to what depth the sound penetrates the sea floor (and how much scattered energy is reradiated back out of the sea floor). Moreover, fluctuations in sediment sound speed may be responsible for the scattering of acoustic energy penetrating into the sediment.

As part of the geoacoustic measurements collected by the Naval Research Laboratory during Sediment Acoustics eXperiment 2004 (SAX04), sediment compressional wave speed and attenuation were determined at 400 kHz on 58 diver cores. The cores were collected throughout the experiment, from 21 September to 3
November and measurements were made aboard ship within 24-36 hours after collection. Consequently, the measurements exhibit both spatial and temporal variations in these parameters for the SAX04 site.

The important factors controlling sediment compressional wave transmission in sands are porosity, grain size, grain sorting, grain shape, grain packing and mineralogy; although, porosity and grain properties are correlated factors [3]. Previous studies of the area off Fort Walton Beach, Florida show the sediment to be a relatively homogeneous, moderately well sorted, medium quartz sand [4]. Differences in sound speed transmission within the sediment are thought to be essentially a matter of grain packing, which can be changed by bioturbation and hydrodynamic events [5]. Because there were three major storms during the execution of SAX04, the effects of reconfiguring the grain-to-grain structure by storm resuspension and sedimentation may be examined.

2 Methods

Diver cores that were made from 5.9-cm-inside-diameter, clear polycarbonate tubing cut into 48-cm lengths were used to collect the sediment samples from various locations within the SAX04 experiment site. Each core was carefully handled and kept upright during the collection, the sealing of the top and bottom, the recovery through the air-water interface, the storage in the temperature-controlled laboratory, and the acoustic measurements. Upon recovery, each core was sealed with tape to prevent draining of the overlying water and the level of the sediment-water interface was marked on the core to monitor settling.

After allowing the cores to equilibrate to laboratory temperature for at least 24 hours, sediment compressional wave speed and attenuation were measured directly through the core liner with “earmuff” transmit and receive transducers, function generator, pulse generator, dual band-pass filter, and digital storage oscilloscope as depicted in Fig. 1 [6]. Measurements were made at 400 kHz at 1-cm increments downcore.
Figure 1. Equipment used to measure compressional wave speed and attenuation (left) and a close-up view of the “earmuff” transducers with a core inserted between the transducers (right).

Sound speed ratio is calculated as the ratio of sound speed in sediment to sound speed in the overlying water. Sediment compressional wave attenuation values are expressed as dB/m and normalized to the acoustic frequency as dB/m·kHz (k, after Hamilton) [7]. Sediment porosity was measured at 2-cm intervals after transport of the cores to a shore-based laboratory from one to 33 days after collection by divers. Bulk density was calculated from porosity values and measurement of grain density. Grain size distribution was determined by dry-sieving for sand- and gravel-sized particles and pipettes for the silt/clay fraction.

3 Results

Compressional wave speed ($V_p$) ratio and attenuation as a function of sediment depth is illustrated in Fig. 2. Low values of $V_p$ ratio correspond to mud layers and flasers [8] and these features as well as the attenuation values associated with them will be disregarded in all of the subsequent figures, tables, and results for the purpose of this analysis of compressional wave energy in sand. Sediment sound speed increases slightly downcore to about 15 cm depth, and is generally constant below that depth. Sediment sound attenuation exhibits a slight increase throughout the measured depth. Values of attenuation show great variability in the top 14 cm, and these high values that depart from the overall trend are probably indicative of scattering of the 400-kHz sound by the mud-sand interfaces of mud layers and flasers. Note the relative absence of high attenuation values below the sediment depth where the mud is found in Fig. 2.
Figure 2. Compressional wave speed \( (V_p) \) ratio (left) and compressional wave attenuation (right) as a function of depth in the sediment for the SAX04 site.

During SAX04 three significant storm events occurred: Hurricane Ivan, a category 4 storm, made landfall 100 km west of the experiment site on 16 September; tropical storm Matthew approaching from the west produced strong southwest to west winds during 8-10 October; and a cold front passed through the area on 2 November. These storm events effectively divided the experiment into four periods, which were determined from patterns of sediment acoustic data collected from cores (Table 1). The average sediment sound speed excluding obvious mud layers is 1775.6 m/s calculated for 23°C, 35 ppt, and atmospheric pressure and the average sound speed ratio is 1.162 with a coefficient of variation (CV) of 0.55%.

Table 1. Values in sand of compressional wave speed \( (V_p) \), compressional wave speed ratio, and compressional wave attenuation \((\text{dB/m}, \text{dB/m·kHz})\) for four periods during SAX04; values of coefficient of variation (%) for the data; values of the data for all periods of SAX04.

<table>
<thead>
<tr>
<th>Period</th>
<th>Dates</th>
<th>( V_p ) (m/s)</th>
<th>( V_p ) Ratio</th>
<th>Att. (dB/m)</th>
<th>( k ) (dB/m·kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>post Ivan</td>
<td>21-30 Sep</td>
<td>1779.9</td>
<td>1.164</td>
<td>87.8</td>
<td>0.22</td>
</tr>
<tr>
<td>pre Matt</td>
<td>1-5 Oct</td>
<td>1770.6</td>
<td>1.158</td>
<td>99.9</td>
<td>0.25</td>
</tr>
<tr>
<td>post Matt</td>
<td>12-31 Oct</td>
<td>1776.0</td>
<td>1.162</td>
<td>90.2</td>
<td>0.23</td>
</tr>
<tr>
<td>post cold front</td>
<td>3 Nov</td>
<td>1782.7</td>
<td>1.166</td>
<td>89.8</td>
<td>0.23</td>
</tr>
<tr>
<td>All</td>
<td></td>
<td>1775.6</td>
<td>1.162</td>
<td>92.1</td>
<td>0.23</td>
</tr>
</tbody>
</table>

Immediately following Hurricane Ivan, suspended sediments settled and fine-grained mud brought from the lagoon north of the barrier island was deposited on top of the freshly settled sand. For 14 days following Ivan (post Ivan), benthic fauna appear not to have begun to recover from the catastrophic resuspension of the sediment in which they were living. Indeed, with the turbulent fluidization of their habitat sustained for several hours, whatever fauna that were not destroyed were irretrievably buried. In the next 5 days before the effects of Matthew began to be felt, values of sediment sound speed and attenuation appeared to change, perhaps due to a delayed recovery response of the benthic fauna. There is a significant difference \( (\alpha << 0.001) \) in \( t \)-tests of means for sound speed and attenuation values between the four successive periods, with the exception of the attenuation values between the post-Matthew and post-cold-front periods.

Average sediment sound speed ratio at the SAX04 site (1.162) was greater than the average value at the nearby SAX99 site (1.155); average sediment sound attenuation at the SAX04 site (92.1 dB/m) was less than the average value at the SAX99 site (173 dB/m) [4]. Moreover, there were significant statistical differences \( (t\text{-test: } \alpha << 0.001) \) between the average SAX99 sound speed ratio and each of the average sound speed ratios for the four SAX04 periods. The average SAX99 sound attenuation value was also statistically different from any of the average SAX04 sound attenuation values for the
four periods. The coefficient of variation was lower for SAX04 sound speed values (0.55%) than that for SAX99 sound speed values (0.70%). Coefficients of variation for SAX04 and SAX99 sound attenuation values were similar (30.3 vs. 29.9%). A comparison of SAX04 and SAX99 sediment properties of sound speed ratio, sound attenuation, porosity, mean grain size, and sorting are displayed in Table 2. SAX04 sand has faster and less variable sound speed, less attenuation, finer and less variable mean grain size, and is slightly better sorted than SAX99 sand.

Table 2. Comparison of measured properties of SAX04 and SAX99 sands. CV(%) in parentheses.

<table>
<thead>
<tr>
<th>Site</th>
<th>V_p ratio</th>
<th>Att. (dB/m)</th>
<th>Porosity (%)</th>
<th>MGS (φ)</th>
<th>Sorting (φ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAX04</td>
<td>1.162 (0.55)</td>
<td>92.1 (30.3)</td>
<td>36.7 (1.84)</td>
<td>1.51 (11.3)</td>
<td>0.61 (9.76)</td>
</tr>
<tr>
<td>SAX99</td>
<td>1.155 (0.70)</td>
<td>173.0 (29.9)</td>
<td>37.2 (1.92)</td>
<td>1.27 (13.3)</td>
<td>0.63 (8.06)</td>
</tr>
</tbody>
</table>

4 Relationships of sound speed and attenuation to physical properties

There are established empirical relationships between sound speed and sediment physical properties such as porosity, density, and grain size [9-11]. For sands, sound speed typically increases with decreasing porosity, increasing mean grain diameter, and decreasing sorting (a measure of dispersion around the mean grain size). Relationships between sound attenuation and sediment porosity, density and grain size are poorly defined, though the presence of coarse grains that can scatter high-frequency sound can contribute to high attenuation values [12].

Figure 3. Sediment porosity (%) as a function of depth in the sediment for the SAX04 site.

Based on measurements on the same cores from which the sediment sound speed was measured, porosity, density and grain size of the SAX04 sediment exhibit little variability throughout the experiment site. Sediment porosity profiles (exclusive of high-
porosity mud layers) from 22 of the 58 collected cores exhibit only small variations within the sandy sediment (Fig. 3). Sediment bulk density profiles (not shown) exhibit the same, though inverted, pattern. Sediment mean grain size profiles (exclusive of mud layers) of 11 of the 22 cores assayed for porosity and bulk density also show little variation with sediment depth or location within the site (Fig. 4). Sediment sorting also shows little variation with depth in the sediment or location (Fig. 4). Moreover, the average value of sediment porosity at the SAX04 site, derived from all 11 locations fall within the range of variation for each site; average values of mean grain size show slightly more variation due to mud clasts (Fig. 5). Thus, it is unlikely that differences in sediment sound speed portrayed in Fig. 2 are due to spatial variability of sediment properties within the experiment site.

Figure 4. Sediment mean grain size (φ) and sorting (exclusive of mud layers) as a function of depth in the sediment for the SAX04 site. Phi (φ) units are –log₂(dia. in mm).
Figure 5. Sediment porosity (%) and mean grain size (φ) of sand as a function of location within the SAX04 site. Bars are ± 1 standard deviation. Phi (φ) units are −log₂(dia. in mm).

Based on an analysis of historical wave data from an offshore NOAA data buoy [8] and the changes in the sound speed profiles displayed in Fig. 2, we believe that at least the top 20 cm of sand was suspended during Hurricane Ivan and redeposited upon the passing of the storm to the north. Indeed, a slight fining-upward trend in mean grain size is evident in Fig. 4, indicating the grain sorting that would occur during settling under the waning effects of waves and currents from the passing storm. Immediately after the storm, the arrangement of the freshly settled grains should have presented a low-density, high-porosity packing of the sand. Over time, with the resumption of biological mixing from benthic infauna, the packing should have changed to a higher density conformation, especially in the top 10-15 cm where the infauna predominantly reside.

Our results, however, indicate that changes in porosity and density were not commensurate with the fluctuations of sediment sound speed. Thus, the changes in the sediment effected by storms and bioturbation, as evidenced by changes in sediment sound speed and attenuation, had little effect on the spaces among sand grains. This conclusion relies on the assumption that the sediment porosity, density, and grain packing were not altered during the interim between the time the cores were logged on board and the cores were later assayed for water content ashore. Although precautions were taken during storage and transport (refrigeration and isolation from agitation), some settling may have occurred in the interim. The sediment-water interface was marked on the core liner upon recovery of the core and before the core was logged acoustically. The amount the core sediment settled was noted immediately before analysis for water content. Of the 22 cores assayed for water content, 16 showed some amount of settling that varied from 1-5 mm. Adjusting for the length of each core, settling varied from 0.6-3.3 % of the core volume and averaged 1.3 % for the 16 cores. Of the six cores with volume changes due to settling greater than 1 %, three had mud layers or clasts that, as de-watering occurred, contributed to the settling. Settling may have been facilitated by bioturbation more than any other factor, because the cores collected immediately post Ivan did not exhibit evidence of bioturbation or settling. Until porosity can be
determined immediately after acoustic logging, the correlation between sediment porosity and sound speed is uncertain for these data.

An alternate explanation for the temporal variations in sediment acoustic properties is that differences in the grains are responsible. That is, the grain shape or geometry of grain aggregations, influenced by the settling of grains during the post-storm periods, may control sound speed and attenuation in sediments. During the waning of the storms, the larger and more spherical grains settle first; the finer and more platy grains settle later. This scenario would result in a mixture of smaller spherical and larger platy grains near the surface and a dearth of platy grains deeper in the sediment at the beginning of SAX04. Such a segregation of grain shapes would not necessarily be accompanied by differences in average values of porosity or grain size, but might result in faster sound speeds and lower attenuation in the fine/platy aggregation than in the coarse/spherical grains deeper in the sediment. Conceivably, bioturbation would tend to destroy such a vertical segregation of grain shapes and tend to bring sound speed and attenuation values back to those values typical of well mixed sediments. According to this scenario, (1) the locus of change in sound speed and attenuation before and after storms would be the uppermost centimeters where the fauna are the most active and (2) the biogenic mixing response to the storms would be more rapid following weaker storms and delayed or retarded following catastrophic storms (e.g., Hurricane Ivan). This is, in fact, the pattern exhibited by the data in Fig. 2 and Table 1. An examination of the grain shape of SAX04 sediments as a function of depth in the sediment is warranted in order to substantiate these observations. Furthermore, a physical model to explain the acoustic behavior of the fine/platy aggregation is required to validate these assumptions.

Concerning the presence of calcareous shell fragments and their effect on sound attenuation: we do observe a significant ($\alpha << 0.001$) depletion in gravel-size grains, which are predominantly mollusk shells and shell fragments, in SAX04 sediment when compared with nearby SAX99 sediment (0.05% vs. 0.72%, respectively). This observation and the observation of lower attenuation in SAX04 sediment when compared with nearby SAX99 sediment (Table 2) imply that scattering from shells and shell fragments contribute to acoustic attenuation.

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References


IN SITU ASSESSMENT OF THE ORIENTATION AND PERFORMANCE OF BURIED DIRECTIONAL RECEIVERS FOR USE IN SEDIMENT ACOUSTIC STUDIES

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A technique is being developed to measure the speed of sound in marine sediments at discrete frequencies from 0.6 to 10 kHz by transmitting pulses from acoustic projectors within the water column and measuring the pressure and acceleration components of the acoustic field on receivers buried in the seabed. The analysis and interpretation of this data set requires the location and orientation of the receivers. The receivers are vector sensors that measure three-axis acceleration and pressure thereby allowing acoustic intensity, impedance, and arrival angle to be computed. A special jig was designed to bury four vector sensors in the seabed, and to control their approximate orientation and depth of burial in the process. Following sensor burial, the jig was fully extracted to leave only the sensors and their associated cables in the seabed. This paper presents the technique that has been developed to determine the orientation of the vector sensors in situ. This is accomplished by analyzing the amplitude and phase response of the acceleration signals to transmissions from three orthogonal directions, using two acoustic projectors also buried in the seabed by the jig and a third in the water column directly above the buried receivers. The orientation is determined by the mean value of the measured arrival angle and the performance is evaluated by examining the stability of arrival angle as a function of frequency.

1 Introduction

Sediment sound speed measurements during several recent experiments indicate that the speed of sound travelling through marine sediments depends on the frequency of ensonification when the seabed is principally composed of sand [1]. In all cases, the speed of sound was found to increase with increasing frequency. This dispersion behaviour has implications for any application or research that involves the ratio between water and sediment sound speeds. For example, it defines the critical angle, an important quantity in the detection of buried mines, and more generally in the science of underwater acoustics as it is used in modeling bottom loss, scattering, and propagation. The dispersive behaviour observed during SAX99 is generally consistent with Biot theory using model parameters based on geophysical measurements made at the site [1].
Measurements from 1 to 10 kHz are particularly important since the most significant differences in model behaviours are manifest in this band. Unfortunately, only a limited data set was available in this frequency regime. To address this deficiency in SAX04 [2], DRDC Atlantic and the Applied Research Laboratory at the Pennsylvania State University conducted a series of joint experiments to measure the acoustic wave speed in the frequency band 0.1 kHz – 20 kHz using several complementary techniques. It is hoped that employing several independent techniques to measure the sound speed will provide a more robust estimate. One technique involved transmitting acoustic pulses from the water column into the seabed at different grazing angles and measuring the pressure and acceleration components of the acoustic field on receivers buried in the seabed. The preliminary analysis [3] revealed that the interaction between the refracted and evanescent fields might limit the applicability of Snell’s Law and that, as anticipated, an assessment of sensor orientation and performance was required.

Figure 1: Experimental geometry to measure sediment sound speed using complementary techniques. A three-point mooring is used to adjust the position of a projector in the water column, TX_{ABC}, from vertical incidence (as used in this paper) to shallower grazing angles. Buried vector sensors, V1-V4, measure the pressure and tri-axial acceleration of the acoustic field. Two buried projectors, TX_A and TX_D, are used in time-of-flight measurements and for determining the position and orientation of the buried vector sensors. Hydrophones, H1-H3, are used to determine the position of TX_{ABC} and as receivers in other experiments.

This paper begins with a description of the experimental geometry, followed by the theory for processing vector sensor signals to determine arrival angle. The arrival angles
of acoustic transmissions from three orthogonal directions are then analyzed to determine the orientation of a buried vector sensor relative to its intended orientation. The frequencies at which stable and consistent arrival angle estimates are obtained define a band in which the fidelity of the vector sensor is such that analysis of the SAX04 data set may be pursued.

2 Experimental Setup

The experiment was conducted in the Gulf of Mexico at 086°38.706’W, 30°23.232’N about 2 km off the coast of Fort Walton Beach, Florida. All experiments were conducted from a portable lab situated aboard the RV Seward Johnson. The water depth at the experimental site was approximately 17 m. A purpose built burial jig was used to deploy 6 transducers (2 projectors and 4 vector sensors) in the top 1 m of seabed with known horizontal separations [3]. After inserting the transducers, the insertion tools and burial jig were removed leaving only the low profile cabling for each sensor. The two buried projectors, TXA and TXD in Fig. 1, were ITC-1032 spherical projectors measuring approximately 7 cm in diameter. The in-water source, TXABC in Fig. 1, was a Sensor Technologies SX-100, a cylindrically shaped flextensional projector approximately 6 cm in diameter and 14.8 cm in length. A three-point mooring (Fig. 1) kept the source at a stable location in the water column and ensured that the seabed directly beneath it was free of any mooring apparatus. The mooring also allowed the grazing angle to be varied while keeping the broad main lobe radiating from the ends of the cylinder pointing at a reference point on the seabed [4]. For the experiments described in this paper, TXABC was located 8.5 m above the seabed, directly above V1 and V2 (Fig. 1).

Figure 2. Beam pattern calibrations of the pressure and two acceleration components of a TV-001 vector sensor measured at four of the frequencies used in experiments.
The buried receivers were Wilcoxon model TV-001 “vector sensors” denoted V1-V4 in Fig. 1. A vector sensor consists of an all-in-one pressure plus tri-axial accelerometer. This combination of signals permits several forms of analysis using: the pressure alone, the acceleration components alone, and combinations of pressure and acceleration signals to calculate acoustic intensity and impedance. The housing of the vector sensor was approximately 4 cm in diameter and 7 cm in length. Before the experiment, each vector sensor was calibrated at the discrete frequencies used in the experiment: 0.6, 0.8, 1.0, 1.2, 1.6, 2.0, 3.0, 4.0, 6.0, 8.0, 10.0, and 12.0 kHz. Following the experiment, the calibrations were repeated at several frequencies to confirm that sensors were not damaged during insertion or recovery. The calibrations revealed that the idealized dipole beam pattern of the accelerometers is observed on all vector sensors up to at least 4 kHz. Above that frequency, differences between individual sensors become apparent and the units with the best high frequency response were selected for burial in the seabed. By 8 kHz and above, the dipole beam pattern was severely degraded on almost all of the vector sensors (Fig. 2), as predicted by the manufacturer. The pressure sensor in the TV-001 was operational up to 40 kHz and used in time-of-flight experiments. In practice, low-pass filters in the data acquisition system limited the upper frequency of all experiments to 20 kHz. The lower frequency limit for all of the experiments was dictated by the source level of the projectors (0.6 kHz for the SX-100, 0.8 kHz for the ITC 1032).

3 Arrival Angle

If one plots the signals from two accelerometers in a vector sensor against each other, the acoustic waves display an elliptical motion with the major axis roughly aligned with the direction of propagation. This section of the paper considers how to infer the ellipse characteristics—particularly the orientation and shape—from the acoustic data. The following section applies that information to determine sensor orientation using transmissions from three orthogonal directions.

In general, for a narrowband signal of angular frequency $\omega$, the complex horizontal and vertical components of particle displacement (denoted $u_x$ and $u_z$, respectively) will have unequal amplitudes and phases, tracing an ellipse of a certain size, shape, and orientation. Assume there is an orthogonal coordinate system in which the elliptical displacements have the simple parametric form

$$u_x' = a \cos(\omega t) = \text{Re}(ae^{-i\omega t})$$

$$u_z' = b \sin(\omega t) = \text{Re}(-ib e^{-i\omega t})$$

in which $a$ is the semi-major axis of the ellipse and $b$ is the semi-minor axis of the ellipse. The ratio of complex amplitudes $u_x'/u_z'$ is obviously $\frac{-ib}{a}$, the $-i$ factor denoting the 90-degree phase lag of $u_z'$. If the rotation angle between the $x'$-$z'$ system and the $x$-$z$ system is $\theta$, then the complex amplitudes in the $x$-$z$ system are $\theta$, then the complex amplitudes in the $x$-$z$ system are given by

$$\begin{pmatrix}
    u_x \\
    u_z
\end{pmatrix} = 
\begin{pmatrix}
    \cos \theta & -\sin \theta \\
    \sin \theta & \cos \theta
\end{pmatrix}
\begin{pmatrix}
    a \\
    -ib
\end{pmatrix} = 
\begin{pmatrix}
    a \cos \theta + ib \sin \theta \\
    a \sin \theta - ib \cos \theta
\end{pmatrix}. \quad (2)
$$

The ratio of the $z$ and $x$ complex amplitudes is then
\[
\frac{u_z}{u_x} = \frac{a \sin \theta - ib \cos \theta}{a \cos \theta + ib \sin \theta} \frac{-\tan \theta - ib/a}{1 + i(b/a) \tan \theta}.
\]  
(3)

Using the substitution \(ib/a = \tan \varphi\), and the trigonometric identity

\[
\frac{\tan \theta + \tan \varphi}{1 - \tan \theta \tan \varphi} = \tan (\theta + \varphi),
\]  
(4)

we find

\[
\frac{u_z}{u_x} = \tan [\theta + i \tanh^{-1}(b/a)].
\]  
(5)

or

\[
\theta = \text{Re}\{\tan^{-1}(u_z/u_x)\}
\]  
(6a)

and

\[
b/a = -\tanh\{\text{Im}\{\tan^{-1}(u_z/u_x)\}\}.
\]  
(6b)

The eccentricity of the ellipse (if desired) is  
\[e = \sqrt{1 - (b/a)^2}.
\]

In the frequency domain, the x-velocity is  
\(-i \omega u_x\), the z-velocity is  
\(-i \omega u_z\), the x-acceleration is  
\(-\omega^2 u_x\), and the z-acceleration is  
\(-\omega^2 u_z\), so identical results would be obtained by using ratios of complex amplitudes from velocity or acceleration spectra, as the harmonic factors cancel. To apply this to real data, one simply calculates the complex FFT of the sensor time series channels and divides the vertical and horizontal components, one frequency bin at a time, averaging over frequency if necessary.

4 Sensor Orientation and Performance

In order to determine the orientation and assess the performance of the buried vector sensors, transmissions were made from three orthogonal directions using projectors \(TX_{ABC}\) in the water column, and \(TX_A\) and \(TX_B\) buried in the sediment (Fig. 1 inset). The results for vector sensor V2, buried 1 m deep in the seabed, are shown in Figs. 3 and 4. The arrival angles are calculated using Eq. (6a) and the \(b/a\) ratio using Eq. (6b). The symbols denote the results from individual transmissions and the solid lines are the median value of 20 pings. The results from an alternative technique to determine arrival angle using acoustic intensity [3] are also shown (dashed line) and found to be largely consistent with the angles determined from the tilt of the acceleration ellipses.

The transmissions from the source in the water column may be used to determine the orientation of the vector sensor in the \(z-x\) and \(z-y\) planes. (No results are shown for the \(x-y\) plane because it is orthogonal to the source). Using the coordinate system defined in Fig. 1 relative to the sensor, an arrival angle of 270º would be expected in both of these planes if the source were located directly above the buried sensor and the sensor had no rotation relative to the vertical. The three-point mooring system for the in water source was designed to minimize its motion. To monitor the motion, the absolute positions of the source, \(TX_{ABC}\), and receivers, H1-4 and V7, were determined using a regularized inversion technique [5]. For the results in Fig. 3, the source was never more than 0.03 m from the \(x-y\) origin. With regards to the location of the buried sensors, nylon ground lines were run between the sand screws A-B and C-D (Fig. 1) to mark the origin of the experimental site. These ground lines were used to position the burial jig that deployed the buried sensors [3,4]. The hole for V2 was displaced approximately 0.098 m to the...
north and 0.103 m to the west of the origin. For a vertical separation from source to receiver of 9.5 m, this offset would introduce a bias of 0.86° from vertical incidence. The uncertainty in source location introduces an uncertainty of +/- 0.18°.

The arrival angle results in Fig. 3 suggest that the vector sensor is rotated by approximately 2-3° relative to vertical in the z-y plane and by approximately 1-2° relative to vertical in the z-x plane. The results at 0.6 kHz are suspect due to the limited source level that could be generated using the SX-100 transducer well below its first resonance of 1.6 kHz [4]. In the z-x plane, the results at greater than 6 kHz, and possibly even at 4 kHz, depart from the relatively constant angle measured at lower frequencies. This suggests that either a) the assumption of an idealized dipole beam pattern for the vector sensor is not valid at these frequencies when it is buried or b) other arrivals (possibly scattered from other buried objects) are biasing the arrival angle estimate.

Figure 3. Acoustic transmissions from the in-water source, TX\textsubscript{ABC}, located directly above buried vector sensor V2. Left panels, arrival angle measured using the z-y and z-x acceleration signals. Right panels, ratio of the semi-minor and semi-major ellipse axes.

The transmissions from sources TX\textsubscript{A} and TX\textsubscript{D}, buried at the same depth in the seabed as V2, may be used to determine the orientation of this vector sensor in the x-y plane. In principle, these transmissions can also be used to orient the sensor in the z-x plane (for TX\textsubscript{A}) and z-y plane (for TX\textsubscript{D}). However, the arrival angles in these planes are biased by the multi-path reflection from the overlying water-sediment interface, particularly at lower frequencies, where the interference is inescapable. The results in this paper only consider the x-y plane where the effects of multi-path interference should be minimal. In the x-y plane, arrival angles of 180° and 270° would be expected for transmissions from TX\textsubscript{D} and TX\textsubscript{A}. The arrival angles in Fig. 4 are less than these values, indicating that the receiver is rotated by approximately 8° to 10° (for TX\textsubscript{D}) or 12 to 13° (for TX\textsubscript{A}). The sources and receivers were buried in individual holes using a purpose built burial jig to
control their separation and position with respect to each other [3]. If the buried sources were transmitting from two directions orthogonal to the vector sensor, as expected because of their placement by the burial jig, then one would expect the apparent rotation of the sensor to be the same for both sources. The apparent discrepancy may arise from the fact that sensor also has a rotation from the vertical and it may be displaced vertically from its intended depth [6]. The scatter in the results at the lower frequencies is due to the limited source level that could be generated by the ITC-1032 operating well below its resonance at 30 kHz. (An angular resolution of +/-1° requires approximately 30 dB of SNR). Despite the scatter, the median arrival angle appears stable, except perhaps at the lowest frequency. The scatter can be somewhat reduced by averaging Eq. (6a) over several frequency bins within the bandwidth of the pulse.

Considering the ratio of the semi-minor and semi-major axes for all of the calibration transmissions in Figs. 3 and 4, the ratio of $b/a$ is generally quite small and stable. This behaviour (indicating that the ellipses are elongated along their semi-major axes) is expected until inhomogeneous components of the acoustic field are also present, such as the evanescent field at shallower grazing angles. The larger values of $b/a$ that are observed occur for transmissions that were identified as having irregularities in arrival angle, at lower frequency (due to insufficient signal-to-noise ratio) and at higher frequency (possibly due to the breakdown of the dipole beam pattern or scattering).

Figure 4. Acoustic transmissions from the buried sources, $TX_A$ and $TX_D$, located north and east of buried vector sensor V2. Left panels, arrival angle measured using the x-y acceleration signals.
Right panels, ratio of the semi-minor and semi-major ellipse axes.
5 Summary

An analysis technique has been developed to determine the arrival angle of an acoustic pulse based on the properties of the elliptical motion exhibited by a pair of orthogonal acceleration signals. This technique was used to analyze transmissions from three orthogonal directions to a buried vector sensor that measures pressure and tri-axial acceleration. The mean value of the arrival angle is being used to determine the rotation of the vector sensor relative to its intended orientation. The stability of the arrival angle as a function of frequency is being used to evaluate the performance of the vector sensor, in particular to confirm that the angular resolution is sufficient for use in sediment sound speed dispersion measurements [7]. The preliminary results in this paper suggest that an angular resolution of approximately +/- 1.5º has been achieved. This should be sufficient for measuring frequency-dependent changes in the angle of refraction into the seabed due to sediment sound speed dispersion [7].

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TIME-OF-FLIGHT MEASUREMENTS OF ACOUSTIC WAVE SPEED IN SANDY SEDIMENTS FROM 0.6 – 20 KHZ

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There is considerable interest within the underwater acoustics community as to whether a fluid model or a poro-elastic (Biot) model provides a more accurate representation of sandy sediments. One key metric used to determine this is the acoustic wave speed in the seabed, since the Biot model predicts a sound speed that is frequency dependent whereas the traditional fluid model assumes a sound speed that is constant with frequency. Results obtained during the SAX99 experiment (a US Office of Naval Research Departmental Research Initiative) showed evidence of sound speed dispersion and were consistent with Biot model predictions which employed inputs based on geophysical measurements made at the site. However, only a limited data set were obtained in the frequency range where the model exhibited its greatest sound speed variation; that is, in the vicinity of 1 – 10 kHz. During the SAX04 sea trial conducted in the autumn of 2004, acoustic data were collected on receivers buried in the seabed using transmitters located within the seabed as well as in the water column directly above the buried receivers. This source geometry assists in the localization of the receivers and enables direct time-of-flight measurements of acoustic wave speed along all three Cartesian axes. In this paper the experimental geometry employed to make these complementary measurements is discussed and estimates of the sound speed at frequencies 0.60 – 20 kHz are presented.

1 Introduction

The acoustic wave speed in undersea sediments has long been considered a key parameter in the science of underwater acoustics; it is required to calculate the transmission and reflection coefficients, and the critical angle, which are in turn employed in modelling bottom loss, scattering, and propagation. Traditional fluid-bottom models have employed a frequency-independent acoustic wave speed; however, recent experimental evidence [1] taken across a broad band of frequencies (0.1 – 400 kHz) during the SAX99 experiment, suggests that it is dispersive and is generally consistent with Biot model predictions made using inputs based on geophysical measurements made at the site. Unfortunately, only a limited data set was available in the frequency regime across which the model shows its greatest frequency dependence –
the band $1 – 10$ kHz. Furthermore, the data within this reduced frequency regime only estimated the slope of the compressional wave speed with frequency rather than its absolute level [1]. To address this deficiency, DRDC Atlantic conducted a series of experiments to measure the acoustic wave speed in the frequency band $0.6 – 20$ kHz using several complementary techniques [2]. It was hoped that employing several independent techniques to measure the sound speed would provide a more robust estimate. This effort was conducted as part of the SAX04 experiment discussed in [3]. In one such technique acoustic data were collected on receivers buried in the seabed using transmitters located within the seabed and in the water column directly above the buried receivers. This source geometry assists in the localization of the receivers and enables direct time-of-flight (TOF) measurements of acoustic wave speed $c_s$ along all three Cartesian axes.

In a recent paper [4], preliminary results from the TOF estimates of $c_s$ were obtained using the buried sources at frequencies from $0.8 – 20$ kHz. These were compared to data collected during the SAX99 experiment. In the present paper we augment these results by examining the TOF data from the in-water source to estimate $c_s$ at frequencies from $0.6 – 6$ kHz. In addition to extending the low-frequency range of the measurements, the vertical incidence data is used to revise the depth estimate of the buried receivers, which in turn improves the estimate of $c_s$ made using the buried projectors. Following the introduction, the experimental set-up is described and the results from the experiment are presented.

2 Experimental Setup

The experiment was conducted in the Gulf of Mexico at $086°38.706’W, 30°23.232’N$ about $2$ km off the coast of Fort Walton Beach, Florida. All experiments were conducted from a portable lab situated aboard the RV Seward Johnson. The water depth at the experimental site was approximately $17$ m. In order to collect TOF data, 2 projectors and 4 receivers were buried in the top $1$ m of the seabed and an in-water source was located $8.67$ m above the seabed. Each buried receiver was a Wilcoxon TV-001 vector sensor (denoted V1-V4) which consisted of an all-in-one pressure plus tri-axial accelerometer. This set-up allows pressure, intensity, and impedance to be obtained and aids in separating the direct arrival from boundary reflections. The sensor was approximately $4$ cm in diameter and $7$ cm long. The buried sources used in the experiment ($TX_D$ and $TX_A$) were ITC-1032 spherical projectors measuring approximately $7$ cm in diameter. The in-water source was a Sensor Technologies SX-100, a cylindrically shaped flextensional projector, $6$ cm in diameter and $14.8$ cm in length. This source, referred to as $TX_{ABC}$, was oriented such that the broad lobe radiating from the ends of the cylinder pointed vertically. Along this axis, $1$ m below, an un-amplified omni-directional hydrophone, H1 (DRDC model 31A24) was fixed to monitor the source level [2].

The pressure sensor in the TV-001 was operational up to frequencies in excess of $40$ kHz but low-pass filters in the data acquisition system limited the upper frequency to $20$
kHz. The lower frequency limit (600 Hz for the SX-100, 800 Hz for the ITC 1032) was controlled by the low-frequency performance of the projectors.

To successfully measure acoustic wave speed using time-of-flight, an accurate measurement of the sensor geometry is critical since, $c_s = \frac{d}{t}$ where $d$ is the source to receiver separation and $t$ is the time of flight. To do this, a purpose-built burial jig was developed to allow insertion of the six transducers (2 projectors and 4 receivers) into the seabed in a closely controlled geometry. A photograph of the jig and the transducer insertion tools is shown in Figure 1. After insertion, the tools and burial jig were removed leaving only the low-profile cabling for each transducer. The in-water transducers were mounted to an inverted Y-shaped yoke to which a float was fixed. The yoke was fastened to the seabed in a three-point mooring using sand screws. This mounting technique ensured that the mount and mooring lines were well removed from the acoustic path and allowed the grazing angle of the projector to be changed for use in complementary experiments [5]. The in-water source was located directly above V1. An underwater photograph of the yoke and the in-water transducers is shown in Figure 2. The projector cabling went directly back to the portable lab on board RV Seward Johnson from where the experiment was controlled. The receiver cabling was fed into the data acquisition system placed on the seabed about 5 m away from the burial location. The system was capable of recording 1 gigabyte of data in CompactFlash memory. Data were periodically transmitted back to the ship for analysis and permanent storage using a 100 megabit/s fibre optic Ethernet link. For each experiment, a series of 50 pulses (hamming weighted) were transmitted from the projector at each frequency. The pulse train received by the TV-001 sensors and the transmitting voltage and current time series were all recorded and synchronized to a single time reference. The 50 pulses were upsampled, coherently averaged, and band-pass filtered.

![Figure 1. Photograph of prototype of the burial jig showing a transmitter (circled) in its insertion tool on the left and a pair of receivers (circled) in the receiver insertion tool on the right. (The arrows indicate which sensors were placed in which holes; see also Figure 3).](image-url)
3 The Time-of-Flight (TOF) Measurements

Figure 3 shows a 3-dimensional schematic of the geometry of the buried sensors. The design of the burial jig and the deployment methodology [5] enabled sensor placement to an accuracy of ±1 cm in the horizontal plane. Because control over the depth of the

Figure 2. Photograph of inverted Y-yoke mount that held the in-water sensors. Dashed ellipses show $TX_{ABC}$ (top) and H1 (bottom). The three mooring lines fixing the mount to the seabed are marked by the arrows. (Photograph courtesy of the Applied Physics Laboratory–University of Washington.)

Figure 3. Schematic of the proposed geometry for the buried sensors. The in-water projector and monitor hydrophone (not shown) were located directly above sensors V1 and V2. Samples of the direct and interface-reflected paths are shown by the shaded areas. The actual burial location of each sensor was displaced vertically from the proposed geometry; in the figure, this is represented for V4 by the dashed oval which is displaced by $\delta z$. 
sensors was somewhat more difficult, a recursive approach to estimating $c_s$ was adopted. Referring to Figure 3, it is clear that moderate vertical displacements ($\delta z$) will have only a small effect on TOF in the horizontal plane since $y >> \delta y$. Therefore, an initial estimate of $c_s$ was made using the TOF from $TX_D$ and $TX_A$ to V2 and V4. This minimized the impact of uncertainties in the vertical location of the sensors. These results are contained [4]. Next, an estimate of the depth of V1-V4 can be obtained by employing the initial estimate of $c_s$, the value of $c_w$ measured during the experiment, and the TOF results using $TX_{ABC}$ located overhead. Figure 4 shows a sample of the 1 kHz pressure time series collected on sensors H1 and V1-V4. Table 1 lists the depth of the buried sensors obtained from this rudimentary localization. Also contained in the table are the planned burial depths from Figure 3 and the vertical positions of the in-water sensors obtained using a more sophisticated localization technique based on Dosso et al [6]. Although analysis is incomplete, we estimate that the design of the transmitter insertion tool enabled burial accuracy of about ±3 cm in the z direction.

**Table 1. Estimated depths of sensors. Positive z is downward and z = 0 is at the seabed.**

<table>
<thead>
<tr>
<th>Transducer</th>
<th>Depth (m)</th>
<th>Intended Burial Depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$TX_{ABC}$</td>
<td>-8.67</td>
<td>n/a</td>
</tr>
<tr>
<td>H1</td>
<td>-7.66</td>
<td>n/a</td>
</tr>
<tr>
<td>V1</td>
<td>0.60</td>
<td>0.5</td>
</tr>
<tr>
<td>V2</td>
<td>1.07</td>
<td>1.0</td>
</tr>
<tr>
<td>V3</td>
<td>0.54</td>
<td>0.5</td>
</tr>
<tr>
<td>V4</td>
<td>0.89</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Figure 4. Time series of a 1 kHz pulse from SX-100 as received on hydrophone H1 (top left trace), pressure sensors in V1, V2 (top right traces) and V3, V4 (lower right traces).
As discussed in [4] two methods were used to estimate the TOF. The first was a direct examination of the onset of the pulse in the time series data. The difference in onset time on the two channels yields the TOF. The second method employed a replica-correlation technique. The sound speed ratio $c_s/c_w$ computed in [4] was corrected for path length using the data from Table 1 and is plotted in Figure 5. Errors resulting from the ±3 cm uncertainty in the depth of the buried transmitters are less than ±0.3%; that is, approximately the size of the symbols used in the figure. The replica correlation technique should provide a better estimate since it averages the result across several cycles; however, contamination by the interface-reflected path (Recall Figure 3) can lead to errors. This is particularly true at low frequencies where the time difference between the direct and interface-reflected path is less than 1 cycle. This is the likely cause of the high variance in the correlation results at low frequency.

At the time of writing, it was not possible to get an absolute measure of $c_s$ in the vertical direction since there has been no independent measure of the vertical separation $V_1-V_2$ and $V_3-V_4$. (That is to say, the TOF from the in-water source was required to estimate the depths of the buried receivers so it cannot then be used to estimate $c_s$.) Nonetheless, the frequency dependence of the sound speed can be obtained using the in-water source by examining the TOF from $V_1$ to $V_2$ and from $V_3$ to $V_4$. Figure 6 shows these data overlaid with the data from Figure 5.

The data from Figure 5 that were obtained using replica correlation have been omitted from the figure due to the interference effects discussed earlier. The data are compared to the experimental results from SAX99 [1] in Figure 7. The Biot model evaluated for the conditions measured at the site during SAX99 is given by the solid line. Differences between the present data set and data from the SAX99 data may well result from changes to environmental parameters during the period between experiments rather than errors in either set of data. That said, the low frequency trend of the present data is consistent with the 125 Hz and 400 Hz data points from SAX99, both of which lie well below the
Biot curve. Also, one should note that the 1–10 kHz data set (diamonds) from SAX99 was only a relative measurement and the slope is in reasonable agreement with the present results.

Figure 6. Normalized compressional wave speed using the buried sources (circles and squares) and the in-water \( TX_{ABC} \) source (triangles) based on onset time. Note that the \( TX_{ABC} \) data only provide a relative measure and have been adjusted vertically to align with the absolute measure of the buried sources.

Figure 7: Comparison of data from Figure 6 above (solid points) to results from the SAX99 experiment [1]. The curve corresponds to the Biot model evaluated for the experimental conditions measured at the experimental site in 1999.
4 Concluding Remarks

Preliminary compressional wave speed estimates based on time-of-flight (TOF) measurements have been presented for the frequency band 0.6 – 20 kHz. The results, normalized by the wave speed in the overlying water column, indicate that the compressional wave is dispersive in this regime with the normalized wave speed increasing from approximately 1.04 to 1.15. These dispersion results have a stronger dependence on frequency than those obtained at approximately the same location 5 years earlier. Although the initial dispersion measurements are promising, substantial analysis remains. An examination of the errors and variability that contribute to the variance in the data is ongoing. Also, the directional sensors in the receivers will be used to help discriminate the direct from the interface-reflected path which should improve the sound speed estimates in the horizontal plane using replica correlation. Related to this, an additional data set was collected during the experiment using longer (5 ms) pulses; data received during the steady-state portion of these pulses will be compared to model estimates using the reflection coefficient so as to remove the interface-reflected component.

Acknowledgements

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References

FREQUENCY DEPENDENT SOUND SPEED AND ATTENUATION MEASUREMENTS IN SEAFLOOR SANDS FROM 1 TO 400 KHZ

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As part of the SAX04 experiment, sound speed and attenuation were measured in the seabed off of Ft. Walton Beach, Florida, USA, at frequencies from 1 to 400 kHz. For the lowest frequencies, from 1 to 20 kHz, signals from two acoustic sources were recorded on an array of hydrophones emplaced at depths of up to 1 m below the seafloor within a 4 m by 4 m area. At frequencies from 15 to 200 kHz, sound speed and attenuation data was obtained using the In Situ Sediment Acoustic Measurement System (ISSAMS), a linear array of four piezoelectric probes that were inserted into the seabed to a depth of 0.3 m. Sound speed measurements were also made at 60, 100, 200, and 400 kHz on diver-collected cores using four separate pairs of ultrasonic transducers. Sound speed data from the core and ISSAMS measurements demonstrates an essentially uniform sound speed near 1780 m/sec. Preliminary analysis of the sound speeds from the low frequency array data demonstrate an anomalous increase in sound speed values with decreasing frequency when sources were emplaced below the seafloor, attributable to the influence of multi-path arrivals. Data from source locations at the seafloor demonstrate a decrease in sound speed with decreasing frequency, consistent with the trend predicted by the Biot model, but with large uncertainties. Attenuation values from seafloor source positions follow a square-root frequency dependence below 20 kHz, similar to the Biot predicted trend, while the core and ISSAMS data demonstrate a near linear trend at higher frequencies. A fit of the Buckingham model to the sound speed and attenuation data results in a good fit to the higher frequency attenuation data, but underpredicts the attenuation observed at frequencies below 20 kHz. Future work, including full waveform inversion of the low frequency data and detailed error analysis, should reduce the uncertainty in the sound speed analysis at low frequencies and determine the ability of the measurements to discriminate between the models.

1 Introduction

Frequency-dependent variation in the sound speed and attenuation in seafloor sediments produces consequent frequency-dependant variation in the magnitude of the wave energy reflecting from and transmitted into the seafloor at a given angle of incidence. An understanding of this frequency dependence is important for reliable detection and imaging of sub-seafloor features and for prediction of long-range sonar losses resulting from acoustic interactions with the seafloor. While sound speed and attenuation measurements at high frequency are relatively straight forward, the
measurement of their frequency dependence is more difficult due to the limited frequency band of individual measurement systems and to the wide range of scales required for measurements over a broad frequency band. Nevertheless, the extrapolation of a single frequency measurement to a broader range of frequencies can be performed if reliable empirical or theoretical relationships have been established to describe the frequency dependences over the desired frequency range. The objective of this study was to measure the sound speed dispersion and frequency-dependent attenuation in a homogenous seafloor sand over a wide range of frequencies, and to assess the ability of Biot-Stoll and Buckingham propagation models to predict the observed frequency dependences.

Biot’s model [1,2] predicts the frequency dependence of the sound speed and attenuation due to relative motion between a viscous pore fluid and a porous framework caused by the deformation and displacement occurring with the passage of small-strain elastic waves. As pore fluid movement is central to this model, its inputs include a number of pore space descriptors, including the porosity, permeability, pore size, and tortuosity, as well as the pore-fluid density, bulk modulus, and viscosity, the sediment-grain bulk modulus and density, and the elastic moduli of the dry grain framework. This model predicts significant sound speed dispersion and a characteristic double power law dependence of the attenuation on the frequency, which is proportional to the square of the frequency at low frequency and to the square root of the frequency at high frequency. The Buckingham model [3,4] describes the frequency dependence resulting from stochastic stick-slip sliding at grain contacts in a grain framework with no global elastic stiffness. This model requires knowledge of the grain and pore fluid properties, as well as inputs that describe the frictional sliding at the grain contacts. These parameters cannot be determined from an independent characterization of the sediment, but can be derived from calibration based on measurement of the wave speed and attenuation at a single frequency, or from a fit of the model to multi-frequency measurements. The Buckingham model predicts a weak, approximately logarithmic frequency dependence for the sound speed, and a nearly linear frequency dependence for the attenuation.

Buckingham and Richardson [5] and Williams et al. [6] compared sound speed dispersion and frequency-dependent attenuation, measured with a variety of techniques during the Sediment Acoustics eXperiment of 1999 (SAX99) off of Fort Walton Beach, Florida, USA, to the Biot-Stoll and Buckingham model predictions over a frequency range from 0.4 to 400 kHz. Buckingham and Richardson [5], using a subset of the data over a frequency range from 25 to 100 kHz, found that while the sound speed dispersion predicted by both the Biot and Buckingham models fit the measured dispersion, the attenuation data was more consistent with the Buckingham model. Williams et al. [6], with the larger dataset and with inputs from detailed characterization of the seafloor, found that below 50 or 100 kHz the Biot model successfully describes the trend of the observed attenuation and sound speed. Above this frequency, the measured attenuation deviates from that predicted by the Biot model, but follows a trend attributable either to scattering or to the Buckingham sliding mechanisms.

This study, conducted as one component of the SAX04 experiment, involved measuring the sound speed and attenuation at frequencies from 0.6 kHz to 400 kHz in the relatively homogenous sands in the first meter below the seafloor at a site about 1000 m off of Fort Walton Beach, Florida, USA. This frequency range spans the high frequency,
sound speed maximum of the Biot-Stoll model and most of the predicted transition to the low frequency minimum. A prime focus of the experiment was to make accurate measurements at lower frequencies (< 20 kHz), as most of the Biot-predicted dispersion occurs at these low frequencies and as there were large measurement uncertainties at these low frequencies in previous studies [6].

2 Experimental Measurement Systems

To cover the frequency range of interest, sound speed and attenuation were measured with three separate measurement systems. These included a diver-emplaced hydrophone and geophone array for measurements at frequencies below 20 kHz, a four probed piezoelectric array from 15 to 200 kHz, and a laboratory core measurement system from 60 to 400 kHz. Here each of these systems is described in detail.

2.1 Buried Hydrophone and Geophone Array: 0.6 to 20 kHz

The low frequency recording system consists of a sub-seafloor array of 35 hydrophones and 5 three-component accelerometers which was used to record signals from two acoustic sources positioned on or below the seabed near the array. The hydrophones each consist of a piezoelectric element, attached to a small pre-amp and potted in polyurethane. Each three-component accelerometer consists of three high sensitivity (1 V/g), uniaxial piezoelectric accelerometers, mounted orthogonally in an aluminum pressure case. Divers implanted the receivers along three azimuths within a 4 m by 4 m area at depths of up to 1 m (Figure 1a) using a positioning template consisting of an aluminum frame with guide tubes mounted at each of the receiver locations (Figure 1b). The water jet tools used to insert the sensors into the seabed required re-engineering in the field, resulting in inaccuracies of several cm in the positions of the receivers. Each of the receivers was connected to a seafloor data acquisition unit, which provided signal conditioning (amplification and analog filtering) to each receiver output and power to each receiver. The outputs from each receiver were recorded eight at a time at a sample rate of 102.4 kHz, and stored on a computer. The acquisition system was attached to the ship with a cable which provided power to the system and allowed fiber-optic communication with the acquisition computer.

The sources, a Helmholtz generator, driven at frequencies from 0.6 to 6 kHz, and an ITC 3013 hemispherical transducer, driven at 6 to 20 kHz, were each positioned at points along each of the main azimuths of the receiver array at offsets from 3 to 18 m from the center of the array (Figure 1a). At most source locations, the sources were water jetted to a depth of 50 cm below the seafloor, although at locations nearest to the array they were also placed at the seafloor and at depths of approximately 1 m. Source signals, consisting of 10 cycle tone bursts at each frequency, were generated with a D-to-A card at a 250 kHz update rate, passed through a 50 kHz low-pass analog filter, amplified with an amplifier, and sent down a 120 m long cable to the source. The signals recorded on each receiver were stacked at least 10 times.

Figure 2 shows representative signals from each source recorded on the hydrophone (Fig. 2a) and accelerometer (Fig. 2b) located at the center of the array. Though the accelerometers are significantly more sensitive than the hydrophones, they are much too
ringy to provide usable signals. Nevertheless, high quality signals are recorded with each of the hydrophones at all but the highest frequencies (above 15 kHz), where electrical system noise starts to be significant relative to the strength of the signal at far offsets.

![Map of source and receiver locations for the low frequency, buried array system](image1)

**Fig. 1:** a) Map of source and receiver locations for the low frequency, buried array system, and b) photograph showing a diver water jetting a hydrophone into the seafloor.

![Typical receiver signals recorded with the low frequency array](image2)

**Fig. 2:** Typical receiver signals recorded with the low frequency array on a) a hydrophone, and b) a vertical accelerometer channel, for a source offset of 3 m.

### 2.2 ISSAMS: 25 to 200 kHz

The In Situ Sediment Acoustic Measurement System (ISSAMS) consists of two linear, 4-probe piezoelectric arrays, mounted rigidly on a diver-emplaced frame at a spacing of 30 cm (Figure 3a). Each probe extends 30 cm below the base of the frame, and contains a piezoelectric element encased in the tip of the probe. One set of probes contains compressional elements, while the other contains shear elements. The outer probes in each array act as transmitters, while the inner probes serve as receivers. The compressional probes were driven with source signals consisting of tone bursts of
between 5 and 25 cycles at individual frequencies from 15 to 200 kHz. The differential output of the receiver probes was recorded individually at a sample rate of 2.5 MHz with a high speed digital recording system. The system was deployed at three locations within approximately 100 m of the site of the low frequency buried array. A sample set of waveforms from one of these deployments is shown in Figure 3b.

![Image](image1.png)

**Fig. 3**: a) Photograph of ISSAMS frame and probes, resting in its support stand. The acoustic probes are pointed, while the shear probes are paddle shaped. b) Typical acoustic signals collected on two receivers from the same source.

![Image](image2.png)

**Fig. 4**: a) Photograph of the core measurement system, and b) signals collected from one of the cores at 200 kHz.

2.3 **Cores: 60 to 400 kHz**

Sound speed and attenuation measurements were also made on sediments retained in 5 cores collected around the site of the buried array system using 4 individual sets of
transducers with nominal resonance frequencies of 60, 100, 200, and 400 kHz. Each pair of transducers was placed on either side of the core tube, and one transducer was driven with 5 cycles at the resonance frequency. The waveform received by the other transducer was recorded with a digital oscilloscope, with a sample rate varying with the frequency of the transducers used. For each set of measurements, signals were recorded through the water in the core tube overlying the relatively undisturbed sediment, and at depths of 5, 10, 15, and 20 cm below the sediment-water interface. Figure 4 shows a photograph of the set-up and examples of waveforms collected for one of the cores at 200 kHz.

3 Data Analysis and Results

Waveforms recorded with each of the three measurement systems were processed to calculate values of the sound speed and attenuation at each measurement frequency. Core data were resampled 100 fold, windowed over the first five cycles, and cross-correlated with the windowed signal propagated through the overlying water. The sound speed was calculated from the time lag between the two signals and the inside diameter of the core (5.9 cm), assuming a water velocity of 1526 m/s (room temperature), and then corrected to in situ conditions. The attenuation was calculated as 20 times the log of the ratio of the RMS magnitudes of the windowed segments of the sediment and water signals, assuming negligible attenuation in the water. The sound speeds at the higher three measurement frequencies (100, 200, and 400 kHz) are essentially constant with frequency, varying from 1775 to 1810 m/sec (Figure 5a). At 60 kHz, the sound speeds are approximately 30 m/sec higher. We presume the higher values at this frequency result from bias in the measurement technique. The attenuation measured in the cores demonstrates an approximately linear frequency dependence at all four measurement frequencies (Figure 5b).

The ISSAMS data were filtered to a band from 25% below to 25% above the nominal frequency of the tone burst. The sound speeds were then calculated from time-delay differences between signals recorded from the two receivers, with the effective receiver-receiver spacing calculated from the time delay between signals recorded while the system was suspended in the water column. Attenuation was calculated from the ISSAMS measurements by the transposition method [7]. The sound speed results from the ISSAMS data are essentially constant with frequency above 50 kHz, generally varying between 1770 and 1790 m/sec and overlapping the higher frequency core data. Below 50 kHz the sound speeds increase anomalously, which we attribute to some sort of interference, whether due to a multi-path arrival or resonance in the support frame, that is also evident in the time delays observed during calibration. Similar behavior is evident in the attenuation results, where above 50 kHz the data follow a trend consistent with that observed in the core data, while at lower frequencies they rise anomalously.

The data from the low frequency array were deconvolved with a source wavelet derived from the signal recorded at each frequency at the hydrophone nearest to the source when the source was positioned 1 m off the south end of the array at a depth of 50 cm. Arrival times for each hydrophone were then picked from the peaks of the deconvolved traces. Sound speeds were calculated for each source location from a linear least-squares fit to the arrival time vs. distance data. Attenuations were calculated by fitting an exponential to the peak magnitudes of the deconvolved traces vs. distance from
source to receiver, and correcting for spherical spreading. Only hydrophones at depths of 50 cm or more below the seafloor were used to calculate the sound speed and attenuation, as tests of the analysis procedure on simulated data demonstrated large biases in the results from the shallower hydrophones due to interference from evanescent energy. Sound speeds calculated from deeper source locations (50 cm or more below the seafloor) demonstrate a consistent increase in speed with decreasing frequency, while the attenuation data from the same source locations decrease to a minimum at 3 kHz, below which they increase with decreasing frequency (black points in Figure 5). Tests on simulated data suggest that these results may be strongly influenced by reflections at the seafloor for the buried source and receivers. Results from data where the source is positioned at the seabed and this multi-path is not present (red points in Figure 5) demonstrate sound speeds between 1730 and 1770 m/sec at frequencies at 10 to 12 kHz, decreasing to values between 1650 and 1700 m/sec below 2 kHz. Uncertainties in these values from the least-squares regressions are on the order of 10%. The attenuation data for the seabed source positions demonstrate a consistent square-root dependence with frequency. Future analyses based on full waveform matching of the signals will be necessary to remove any influence of evanescent energy and to reduce the uncertainty of the results.

Figure 5 also shows the frequency dependent predictions of the Biot and Buckingham models. The Biot model was parameterized both with inputs from [6] based on the characterization of cores collected from the site during SAX99 (dashed line), and with updated inputs, where available, from sediment characterization from SAX04 cores (solid line). The differences in the Biot sound-speed predictions are mostly due to the lower porosity value used (0.3665), an average value from measurements on two cores from SAX04. Williams et al. [6] use a higher porosity value (0.385) chosen from within the range of measured porosity values from SAX99 to fit the model to the sound speed data. The Buckingham model was fit to the data by treating the uncharacterizable parameters as free parameters, as described in [5].
4 Discussion and Conclusions

While the sound speed values from shallow source positions demonstrate a trend similar to that predicted by the Biot model, the fit of the Buckingham model also falls within the uncertainty in the sound speed values at all frequencies. For the attenuation values, the Biot model predictions match the attenuation data at low frequencies, while other phenomena, whether scattering, local flow, or grain contact slip mechanisms, must be invoked to the account for the attenuation of the acoustic energy at higher frequencies. The uncertainties in the sound speed and attenuation values from these preliminary analyses do not permit a conclusive test of the validity of the different propagation models. We hope to decrease the uncertainty in the sound speed and attenuation values derived from these experiments by performing full waveform inversions of the low-frequency data. This approach combined with a detailed error analysis may allow a better assessment of the ability of various models to describe the acoustic propagation properties of these sands.

Acknowledgements

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References

ATTENUATION CHARACTERISTICS OF SANDY SEDIMENTS -
A SIMPLIFIED BIOT APPROACH.

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Shallow water (SW) sound propagating on the coastal margins interacts with a bottom that is usually composed of depositional sandy-silty layers. Measurements of narrow band and broad band sound transmission in several areas ranging from the U.S. continental shelf to the Straits of Korea indicate a geoacoustic attenuation profile with a nonlinear frequency dependence between 100 and 1000Hz [R.B. Evans and W. M. Carey, IEEE J. Oceanic Eng., 23, 439-447 (1998)] [I. Rozenfeld et al., IEEE J. Oceanic Eng., 26, 809-820 (2001)]. These results, when compared to other experiments that have measured the modal attenuation coefficient, sound transmission or the plane wave reflection coefficient ([F. Ingenito, J. Acoust. Soc. Am., 53, 858-863 (1973)] for example) are shown to present compelling evidence for a nonlinear dependence. Furthermore, the intrinsic attenuation in porous media is predicted by a simplified Biot theory that requires the knowledge of a Biot time constant [A.D. Pierce et al., J. Acoust. Soc. Am. 114, 2345 (2003)]. Although the intrinsic attenuation in the sandy layers, when modeled as a porous medium with this simplified model, has a quadratic dependence, the modal attenuation coefficient is shown to be determined by the frequency, mode number and depth dependence of the attenuation profile. The sound transmission field at longer ranges is a superposition of propagating modes, and the overall attenuation results from the attenuation of the individual modes.

1 Introduction

The calculation of sound transmission on the coastal margins and seas with depths of between 40 and 200 m, shallow water (SW), requires an understanding of the bottom sediment layers often formed by deposition of sands and silt. Many coastal areas have these sandy depositional layers and are classified as fast or critical angle bottoms. Exceptions are the depositional fans of major rivers composed of fine silts resulting in slow bottoms. Experimental evidence for this dependence summarized in Table I (adapted from Holmes et al (2005)) that show the accurate calculation of sound transmission for narrow band and broad band signals in the shallow water waveguide with a fast sandy-silty bottom requires a non-linear frequency dependence for attenuation in the upper sediment layer for frequencies between 100 Hz and 1kHz. The nonlinear attenuation at a frequency \( f \), \( \alpha(f) \), can be expressed relative to some known attenuation at a reference frequency \( f_0 \), \( \alpha(f) \), by the following
\[ \alpha(f) = \alpha(f_a)(f / f_a)^n \]  

There are essentially four techniques for in-situ measurement of the frequency dependence of the attenuation in ocean sediments. 1.) Modal techniques usually incorporate a vertical hydrophone array and take advantage of dispersion or wave number analysis to separate modes.

Table I: From Holmes (2005)

<table>
<thead>
<tr>
<th>Author</th>
<th>Frequency Range, Hz</th>
<th>Bottom Type</th>
<th>Estimated Critical Angle (°)</th>
<th>Exponent (\alpha = a f^n)</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ingenito, 1973</td>
<td>400-750</td>
<td>S</td>
<td>19</td>
<td>1.75</td>
<td>Modal</td>
</tr>
<tr>
<td>Beebe, 1982</td>
<td>100-600</td>
<td>M-C S</td>
<td>29</td>
<td>1.76</td>
<td>TL</td>
</tr>
<tr>
<td>Beebe, 1982</td>
<td>25-250</td>
<td>C-S/G</td>
<td>35</td>
<td>1.57</td>
<td>TL</td>
</tr>
<tr>
<td>Zhou, 1985</td>
<td>80-800</td>
<td>S-Si-Cl</td>
<td>19</td>
<td>1.84</td>
<td>Modal</td>
</tr>
<tr>
<td>Zhou, 1987</td>
<td>100-1000</td>
<td>F-S-Si</td>
<td>21</td>
<td>1.6</td>
<td>Inversion</td>
</tr>
<tr>
<td>Tattersal, 1992</td>
<td>100-800</td>
<td>S-Si-Cl</td>
<td>24</td>
<td>2.0</td>
<td>TL</td>
</tr>
<tr>
<td>Tappert, 1993</td>
<td>50-800</td>
<td>S-Si-Cl</td>
<td>19</td>
<td>2.0</td>
<td>TL</td>
</tr>
<tr>
<td>Carey, 1998</td>
<td>500-1000</td>
<td>S-Si-Cl</td>
<td>18</td>
<td>1.5</td>
<td>TL</td>
</tr>
<tr>
<td>Rozenfeld, 2001</td>
<td>47-604</td>
<td>S-Si</td>
<td>23</td>
<td>1.8</td>
<td>TL</td>
</tr>
<tr>
<td>Peng, 2004</td>
<td>100-500</td>
<td>F-S</td>
<td>21</td>
<td>1.65</td>
<td>TL</td>
</tr>
<tr>
<td>Zhou, 2004</td>
<td>100-700</td>
<td>F-S</td>
<td>22</td>
<td>1.63</td>
<td>Inversion</td>
</tr>
<tr>
<td>Knobles, 2005</td>
<td>25-800</td>
<td>F-S</td>
<td>21</td>
<td>2.0</td>
<td>TL</td>
</tr>
</tbody>
</table>

[Table nomenclature: Sand (S), Medium (M), Coarse (C), Silt (Si), Clay (Cl), Fine (F).]

Comparison of measured mode properties to theoretical properties, assuming some bottom attenuation frequency dependence, reveals the best match to data. 2.) Transmission loss, TL, techniques use transmission loss versus range measurements. Using a forward model with assumed frequency dependence and using a metric to determine best fit again, accomplish determination of frequency dependence. 3.) Inversion schemes are also used and encompass many techniques such as generic algorithms or perturbative inversions. These methods often use multi-parameter fitting. 4.) Finally, measurement of the angle dependant reflection coefficient, while more commonly used for higher frequencies, has been used with some success in slow bottoms. This method often makes use of the fact that the sub-critical reflection loss depends on the sediment attenuation but for the case of a slow bottom, it has been performed by examining the reflection coefficient at the angle of intromission for the thin top layer.

In the 1990’s, the Area Characterization Tests were conducted at the following sites: the West Coast of Florida, a site on New Jersey shelf, one above the Hudson canyon, and two sites in the Korean Straits. All produced excellent agreement between measured and calculated sound transmission results when adequate environmental inputs were available and a nonlinear frequency dependent attenuation was used with range dependent codes. More recent experiments have been conducted in the East and
South China Seas and in areas dominated by the depositional sand. A nonlinear frequency dependent attenuation was also required to explain the experimental results.

The result of these sandy-bottom SW waveguide investigations is a nonlinear frequency dependence of attenuation for frequencies below several kHz with $1.5 < n < 2.0$.

2 A Simplified Version of the Biot Model

This paper uses theoretical results from Pierce, Carey and Zampoli (2005) where Biot’s equations were derived from the fundamental Lagrange-Euler equations with the forces per unit volume exerted on the fluid by the solid matter and the equal and opposite force exerted by the fluid. The simplified equation can be written as

$$\rho \frac{\partial^2 \Phi}{\partial t^2} - \lambda \nabla^2 \Phi - \left( \frac{D^2}{b \lambda^2} \right) \frac{\partial^3 \Phi}{\partial t^3} = 0$$

(2)

where $\rho$ is the density, $\lambda$ is a Lamé constant, $b$ is the equivalent dashpot constant per unit volume; and $D$ is a parameter that characterizes the lack of perfect coupling between the fluid and the solid motions and it includes both inertial and elastic constants. The interesting character of this simplified equation is the presence of the third time derivative. The above equation is in fact the standard wave equation with this added term. If we consider plane wave propagation

$$\Phi \Rightarrow \Phi, \exp(-i \alpha \omega + ikx),$$

(3)

then upon substitution the following dispersion equation is obtained:

$$- \rho \omega^2 + \lambda k^2 - i \omega \left( \frac{D^2}{b \lambda^2} \right) = 0.$$  

(4)

The complex wavenumber is readily obtained as

$$k = (\omega / (\lambda / \rho)^{1/2}) [1 + i \omega \left( \frac{D^2}{b \lambda^2} \right)]^{1/2}.$$  

(5)

When the frequency is low and the imaginary term is much less than one, a binominal expansion yields the complex wave number

$$k = \omega / c + i \alpha; \quad \text{with} \quad c = (\lambda / \rho)^{1/2}, \quad \alpha = \left(1 / 2(\rho \lambda)^{1/2} \right) \left(\frac{D^2}{b \lambda^2}\right) \omega.$$  

(6)

Thus we readily see that in the low frequency limit the attenuation is proportional to frequency squared, $n=2$. The attenuation is inversely proportional to $b$. Since $b$ is proportional to viscosity, the attenuation is also inversely proportional to viscosity. This observation may be a test of this theory by laboratory experimentation.
The constant factor \( \tau_B = D^2 / \rho b \lambda^2 \), the Biot time constant, when substituted in equation (2) yields

\[
\nabla^2 \Phi - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \Phi = -\frac{\tau_B}{c^2} \frac{\partial^3}{\partial t^3} \Phi. \tag{7}
\]

Estimates of the order of magnitude of this time constant can be made from experimental results when one considers the attenuation \( \alpha = \frac{\tau_B \omega}{2c} \). Rogers (2000) yields \( 3.4 \times 10^{-6} < \tau_B < 4.8 \times 10^{-6} \) s and the Beebe, McDaniel and Rubano (1982) investigation yields \( 22 \times 10^{-6} < \tau_B < 37 \times 10^{-6} \) s. The Beebe result has a reference attenuation constant which is large while the Roger's results assume a constant depth dependent attenuation and perhaps this reasoning explains the differences. A recent paper by Zhou (2005) has summarized empirical relationships at frequencies less than several kilohertz as \( \alpha = 0.34 f^{1.84} \). By using the data from Beebe, McDaniel and Rubano (1982) with a slightly modified assumption for bottom velocity, Zhou also showed that this previous result aligned very well with data from 15 other locations around the world. The constant 0.34 at 1kHz is consistent with the Hamilton (1956) values of 0.3 to 0.4 at 1kHz. These values correspond to a Biot time constant between \( 2.7 \times 10^{-6} < \tau_B < 3.73 \times 10^{-6} \) s. The Biot time constant is thus on the order of microseconds. Since the time constant is inversely proportional to viscosity and since viscosity divided by density has dimensions of characteristic length squared per unit time, then with geometrically similar sediments with the same composition and the same porosities should yield a time constant that scales inversely with characteristic length squared, the grain size squared.

3 Propagation Effects

The propagation of sound in a SW waveguide with absorption is an improper Sturm-Liouville problem. The depth-separated wave equation is

\[
\rho \frac{d}{dz} \left( \frac{1}{\rho} \frac{dZ}{dz} \right) + \left( \frac{\omega^2}{c^2} + \frac{i \tau_B}{c^2} \omega^3 - k^2 \right) Z = 0 \tag{8}
\]

The Rayleigh quotient for this problem may be written in terms of the complex constant and the modal eigenfunction \( Z_n \) as

\[
k_n^2 = \int \left[ \frac{\omega^2}{c^2} + \frac{i \tau_B}{c^2} \omega^3 \right] Z_n^2 \frac{dz}{\rho} - \int \frac{1}{\rho} \left( \frac{dZ_n}{dz} \right)^2 \frac{dz}{\rho} \tag{9}
\]

The complex modal wave number with modal attenuation \( \alpha_n \) is
ATTENUATION CHARACTERISTICS OF SANDY SEDIMENTS

\[ k_n^2 = \left( \frac{\omega}{V_{ph,n}} + i\alpha_n \right)^2 \]  (10)

A perturbation solution for the modal coefficients that was originally developed by Kornhauser and Raney (1955) and Ingenito (1973) and is further developed here shows that the modal attenuation coefficient is

\[ \alpha_n = v_{ph,n} \frac{\int \alpha(\omega) Z_n^2 dz}{\int \frac{Z_n^2}{\rho} dz} . \]  (11)

The integral is taken over the waveguide and the result is a good approximation if the modal functions determined in the absence of attenuation are used. Since

\[ \alpha = \tau_\rho \omega^2 / 2c , \]

one has

\[ \alpha_n = v_{ph,n} \frac{\int \tau_\rho Z_n^2 dz}{2 \int \frac{Z_n^2}{\rho} dz} . \]  (12)

The modal attenuation coefficient depends not only on the frequency dependence of the intrinsic attenuation but also on the integral of the modal eigenfunction. In the above equation the fraction composed of the integrals has a denominator that is simply a normalization and a numerator that integrates \( Z_n \) over the waveguide. The low-order low-frequency modal eigenfunctions penetrate deeper in the sediment than the higher-order higher-frequency functions. Thus the ratio decreases with increasing frequency. In the case of the Pekeris waveguide this ratio goes as a constant divided by \( \omega^3 \). In general with a sandy bottom that has depth dependent sound speed, attenuation, density and porosity profiles, the measured modal attenuation coefficients and consequently the attenuation of sound in the water portion of the waveguide will have a frequency dependence less than quadratic. However numerical field calculations that use the range-depth dependencies of the bottom should be capable of determining the correct intrinsic frequency dependence when sufficient experimental sound transmission and environmental data are available.

4 Summary and Conclusion

This paper has indirectly discussed the problem of the accurate calculation of the sound transmission in a waveguide with a sandy-silty bottom. A key variable is the depth and frequency dependent attenuation profile in the sediment. We have examined a
variety of areas where the bottom has been formed by the deposition of sand and silt and where sound transmission experiments have been performed over the last several decades. Our conclusion is that a nonlinear frequency dependent attenuation is required. This nonlinear frequency dependence appears to be location specific as the modal penetration in the bottom coupled with the measured attenuation was shown to be important.

Results of a theoretical review of the Biot theory were discussed in terms of a Biot time constant. A simplified equation shows that a quadratic frequency should be observed. The Rayleigh quotient illustrated how this quadratic frequency dependence can be modified by the modal depth penetration and the depth dependent attenuation. Possible tests of this theory based on the viscosity and grain size dependence were proposed.

At frequencies less than 1 kHz, long range sound transmission experiments in constant depth shallow water over known sediment layering may be the best way to determine the frequency dependent attenuation coefficient at low frequencies. SW areas that have these characteristics are known. Such measurements, given a good knowledge of the (possibly range dependent) sound velocity profiles, bathymetry, sub-bottom profiles, and near surface sediment characteristics, may well enable the characterization of this nonlinear dependence of the attenuation. The current state of ocean acoustics technology is such that we have the ability to perform such experiments under calm sea state conditions with an accuracy previously unknown. The numerical codes are quite good and the accuracy of their predictions is limited only by the uncertainties in the input-environmental variables. The experiments quoted in the table in the present paper, along with the analyses performed by the authors who reported these experiments, have most of these features desired for characterizing the nonlinear frequency dependence of the attenuation.

References


A COMPARISON OF MODELS FOR THE INTERACTION OF ACOUSTIC WAVES AND SEDIMENTS WITH REFLECTION COEFFICIENT MEASUREMENTS FROM A SAND/WATER INTERFACE AT THE SEDIMENT ACOUSTICS EXPERIMENT 2004 (SAX04)

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During the Sediment Acoustics Experiment 2004 (SAX04), the reflection coefficient was measured using a three-receiver vertical line array (VLA) and a source mounted on a remotely operated vehicle (ROV). Measurements at angles from 10 to 89 degrees and at frequencies from 10 to 50 kHz were obtained. The sand/water interface was smoothed by divers and visual inspection revealed no significant ripple formations. This was confirmed by side scan SONAR measurements. Coring indicated that there was a nominal half inch mud layer over a sand bed. Experimental effects from spherical wave propagation, and scattering from the rough interface are considered. The data are compared to current models of acoustic interaction with sandy sediments. These models include the visco-elastic model, the Biot-Stoll model, the Biot model with a correction from benthic activity as hypothesized by Stoll, the Biot-Stoll model with contact squirt flow and shear drag (BICSQS) and a grain shearing model formulated by Buckingham. Models will be considered for their ability to predict the reflection coefficient data using measured sediment parameters. [Work supported by ONR, Ocean Acoustics]

1 Introduction

As SONAR is applied more often in littoral environments, understanding the interaction between sound waves and the ocean bottom becomes crucial. One important parameter is the acoustic reflection coefficient which is a function of grazing angle and frequency. The raw reflection coefficient can be used directly in long-range propagation models, while analysis of the reflection coefficient can be used to discriminate different physical models of the interactions.

Currently, there are five major acoustic interaction models of the sediment. First, the visco-elastic model considers the sediment as a visco-elastic solid which can support both shear and compressional waves. Next, in the Biot/Stoll model, the sediment is modeled as a poro-elastic solid in which the motion of both the grains and the interstitial
fluid are considered.\cite{1,2} Third, is a gas bubbles model. For this model, Stoll suggested that the presence of bacteria in the sediment may lower the value of the fluid bulk modulus in the poro-elastic model, and Chotiros and Isakson specified that the bacteria produce small amounts of gas bubbles which would lower the fluid bulk modulus and calculated the percentage.\cite{3,4} The fourth model considered is the grain-shearing model which is based on a stochastic stick/slip model of grain interaction.\cite{5} The last model is the Biot-Stoll model with contact squirt flow and shear drag (BICSQS) in which the physics of the motion of the fluid between the grains and the gap contact are considered.\cite{3}

The five models for acoustic interaction with sandy sediments itemized above predict different reflection coefficient values for a specific frequency and grazing angle. Plotted in Figure 1 is the reflection coefficient magnitude plotted versus 3 decades of frequency for three grazing angles: a subcritical angle, the critical angle and normal incidence. Especially in the transition region, 1-10 kHz, the models predict reflection coefficient magnitudes which may vary up to 6 dB. This difference can be very important in naval models for long range propagation in which the acoustic ray interacts with bottom several times.

![Figure 1: Reflection coefficient magnitudes for the five acoustic models of the sediment. The data is plotted at three different grazing angles across 3 decades of frequency.](image)

Although the models predict some large differences, are the reflection coefficient measurements accurate and complete enough to distinguish between the models? The reflection coefficient magnitude must be able to be measured within at least 2 dB. In previous laboratory studies on a smoothed sandy sediment similar to SAX04, reflection coefficient magnitude data, at sub-critical angles, are accurate to within 1 dB at a 95% confidence interval. At normal incidence the data are accurate within 2 dB. Much of this error has been shown to be related to the scattering from the individual sand grains at the interface.\cite{6} This accuracy is within the limits to distinguish the models and provide good measurements for propagation modeling.
2 Methods and Data Analysis

The SAX04 reflection coefficient experimental set-up is described in a previous publication and will only be summarized here.[7] The experiment consisted of a spherical source mounted on a remotely operated vehicle (ROV) and a three transducer receiving vertical line array (VLA). (See Figure 2.) Backscatter, normal incidence reflection and transmission data were also gathered and will be discussed in subsequent publications. Behind the source was a reflector angled at 45 degrees to reduce the reflections from the ROV. Because of a complete lack of visibility in the aftermath of a hurricane, the ROV was most often positioned directly on the sediment with the sending transducer nominally 0.5 m from the sediment interface.

Data was taken using three different LFM chirps at a 1 ms pulse length. The first chirp was from 4.5-10 kHz. The second chirp spanned 10-22 kHz and the third, 22-50 kHz. Data was taken at grazing angles from 10-89 degrees grazing.

The position of the ROV was determined from the arrival times at the three VLA transducers. Additionally, a navigational transducer was placed at the edge of the experimental area to determine the azimuth angle to the VLA. There are some concerns about a beam pattern effect from the transducers so only data taken within one meter of either side of the VLA were considered.

![Figure 2: The experimental set-up.](image)

The reflection coefficient was determined from the ratio of the direct path peak to the reflected path peak of the replica correlated time series. The replica was determined from the ensemble averages of 100 pings to each receiver. For the ensemble average, each ping was normalized by the path length to the receiver and aligned by the first identifiable peak arrival. Since the reflections from each ping are not correlated, they will average to zero in an ensemble leaving only the direct path. Additionally, for arrivals in which the direct and reflected paths arrive close in time, the direct path replica may be subtracted from the time series to isolate the reflected path. Replica correlated time series from the middle and bottom receiver are shown in Figure 3a and 3b for 49 and 18 degrees grazing respectively. The time series in red has had the direct path...
replica subtracted, leaving only the reflected response. As seen in Figure 3(b), this method can isolate the reflected path well, even for signals that arrive closely in time.

Figure 3: The replica correlated time series for the 10-22 kHz signal taken at 49 degrees (a) and 18 degrees (b).

3 Experimental Results

The reflection coefficient magnitude for the 10-22 kHz and the 22-50 kHz chirps are shown in Figure 4. The lowest frequency band, 4.5-10 kHz, is still being investigated and results will be provided in subsequent publications.

Figure 4: Reflection data collected at 10-22 kHz (a) and 22-50 kHz (b) compared with the five models of acoustic interaction with a sandy sea bed.
The data are quite scattered due to the interface roughness and sediment variability over the region. Furthermore, the method of determining the reflection coefficient by comparing the amplitudes of the replica correlation for the direct and reflected paths, is inherently averaged over the frequency band. This may introduce further uncertainty. The response for each chirp has a rich frequency dependence as shown in Figure 5 for the 4.5-10 kHz chirp and the 10-22 kHz chirp. There is significant banding in the higher grazing angles which could be due to scattering from a shallowly buried shell layer. Such layers were commonly found by Richardson and Briggs by coring.[8] At around 20 degrees grazing, two regions of high reflectivity were found centered at 9 and 18 kHz. The genesis of these regions is still being investigated.

4 Model Comparison

4.1 Spherical Wave Effects

Spherical wave effects have been shown to be important in the analysis of reflection coefficient data using omni-directional transducers.[6] The importance of the effect is determined from the geometry and the frequency of the interaction. For geometries in which the source and receiver are close to each other or to a boundary, the effect can be up to 8 dB. Spherical wave effects can be calculated for a given model using plane wave decomposition provided that the waves are homogeneous at the boundary. This method of determining the bistatic response using plane wave decomposition is discussed in references 9 and 10.

For the SAX04 geometry, the spherical wave effect was calculated for the three receivers modeling the sediment as a Biot poro-elastic solid. The result is shown in Figure 6. At angles steeper than 30 degrees, spherical wave effects are mild and can be ignored.

For the lower angles, spherical wave effects can be significant and can falsely indicate a change in the critical angle which could be interpreted as a change in sound speed. Therefore, care must be taken in interpreting results from the first and second receivers between 20 and 30 degrees grazing.
4.2 Model Comparison

The data were compared with the five models of acoustic interactions with sediments. The parameters used in each model are shown in Table 1. Additional parameters for the gas bubbles, BICSQS and grain shearing models were taken from references 3 (Table I), 3 (Table IV, last column) and 5 respectively. The results of the comparison are shown in Figure 4.

Table 1: Parameters used in Models

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Source</th>
<th>Relevant Model(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity in Water Column</td>
<td>1548 m/s</td>
<td>CTD Data at SAX04</td>
<td>All</td>
</tr>
<tr>
<td>Compressional Sound Speed</td>
<td>1779 m/s</td>
<td>Measured by NRL at SAX04</td>
<td>Visco-Elastic</td>
</tr>
<tr>
<td>Compressional Attenuation</td>
<td>0.23 dB/λ</td>
<td>Measured by NRL at SAX04</td>
<td>Visco-Elastic</td>
</tr>
<tr>
<td>Sediment Density</td>
<td>2.064 kg/m³</td>
<td>Measured by NRL at SAX04</td>
<td>Visco-Elastic</td>
</tr>
<tr>
<td>Shear Sound Speed</td>
<td>90 m/s</td>
<td>Laboratory Measurement [11]</td>
<td>Visco-Elastic</td>
</tr>
<tr>
<td>Shear Attenuation</td>
<td>0.5 dB/λ</td>
<td>Reference [12]</td>
<td>Visco-Elastic</td>
</tr>
<tr>
<td>Porosity</td>
<td>0.367</td>
<td>Measured by NRL at SAX04</td>
<td>Biot/Stoll, Gas Bubbles, BICSQS</td>
</tr>
<tr>
<td>Permeability</td>
<td>4e-11 m²</td>
<td>Measured by NRL at SAX04</td>
<td>Biot/Stoll, Gas Bubbles, BICSQS</td>
</tr>
<tr>
<td>Tortuosity</td>
<td>1.35</td>
<td>Core Measurement from SAX99 [14]</td>
<td>Biot/Stoll, Gas Bubbles, BICSQS</td>
</tr>
<tr>
<td>Fluid Viscosity</td>
<td>0.001</td>
<td>Table Value</td>
<td>Biot/Stoll, Gas Bubbles, BICSQS</td>
</tr>
<tr>
<td>Fluid Bulk Modulus</td>
<td>2.4 GPa</td>
<td>Table Value</td>
<td>Biot/Stoll, BICSQS</td>
</tr>
<tr>
<td>Fluid Density (Biot)</td>
<td>1020 kg/m³</td>
<td>CTD Data at SAX04</td>
<td>Biot/Stoll, Gas Bubbles, BICSQS</td>
</tr>
</tbody>
</table>
Both the grain shearing and visco-elastic model over estimate the value for the reflection coefficient at high grazing angles. The three poro-elastic models, Biot/Stoll, gas bubbles and BICSQS, have a much closer prediction of the value of the high grazing angle reflection coefficient. At the critical and sub-critical angle, the best fit model is more difficult to discern since the data is sparse.

4.3 Rough Interface Contribution

Although the predictions from the poro-elastic models are closer to the measured values, there is still a 2-3 dB difference in the prediction of the models and the measured data. Also, there are large deviations in the data that are difficult to justify by sediment variability alone. In fact, for a 9 dB spread as seen in the data, the sediment density would have to vary from 1.2 to 2.0 g/cc! However, it can be shown that the scattering from rough interface contributes to the both the random deviations and bias in the data. This is illustrated in Figure 7. A simulation of the effects of rough interface scattering for the SAX04 geometry was created using the Bottom Response from Inhomogeneity and Surface using the Small Slope Approximation (BoRIS) from the NATO Undersea Research Center (NURC).\(^\text{15}\) BoRIS is a time domain model in which a surface is created using input parameters. In this case, a power law surface was created using a RMS surface height of 0.5 cm and an exponent of 3.21 as measured by NRL at SAX04.\(^\text{[8]}\) The pulse is propagated from the source to the surface, interacts with the surface and then propagated to the receiver. Realizations can be made on different locations on the surface to give an ensemble average. In order to determine the reflection coefficient, the average of the Fourier transform of the reflected pulse over the frequency range of interest was compared with the average value of the Fourier transform of the input pulse. The ratio was then corrected for the spherical spreading due to the path length of the reflected pulse. As seen in Figure 7, scattering can cause a large spread in the data even with a relatively smooth interface. Rough interface scattering also introduces a bias which could explain the low values for the reflection coefficient at high grazing angles. The bias effect is most strong at higher frequencies and grazing angles. This effect was also noted in Reference 16.
5 Conclusion

The three poro-elastic models, Biot/Stoll, Gas Bubbles and BICSQS, have the closest predictions the value for the high grazing angle reflection coefficient. The value for the elastic and grain shearing models are higher than the measured average value. The average value for the reflection coefficient are lower than what is predicted by even the poro-elastic models and have large random deviations. Simulations using the BoRIS code with roughness parameters measured by NRL indicate that both the bias and random deviations could be due to rough interface scattering.

These results should be considered as very preliminary. Future work will include additional modeling to include the effects of the mud layer, and additional roughness scattering models, and further processing the experimental data to examine the variation of reflection loss as a function of both angle and frequency and its statistical characteristics. Lastly, the backscatter and transmission data will be analyzed.

Acknowledgements

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References


QUANTIFICATION OF SEDIMENT PROPERTIES FROM PORE STRUCTURE AND GRAIN CONTACTS: A MICROCOMPUTED TOMOGRAPHY ANALYSIS OF SAX04 SANDS

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During the Sediment Acoustic eXperiment (SAX04), sediment physical properties (e.g., porosity and permeability), determined by the arrangement of sand grains and the topology of the pore space, were evaluated in two ways: first, packing density in unconsolidated sand ($d_{50} = 371 \mu m$) was adjusted from minimum to maximum density by vibration; and second, diver-collected cores were impregnated with polyester casting resin to maintain pore and grain morphologies. Sediment pore-morphology and grain data was captured in volumetric x-ray Computed Tomography (CT) images (~10 $\mu m$ resolution) and quantified using a new grain-based algorithm. Porosity was calculated from the image data by voxel counting and permeability was determined using the Kozeny-Carman method, which is determined from porosity and grain size data. Grain contacts, an important determinant of frame modulus, were also determined. Bulk porosity and permeability measurements from diver-collected cores (6-cm diameter) compared relatively well with image-based predictions. In general, sediment physical property values for laboratory packed sand were wider than those of the resin-impregnated and bulk samples. This study demonstrates the ability of high-resolution CT to image the micro-scale pore and grain morphology and of a new grain-based algorithm to quantify relevant features within these images. It is demonstrated that these features may then be used to quantify potential sediment physical properties for potential organizational states that may occur within a homogeneous sandy sediment that is reorganized by physical and biological forces.
1 Introduction

1.1 Select geoacoustic properties and relevant pore and grain scale parameters

Sediment geoacoustic properties determine compressional wave speed and attenuation, and these properties change at varied spatial and temporal scales due to physical and biological forcing of wind waves, currents, and bioturbation that suspend, deposit, consolidate, and generally alter sediment morphology. Therefore, ranges of geoacoustic properties exist due to spatial and temporal variability in sediment packing that may correlate with the scales of the forcing. To determine the potential upper and lower bounds of geoacoustic properties (e.g., porosity, permeability, and frame modulus) for the siliciclastic sediments that occur south of Ft. Walton Beach, FL, at the Sediment Acoustic eXperiment 2004 (SAX04) site, sediments were collected by divers and preserved. In this paper, we present data and properties extracted from a series of X-ray computed tomography (CT) scans of SAX04 sands, including resin-impregnated natural cores as well as cores packed to maximum and minimum density. A grain-based algorithm was used to quantify the properties of the sand grains as well as the pore geometry and topology. The physical properties of these systems can then be compared to results of field measurements of SAX04 geoacoustic properties and may also serve as potential upper and lower bounds for geoacoustic properties in SAX04 sands.

Pore-scale measurement of the pore and grain volumes enable calculation of porosity, the ratio of void space to total volume, and permeability, the area within the sediment that is available for fluid flow. CT images provide the high-resolution, three-dimensional datasets necessary for quantitative measurement of the void and pore space. Porosity is determined simply by dividing the number of void-space voxels by the total number of voxels in the system. Permeability may be determined using either modified Kozeny-Carman equations or Effective Medium Theory approaches [1,2]. For the permeability determinations, it has proved useful to determine the effective hydraulic radius of the pore space and to treat these pores as conduits for fluid flow. Permeability determined with the Kozeny-Carman equation, $k_{ck}$, is indirectly related, through grain size, to the interconnectedness of the pore space (i.e., the pore coordination number), which has been shown to be important in both averaging (e.g., Effective Medium Theory) and discrete methods (i.e., Lattice-Boltzman simulations). However, the Kozeny-Carman equation is useful for determining permeability in well-rounded sands, where $k_{ck}$ is determined as,

$$k_{ck} = \left[ \frac{n^3 d_{50}^2}{180(1-n)^2} \right]$$

In equation 1, $n$ is the fractional porosity and $d_{50}$ is the mean grain diameter and the constant in the denominator accounts for the path length a fluid must travel, which must vary as the sediment sample is compressed, repacked, or reorganized. Studies have shown that permeability and porosity may be the most important sediment properties affecting acoustic attenuation and sound speed dispersion [3]. However, concurrent with changes in these properties are changes in the sediment moduli. That is, the granular interactions that determine sediment compressibility become more or less rigid for different grain packings, depending upon the number and types of grain contacts. Evaluations of the grain packing by quantification of the grain contacts, may ultimately
enable determinations of frame modulus, currently a weakly understood phenomenon in naturally occurring sands that has proved difficult to evaluate with existing models [4]. The difficulty arises due to generalizations made by these models: sediments exist as a random packing of monosized spheres; porosity is non-varying; and grain contacts are “point-contacts” for which frictional influences are negligible (i.e., no-slip conditions at contacts). A relationship between porosity and grain coordination number has been previously established; simply put grain coordination number (i.e., the number of point contacts) increases as sample porosity decreases [5]. However, within these models, average grain coordination number is an important component that is rarely determined for natural sediments. For marine sand, porosities that range from 0.35 to 0.45 are reasonable estimates, and may be close to the lower and upper bounds of the SAX04 sands; for such porosities, according to Murphy [5], the grain coordination number could be expected to range from 9.5 to 7.3. Because, grain coordination number and porosity are important components of models that predict sediment moduli, this paper is addressing these parameters. Future work will be to quantify sediment moduli, and more importantly, make predictions of compressional and shear wave velocities from the mean grain coordination number, porosity and grain size.

In this paper, we quantify the solid and void phase properties of sands collected during SAX04, including resin-impregnated and reconstituted diver-core samples. It is also important to note that the aforementioned relationships between pore properties and acoustic properties are starting points from which compressional and shear wave velocities are determined, and that solutions to the Gassmann equation may be required to predict velocities in marine sand [6]. Although a rigorous analysis of predicted and measured velocities was not possible at this early date, our preliminary results indicate promise in using the approach presented in this paper for determining sound speed in natural sands, while still operating under an important Hertz-Mindlin assumption (i.e., no-slip point contacts). In this case, the model would ignore frictional influences that determine sediment rigidity and operate at the face-to-face contacts (i.e., contacts with large areal extent).

1.2 Grain Based Reconstruction Algorithm – A tool for quantifying sediment components from high-resolution images

The determination of the pore and grain properties starts with an evaluation of the spatial arrangement of pores and grains. This grain reconstruction algorithm transforms CT images of sediments into their more fundamental geological components (i.e., grains, aggregates, pores) and has been useful in addressing complex grain shapes, such as quartz sand. This transformation is important because the form of the digital images (typically composed of tens of millions of voxels) is not amenable to direct physical analysis. Performing grain-scale reconstruction, however, allows computation of grain size distributions, pore and grain coordination numbers, surface areas, spatial correlations between pores, as well as other pore and grain parameters that are relevant to sediment physical and geoacoustic properties of natural sand.

We call this approach “grain-based” since the grain centers, located using a burn algorithm, serve as the basis for locating and defining the pore-grain structure in a three-step approach. The first step is to locate grain centers using a voxel burn of the solid
phase. This is coupled with a nonlinear optimization process, if necessary. The second step is to merge grain centers in cases where the first step leads to repeated identification of the same grain (based on the maximum inscribed grain radius at each particle center). The third step is to perform a restricted voxel burn from the grain centers. This last step is a novel procedure that has proved successful for maintaining continuity in nonspherical grains and for ensuring proper division in cases where odd-shaped grains come into contact [2].

2 Methods

SAX04 sediments were carefully collected by scuba divers using hand-held, 6-cm diameter polycarbonate tubes and then carefully returned to the R/V Seward Johnson. Some of these cores were impregnated with polyester casting resin while the core was under vacuum while aboard ship. The solidified system was then subsampled by cutting the cores at 2-cm intervals with a rock saw and coring 8-mm-diameter samples from the center of the 2-cm-thick disks. Additional core samples were retrieved from the SAX04 site and sectioned into 2-cm intervals. These sections were evaluated for bulk density with conventional gravimetric methods and the grain size distribution was determined from the dried sections. A representative sample (standard splitting technique was used) was selected from the dried section, saturated with water, packed to near minimum density by vibration, and then imaged with the CT again. Diver cores were also collected for determination of permeability, which was determined on the ship using a constant-head permeameter.

The 8-mm-diameter resin-impregnated subsamples and the unconsolidated grain packings were x-rayed at high-resolution (~10 μm) using an x-ray Computed Tomography (CT) system that is housed at the Naval Research Laboratory. The industrial CT system operates in a range of 10-225 keV and 0-3 mA to produce images with maximum resolutions of <10 micrometers [7]. To achieve high-resolution images, or maximum magnification, samples were placed in close proximity to the focal spot opening of the X-ray tube and X-ray attenuation data were collected at a high number of line scans numerous times (i.e., 2400 lines per 360° sample rotation with 6 integrations per line to yield well resolved and clearly differentiated pores and grains). The attenuation data were converted to image data using a back-filter algorithm and images were corrected for “beam-hardening”, an artifact that occurs in images made from polychromatic energy sources. The images were then resampled, using a nearest-neighbor algorithm, to produce cubic voxels of ~10 μm in each of three dimensions. The 16-bit gray scale images were converted to 1-bit binary images (i.e., each voxel was designated as either solid or void) using an indicator kriging method in 3DMA [8]. A 300³ subset of the image was then extracted for analysis using the grain-based algorithm. Three hundred voxels corresponds to ~8.5 grain diameters, based upon the mean grain size; this should provide a statistically representative sample.
3 Results of grain- and pore-scale evaluations

3.1 Pore and grain parameters for predictions of physical properties

Resin-impregnated sediment cores were chosen from the “Dalpod” (dc11_res) and “Rail” (dc19_res) sites; samples for the maximum and minimum density packings were taken from dried sections of non-impregnated cores, dc1 and dc24, corresponding to these two sites, respectively. The minimum and maximum values of gravimetrically determined sediment porosity in the 0-2-cm sand sections of diver cores were 0.354 and 0.387 respectively [9]. Porosity values, based on the CT images of the resin-impregnated samples (Table 1), fall within this range. While the porosity values for the maximum and minimum packing of dc24 sand bound the resin-impregnated porosity (dc19_res), the porosity of maximum density packing of dc1 sand is greater than that for the resin-impregnated sample (i.e., dc11_res). Two possibilities exist: 1) the packing of the resin-impregnated core is greater than that of the maximum density sample, or 2) segmentation errors occurred (i.e., assigning individual voxels to either solid or void phases). Segmentation is one of the most difficult steps towards quantifying CT images.

Table 1. Values of pore and grain properties for the 0-2 cm depth interval from two SAX04 diver cores, dc11 and dc19, and maximum- and minimum-packed samples from sectioned cores dc1 and dc24. Dimensions are micrometers. nd = not determined

<table>
<thead>
<tr>
<th></th>
<th>dc11 res</th>
<th>dc1 max</th>
<th>dc1 min</th>
<th>dc19 res</th>
<th>dc24 max</th>
<th>dc24 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity</td>
<td>0.358</td>
<td>0.395</td>
<td>0.459</td>
<td>0.370</td>
<td>0.352</td>
<td>0.458</td>
</tr>
<tr>
<td>Permeability (×10^{-11} m²)</td>
<td>8.51</td>
<td>12.9</td>
<td>25.3</td>
<td>9.76</td>
<td>8.06</td>
<td>25.4</td>
</tr>
<tr>
<td>Inscribed Grain Radii</td>
<td>98.12</td>
<td>92.18</td>
<td>94.24</td>
<td>104.3</td>
<td>118.9</td>
<td>113.8</td>
</tr>
<tr>
<td>Grain Coordination #</td>
<td>7.72</td>
<td>6.88</td>
<td>5.60</td>
<td>6.63</td>
<td>8.04</td>
<td>5.92</td>
</tr>
<tr>
<td>Pore Radii</td>
<td>49.73</td>
<td>52.42</td>
<td>62.82</td>
<td>56.48</td>
<td>56.00</td>
<td>71.17</td>
</tr>
<tr>
<td>Pore Coordination #</td>
<td>5.71</td>
<td>6.52</td>
<td>6.85</td>
<td>5.95</td>
<td>5.75</td>
<td>6.53</td>
</tr>
<tr>
<td>Pore Throat Radii</td>
<td>35.00</td>
<td>35.99</td>
<td>41.86</td>
<td>38.79</td>
<td>38.97</td>
<td>48.04</td>
</tr>
<tr>
<td>Pore Throat Length</td>
<td>213.2</td>
<td>222.4</td>
<td>256.5</td>
<td>253.1</td>
<td>244.4</td>
<td>294.3</td>
</tr>
<tr>
<td>Ave Pore/Throat Aspect Ratio</td>
<td>0.651</td>
<td>0.640</td>
<td>0.611</td>
<td>0.627</td>
<td>0.648</td>
<td>0.614</td>
</tr>
</tbody>
</table>
The minimum and maximum values of sediment permeability, determined from a constant-head permeameter test on 13-cm long cores, were $8.8 \times 10^{-12}$ and $43.4 \times 10^{-12}$ m$^2$, respectively. The average $k_{ck}$ permeability value (calculated from equation 1) for these samples was $16.0 \times 10^{-11}$ m$^2$, roughly ten times higher than constant-head values.

The grain-based algorithm was used to evaluate individual grains and pores (see Figure 1) and determine relevant properties (see Table 1). The CT imagery in Fig. 1 is presented in terms of grains (upper images) and pores (lower images), as well as maximum density packing (left) and minimum density packing (right). The pores in the maximum density packing appear smaller than the pores that occur in the minimum density packing, as would be expected. This qualitative result is confirmed; average pore radii in the maximum density samples are 15-20% smaller than in the minimum density samples (Table 1). Note that systems at maximum density packing have smaller throat radii and shorter throat lengths. Throat radii and length are fundamental properties related to permeability. It appears that the pore coordination number for the maximum density sample is less than for the minimum density sample while the pore/throat aspect ratio is larger. Additionally, these properties have a significant impact on multiphase flow (e.g., drainage/imbibition, gas bubble migration).

Comparisons of the grain sizes between cores are determined as the effective grain size, which is the average of the inscribed grain diameter and the maximum grain length. Cumulative distributions of effective grain sizes are shown in Figure 2. For this data, grain size distributions for the maximum and minimum packing systems are very similar and the difference in the average grain radii is only a few percent (Table 1).
grain radii and particle size distributions for both resin-impregnated cores exhibit some differences compared to the maximum and minimum packing cores. It appears that the dc_11_res grain size distribution is similar to the dc_1 cores, yet grain sizes in dc_19_res are smaller and the distribution is broader than the dc_24 sands.

Particularly important in the calculation of sediment moduli are grain coordination numbers, which were determined with the grain-based algorithm and found to increase with increasing density. One of the primary advantages of the grain-based algorithm is the ability to uniquely identify each individual grain and its properties.

![Graph showing cumulative frequency of effective grain size](image)

**Figure 2.** Frequency percent of effective grain size for select SAX04 sediment samples. “Dalpod” samples include dc11_res and dc1 and “Rail” samples include dc19_res and dc24.

## 4 Discussion

A grain-based algorithm is used to quantify high-resolution CT images of siliciclastic (quartz) sands collected from the SAX04 site and enables several physical properties to be predicted for a range of packings. Values from CT-based imagery are relatively similar for porosity measurements and slightly higher for permeability than measurements presented by Briggs et al. [9]. Permeability values from the Kozeny-Carman formulation are reasonable for “clean” siliciclastic sands found in surficial marine deposits, however they are not in agreement with direct measurements. This may indicate that the simple approach taken, that is the prediction made by a derived formula of Kozeny-Carman, does not account for all the relevant parameters needed to accurately predict permeability in angular sediments. This is also made evident by the small effect that a fairly substantial change in pore throat properties had in this determination. Conceivably, as sediment was converted from minimum and maximum density packings (especially in dc24), a larger difference in permeability might occur, because pore throat sizes decrease markedly and the path length that a fluid travels through the sediment should simultaneously increase. This incongruity in the data will require further
evaluation or the utilization of more rigorous determination of permeability, which will enable the rejection of permeability predictions made using the Kozeny-Carman relationship, which may be better suited for less angular particles than exist at the SAX04 site. While the grain coordination numbers increase as sediment density increases, grain coordination values do not reach the assumed value, 9, commonly used for marine sediments. The relationship between coordination number and density may be addressed as the grain-based algorithm is further developed.

Future work will use more rigorous methods to estimate permeability (EMT, lattice-gas or Lattice-Boltzman) to incorporate pore size variability and pore coordination numbers. Relationships between the grain coordination, sediment moduli and sound speed in angular sediments will be evaluated using the Walton model [10].

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References
BOTTOM ROUGHNESS MEASUREMENTS FROM SAX04:
RESULTS FROM A HIGH-RESOLUTION DIVER-DEPLOYED
STEREO IMAGING SYSTEM.

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An important component of the environmental measurements made during the Sediment Acoustics Experiment 2004 (SAX04) was the measurement of bottom roughness. These measurements are crucial to the modeling of high frequency backscatter from the sediment and hence a number of measurement systems were deployed by various groups at the experiment site. In order to measure the high frequency portion of the roughness spectra, APL-UW developed a diver-deployable high-resolution digital stereo system. The system consists of two black and white Basler digital cameras (1300x900 pixel resolution) and a strobe controlled by an onboard computer which is cabled to the ship for power and data transfer via Ethernet. For SAX04, the operating distance of the cameras from the bottom was 40 cm with an imaged patch size of 25x25 cm and a horizontal resolution of 0.2 mm. The ability to operate very close to the bottom proved to be extremely useful for SAX04 in that both Hurricane Ivan and Tropical Storm Matthew significantly increased the turbidity of the water column during the experiment. This paper discusses influence of both the presence of mud patches and turbidity on the bottom roughness measurements and compares the measurements made with this new system to the results from SAX99.

1 Introduction

Two of the primary goals of the Sediment Acoustics Experiment 1999 (SAX99) were to quantify the acoustic backscattering from the seafloor and the acoustic penetration into the sediment [1]. Both of these processes are affected by the interface roughness and extensive efforts were made to characterize the roughness at the experiment site. Among the techniques used were analog stereo photography, time-lapse stereo photography, digital stereo photography, laser imaging systems, and conductivity probe measurements. Despite this extensive list of measurements, there remain ambiguities in the data/model comparisons which cannot be fully addressed due to a lack of information about the seafloor roughness at the SAX99 site.

During SAX99, three separate systems were used to measure backscatter from the sediment interface over a wide range of frequencies [2]: the sediment-transmission system (STMS), operating from 20 to 150 kHz, the Benthic acoustic-measurement system (BAMS), operating at 40 and 300 kHz, and the “X-celerated” BAMS (XBAMS), which operates at 300 kHz. The roughness was measured near the BAMS site using an analog stereo camera [3]. The spectrum measurements made using analog stereo cameras are extremely labor-intensive, thus limiting the number of measurements typically made...
with this type of system. This difficulty, combined with poor optical clarity during portions of the experiment, made it difficult to take stereo photos at different locations around the BAMS and STMS sites. The roughness data that are available indicates a spatial non-stationarity in interface roughness. This led to significant uncertainty bounds on model results being compared to the backscattering data. As a result data/model comparisons were unable to determine whether a porous media model of sand was more accurate than a fluid model.

The data collected with BAMS and XBAMS at 300 kHz indicate that the scattering strength is much larger than predicted using the roughness parameters measured using the analog stereo system. This may indicate a transition to another scattering mechanism such as volume scattering in the sediment or scattering from shell pieces on the sediment interface. There is some uncertainty, however, as to whether the observed decrease in the roughness spectrum at high frequencies is actual or an artifact of the measurement procedure [3]. If the roughness parameter at high spatial frequencies is actually an artifact and the roughness spectrum follows the same trend as that observed at low spatial frequencies, this may account for the discrepancy between the theory and the data.

For the Sediment Acoustics Experiment 2004 (SAX04), both BAMS and XBAMS were again deployed as well as the backscattering system that was originally deployed with STMS1. In order to measure the spatial variability and the high frequency portion of the roughness spectrum, APL-UW developed a diver-deployable high-resolution digital stereo camera system. This system was designed for mobility as well as flexibility in the length scales it can measure. Section 2 describes the APL-UW system as well as the stereo processing that was developed to produce the surface measurements. In order to understand how the system performs extensive laboratory measurements are being made with this system on several calibrated test pieces. The preliminary results of these measurements and the implications for both the APL-UW system and digital stereo cameras in general are given in Section 3. Results from SAX04 are given in Section 4 along with comparisons to measurements made during SAX04 with the In-situ Measurement of Porosity (IMP2) system. These results are also compared to the measurements made at SAX99.

2 The APL-UW stereo camera system

In order to address the issue of spatial variability, the APL-UW stereo camera system was designed to be a light, self-contained system that could be easily and rapidly moved to multiple positions at the experiment site. The system frame consists of a tripod which supports an aluminum frame to which the computer, cameras, strobe, and altimeter are mounted. The system is shown in Fig. 1. The sides of the frame are 1.2 m in length. At the center is the main pressure case which houses a PC-104 computer which triggers the strobe and cameras and stores the images captured by the cameras for subsequent processing. The computer also has an attitude sensor for measuring the orientation of the camera system at each capture. This could potentially be useful in create mosaics of overlapping surfaces to create larger, composite surfaces. Along one leg of the frame are two smaller pressure cases which house the digital cameras. The cameras are Basler A102f digital cameras which have a 1300x900 pixel resolution. Higher resolution digital cameras are available, especially in consumer SLR models, but the decision was made to
use an industrial camera since this provides the most flexibility in the choice of optics and the most direct computer control of the camera. With these cameras, it was possible to trigger the strobe and the image capture on both cameras simultaneously to provide both rapid image acquisition and to allow for image acquisition when the frame is in motion such as when there is strong swell on the bottom or when the system is suspended above the bottom. The capture rate for the system is roughly 20 stereo pairs per minute. Both the height of the cameras from the bottom and the separation and tilt of the cameras can be changed depending on the measurement to be performed. The camera separation can be varied from 10 cm to 60 cm and the height of the cameras can be varied from 10 to 80 cm from the bottom. The primary light source used with this system is an Ikelite DS-125 substrrobe which is battery powered and can be triggered via the computer. The system can also use an acoustic altimeter to measure the height of the system above the bottom and trigger the image capture when a preset height is reached. Due to the conditions at the SAX04 site, the altimeter was not used.

The system is connected to the ship with 100 m of cable for both power and communication with the ship via Ethernet. For operation at SAX04, the frame was lowered from the ship to the bottom and then moved to the area where measurements were to be made. Typically the system was set in a mode to capture 10 images, taken at 3 second intervals, at a single position followed by a longer 15 second interval in which two divers would move the system to a new position. Multiple images at a single position allows for averaging or other processing to remove the effects of particulate matter moving in the water column or along the bottom.

Prior to deployment and after the cameras have been focused and positioned, a series of stereo images are taken of a calibration plate which consists of a uniform grid with squares of known size. These images are then used to calibrate the camera system by processing them through a matlab toolbox designed by Jean-Yves Bouguet [4]. This calibration procedure removes aberrations in the optics of the cameras, calculates the
orientation and position of the cameras relative to one another, and finally calculates the information necessary to rectify the stereo image pairs.

After the stereo images are captured, the images are rectified, and processed to extract the digital elevation map (DEM). The processing uses area-based cross-correlation of windowed regions on each image pair to produce a matrix of correlation scores as a function of the disparity of the windowed region on the right image relative to the left image [5]. From the disparity of the pixels between the images, the surface height can be found. In a best case scenario, the values with the highest correlation score correspond to the same position as seen in each image. Choosing the highest score can often lead to incorrect matches and errors in the final DEM. There has been a great deal of work done in the computer vision community to find better algorithms to determine the best surface from the correlation matrix. We have chosen to use a technique developed by Sun [6] which utilizes dynamic programming techniques both along and perpendicular to the epipolar lines. This technique assumes that the rough surface is continuous, a reasonable assumption for the sediment interface.

3 Laboratory evaluation of the system performance

In order to assess the performance of the camera system as well as the stereo processing technique, a surface with known roughness was milled into a piece of polystyrene. The final surface was 60 x 40 cm and has an RMS roughness of 0.49 cm. The surface that was programmed into the milling machine is shown in Fig. 2(a) and the marginal spectrum of the programmed surface is shown in Fig. 2(b). The roughness spectrum was chosen for this piece is similar to that measured at the SAX99 site. In order to test the stereo system, a thin layer of sand was glued to the surface to simulate the sediment interface. The sand is well-sorted and has a grain size of 0.35 mm.

The area-based cross-correlation technique determines the pixels on each image which correspond to the same point on the surface. This is done by taking a region of the left image and cross-correlating it with other regions on the right image. Typically these regions are squares of N x N pixels. If this region is large, there is more texture in the region and hence the SNR of the correlation score increases. However, taking larger regions can lead to smoothing of the DEM. Smaller regions can produce a better estimate of the disparity, however the disadvantage of this is that the noise increases and it can be difficult to find a match. The technique developed by Sun can reduce these errors by using information about the entire surface to constrain the range of disparities between the images. The resulting spectra measured for the milled surface using different N x N pixel window sizes are shown in Fig. 2(b). As the size of the window increases, the measured spectrum decreases at high spatial frequencies by as much as 3 dB for N = 23. This produces errors in the measured spectral exponent of 13 %. As a consequence of this analysis, a window size of N = 5 was used for the processing of the SAX04 data.

In order to examine the noise floor of the stereo system, a sand layer was glued to a flat metal plate which was then imaged with the system. The resulting spectra showed that for small N, there was a noise floor that rolled off at high spatial frequencies, the level of which depended on the focus and baseline of the cameras. For the spectra shown in Fig. 2(b), this noise floor is at roughly -42 dB. For the images taken at SAX04, this level is roughly -35 dB. More work needs to be done to determine the origin of noise.
and its dependence on the camera parameters

![Image](image1.jpg)

**Figure 2:** (a) The rough surface used for testing. (b) Spectrum of the test surface determined from the surface shown in (a) and measured using the stereo camera system.

## 4 Results from SAX04

The SAX04 deployment began in late September and lasted until early November and took place approximately 1 km off the coast of Fort Walton Beach, FL. This site was closer to shore than the site used previously for SAX99 but was similar in many respects including depth and sediment type. Just prior to deployment, Hurricane Ivan made landfall at Gulf Shores, AL, approximately 100 miles west of the experiment site, with the brunt of the hurricane hitting the site itself. This had significant implications for the experiment in that the resulting storm surge and waves pulled mud and other materials from shore. This created a mud layer above the sand at the experiment site and greatly increased the turbidity reducing visibility at times to less than a foot. This made it very difficult to deploy the acoustical experiments and made it impossible to make any optically based measurements for the first half of the experiment. It was not possible to make any useful stereo camera measurements until mid October, more than mid-way...
Even after it was possible to make stereo camera measurements, the turbidity of the water column, floating matter ("sea snort"), and mud on the sediment continued to make the collection of stereo images difficult. The turbidity of the water column due to suspended sediment and organic matter varied from day to day and it was necessary to operate the camera close to the bottom. For the stereo images discussed below, the cameras were set placed 40 cm above the sediment.

Floating materials moving above the sediment cause significant difficulties in the processing of stereo images. The material, since it is above the bottom, can have large displacements in the left and right images and hence can occlude different portions of the sediment. To overcome this problem, multiple images were captured at each position of the camera system. The presence of a current or swell will cause these particles to move between each image pair capture such that for a given area of the bottom, it is likely that at least one photo will have an unobstructed view. Averaging the images tends to produce blurred regions in the mean image due to multiple instances of occlusion. As a result, an alternative approach was developed which used the differences between the

![Figure 3: (a) Marginal spectra measured at four positions in the SAS target field during SAX04. (b) Mean stereo spectrum compared to IMP2 data and the SAX99 spectral power-laws. Also shown is best fit of a power law to the SAX04 spectrum.](image)
images. The material in the water column tended to be darker than the sediment interface, so a subtraction of one image from an image at an earlier time should produce negative values for pixels that were suspended matter in the first image and were sediment in the later image. Pixels in the difference image which are below a chosen threshold are then replaced by the corresponding pixels in the later image while pixels above the threshold are replaced by pixels from the earlier image. Through this process, those areas which were occluded by floating material should gradually be replaced be corrected with information from later images.

On October 10, Tropical Storm Matthew passed by the experiment site and the resulting wave action distributed a layer of sand on the previous mud layer. There were still patches of mud and other materials lying in patches on the sediment, but these tended to be mobile and moved from place to place by the current and swell. This is important to the roughness measurements because stereo images of the sediment can only be taken in areas where the sediment is visible. This then biases the sampling to regions without mud and data collected by IMP2, a sediment conductivity system, prior to Tropical Storm Matthew, indicates that areas under mud layers were less rough than exposed areas [5]. This could be because the sand interface was protected from fish activity which would normally produce an increase in roughness. In the later part of the experiment, this roughness variation is less likely because of the mobility of the mud, hence this bias of the stereo imaging may not be as important for measuring spatial variability of the roughness spectra for the time frame considered here.

The images that are discussed here where taken in the first synthetic aperture sonar (SAS) target field on October 25. This is after the SAS rail was moved to the second target field. Image sets were taken at 12 locations along an east-west line approximately 5 m south of the rail position. Of these 12 locations, 4 of the locations were sufficiently clear of mud to process the stereo images. The marginal spectra of the locations are shown in Fig. 3(a) as well as the mean spectra of these locations. The noise floor discussed earlier is present at -35 dB. For the linear portion of the spectra, the spectral exponent is found to have a value of -3.96 and the spectral intercept is 0.000021 cm$^3$. This linear fit is shown as the solid black line in Fig. 3(b). Also shown in Fig. 3(b) is the roughness spectra measured by IMP2 at a position ~25 m west of the stereo camera on October 27. In the region of overlap, there is very good agreement between these two systems.

The slope of the roughness spectra is very steep as compared to the roughness measured during SAX99 by an analog stereo camera [3]. The linear fits to the SAX99 data are displayed as the solid lines in Fig. 3(b). Over the frequency range of the SAX04 spectra, the spectral slopes for the SAX99 data range from -1.99 to -3.00. The spectra measured at SAX99 exhibited a change in the slope at 2 cycles/cm. For spatial frequencies above this point, there is a rapid decrease in the spectral level. The slope of the spectrum after this point is comparable to the value measured at lower spatial frequencies in the target field during SAX04. The SAX04 data does not show this spectral break. More data remains to be processed from the SAX04 site from areas outside the target field and it remains to be seen whether this data will also show similar spectral properties.
References


4. The toolbox is available at [www.vision.caltech.edu/bougetj/calib_doc/index.html](http://www.vision.caltech.edu/bougetj/calib_doc/index.html).


SOUND PENETRATION INTO SANDY SEDIMENTS: COMPARISONS OF MEASUREMENTS AND RESULTS FROM SAX99 AND SAX04

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During SAX99, a buried array of transducers was used to measure sound penetration into a sandy sediment. Four omnidirectional transducers mounted on a tower were used to ensonify the sediment containing the buried array at multiple grazing angles, multiple azimuthal angles, and over a frequency range 11-50 kHz. The data obtained were analyzed to measure both the sound penetration at subcritical grazing angles and the acoustic properties of the bulk sediment itself. From comparisons of the data to simulations, the primary cause of sound penetration at subcritical grazing angles was determined to be diffraction by the sand ripple on the sediment interface. For grazing angles above critical, the measurements of the penetrating field were used to estimate both the speed and attenuation of the sound propagating through the sediment. The measured dispersion was consistent with the predictions of Biot theory. This buried array was redeployed during SAX04 near the SAX99 site and once again in a sandy sediment. The tower used to ensonify the array was modified for this experiment such that two of the original transducers were replaced by transducers which had a frequency range 2-16 kHz. The penetrating acoustic field for grazing angles both above and below the critical was again measured. Preliminary analysis indicates that the coherent penetration that was present in the previous experiment for subcritical grazing angles is not seen in the data due to the absence of a significant ripple on the sediment interface. The acoustic penetration that does occur is now primarily due to the evanescent field which becomes large at low frequencies. Sound speed and attenuation measurements made with the array during the recent experiment are consistent with the measurements from SAX99.

1 Introduction

During the Sediment Acoustics Experiment 1999 (SAX99), APL-UW deployed the Sediment Transmission Measurement System (STMS1), which was capable making several different types of measurements relevant to buried object detection. These included sound propagation measurements in the sediment in the 80-260 KHz range, backscattering measurements in the 10-150 kHz range, and penetration measurements from 10-50 kHz. Details of these measurements are given in Refs. [1-3]. While originally designed to study acoustic interactions with isotropic rough sediment interfaces, a significant ripple was present during SAX99 and this provided a unique opportunity to study the how ripples can affect buried object detection. For sound incident below the critical angle, the data confirmed that Bragg scattering from the...
rippled interface can allow significant coherent acoustic energy to penetrate the sediment. Data/model comparisons also confirmed that first-order perturbation theory can successfully model this penetrating field over the frequency range of the experiment. Sound speed and attenuation determined using the buried array were consistent with the predictions of Biot theory, while measurements made with the high frequency attenuation array found that the attenuation was proportional to frequency, $f$, as opposed to $f^{1/2}$ which is predicted by Biot theory.

2 The Sediment Transmission Measurement System.

When the opportunity arose to redeploy the array during the Sediment Acoustics Experiment 2004 (SAX04), the decision was made to modify STMS1 to cover a much broader frequency range. Two sources were added to allow penetration measurements from 2-16 kHz. This extends the range of the system down to frequencies where the evanescent wave becomes the dominant penetration mechanism. Likewise, the attenuation array was modified to cover frequencies from 40-80 kHz providing continuous coverage of the sound speed and attenuation from 2–260 kHz.

The STMS1 as modified for SAX04 consists of two components: the buried array and source tower which make penetration measurements at multiple grazing and azimuthal angles and the attenuation array which is capable of making high frequency sound speed and attenuation measurements at multiple locations in the sediment. The backscattering components were removed for SAX04 and deployed with a second system designated STMS2.

The buried array consists of 30 transducers inserted into the sediment via a cofferdam to avoid disturbing the sediment interface. The transducers are arranged in 5 vertical columns of 6 hydrophones each with the deepest 45 cm below the interface. The positions of the buried array hydrophones are determined to within ± 1 cm by transmissions from a set of tracking hydrophones which are suspended above the buried array in the initial portion of the deployment. After the buried array is in place, the tracking phones are mounted on a frame behind the array and used to track the position of the mobile source tower. The source tower has two sources which transmit at 11-50 kHz and two sources which transmit from 2-16 kHz. The sources are staggered along the height of the tower such that several different grazing angles are examined at each tower position. The tower is moved around semicircular arcs centered on the buried array. The arcs used during SAX04 had radii of 7, 10, and 15 m. The position of the source tower was determined to within ± 5 cm relative to the position of the buried array.

3 Preliminary penetration analysis

At the very beginning of the deployment, the site was severely impacted by Hurricane Ivan which made landfall 100 miles to the west. Deployment of STMS1 did not begin until roughly midway through the experiment, by which time the clarity of the water had improved such that an area could be surveyed which had only a fine layer of mud over the sand interface. During the initial stages of the deployment of STMS1, Tropical Storm Matthew passed near the site. While it distributed sand over areas which had a thick mud layer, it removed the fine mud layer from the STMS1 site and produced a
short-lived significant ripple. By the time deployment of STMS1 was completed and data collection was underway, the ripple had deteriorated and the surface had only isotropic small scale roughness.

The absence of ripple can be seen in the speed-angle ambiguity plots shown in Fig. 1. This processing method is essentially a time-domain, plane-wave beamformer in which the hydrophone outputs are scaled, delayed and summed coherently. The maximum output displayed in these plots is expected to occur when the speed and angle agree with the true values [4]. Examples of subcritical incident sound at 25 kHz are shown for SAX99 in Fig. 1(a) and for SAX04 in Fig. 1(b). In the SAX99 results, the penetration due to the ripple can be seen in the peak well off the value predicted by Snell’s law. In the SAX04 data, this peak is absent, and there is no indication of any strong coherent field for subcritical grazing angles. This was found for all azimuthal angles indicating the absence of any significant ripple or anisotropic roughness.

Penetration results for 4 kHz are shown in Fig 2(c) and 2(d). The penetration of sound incident above the critical angle is shown in Fig. 2(c). The peak in the ambiguity plot corresponds to the refracted wave, however the peak is much broader than observed for higher frequencies. This is due to the size of the buried array which was originally optimized for the high frequency data collected during SAX99. For the case of subcritical grazing angles, the low frequency incident sound creates a large evanescent wave seen as a peak at zero penetration angle.
4 Sound speed and attenuation measurements.

4.1 Sound speed and attenuation results from the buried array.

For the source tower locations along the 7 m arc, the incident sound is above the critical grazing angle and the refracted field is weakly affected by the surface roughness. For these positions, the speed-angle ambiguity plots can be used to extract the sound speed of the sediment. Details of this analysis are given in Ref. [3]. The preliminary results of this analysis are shown in Fig. 2(a). For comparison, the data from SAX99 are also shown along with the SAX99 predictions of Biot theory. Note that the sound speed measured using the buried array is relative, and all of the data have been scaled by a
ommon factor such that the value at 43 kHz corresponds to the value measured by the attenuation array at 40 kHz. The preliminary values show little dispersion over most of the frequency range of the buried array. Analysis is ongoing to confirm that the techniques used during SAX99 are applicable to the new low frequency data collected during SAX04. Efforts are also being made to confirm that the errors have been properly estimated.

Attenuation can also be estimated using the buried array by using the decrease in amplitude of the refracted wave with increasing depth [3]. The preliminary results of the analysis are shown in Fig. 2(b) along with the results from SAX99 and the attenuation predicted by Biot theory. For the most part, the data are consistent with the results from SAX99, however there is a discrepancy between the results from the low frequency source and the original source. The cause of this discrepancy is currently being examined and is likely due to an error in the application of the processing technique.

4.2 Sound speed and attenuation results from the attenuation array.

The attenuation array was used to make sound speed and attenuation measurements at positions around the STMS1 frame towards the end of the deployment. The results of these measurements are shown in Fig. 2(a) and (b). The attenuation array has four transducers which are pushed into the sediment by the diver. Two of the transducers are receivers while one of the sources transmits from 40-80 kHz and the other transmits from 100-260 kHz. The sound speed is determined from the differences in the time-of-flight between the two paths to the receiving transducers. The attenuation is determined by taking the ratio of the spectral amplitudes for measurements in water and in the sediment for each path length and then taking the log of the difference of the values. This technique is described in detail in Ref. [5].

Also shown in Fig. 2(a) and (b) are the results of 400 kHz measurements made on cores taken at the SAX04 site by Kevin Briggs at NRL-Stennis. The results from the attenuation array and from the cores are consistent with one another. The sound speed
shows minimal dispersion and is slightly lower than values measured during SAX99 but not significantly so. The attenuation does, however, show significant differences from the SAX99 measurements. There is roughly an 80 dB/m drop in the measured attenuation at 400 kHz. The frequency dependence of the attenuation measured during SAX99 showed a linear frequency dependence, while the SAX04 data shows what could be interpreted as two power laws as shown in Fig. 3. From 40-180 kHz, the attenuation varies with frequency as $f^{0.61}$ while for higher frequencies the attenuation varies as $f^{1.86}$. The former dependence is consistent with that predicted by Biot theory which says that the attenuation should go as $f^{1/2}$.

The decrease in the overall attenuation values may be due to a decrease in the number of scatterers present due to the effects of Hurricane Ivan. Due to the large waves which came to shore at the site, it is believed that the sediment at the site became an active bed where the top meter of sediment was fluidized. During the process, the larger scatterers may have dropped out of suspension sooner than the smaller sand grains. As a consequence, the top layer of sediment may have been much “cleaner”, having fewer shell fragments than were present during SAX99. The attenuation due to scattering would then be reduced. Among the observations which were considered evidence for scattering during SAX99 was the distortion of the attenuation array waveforms as shown in Fig. 5 of Ref. [3]. This distortion is largely absent from the waveforms at similar frequencies for the attenuation array as seen in Fig. 4. A possible explanation for the frequency dependence seen in Fig. 3 may be that in the absence of scatterers, the attenuation mechanism is explained by Biot theory for frequencies below 180 kHz while above this frequency the attenuation is dominated by a second, as yet unknown intrinsic attenuation mechanism similar to that observed in glass-bead sediments saturated with water and silicone oil [6]. However the frequency dependence in the glass bead sediments was linear while the SAX04 dependence is nearly $f^2$.

Figure 4: Example waveforms from the attenuation array. The left column are signals acquired at 120 kHz and the right column are signals acquired at 240 kHz.

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<th>Time (ms)</th>
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$0.0 0.1 0.2 0.3 0.4 0.5 0.6$
5 Future work

In addition to the ongoing efforts to confirm that the sound speed and attenuation have been properly analyzed and the errors correctly estimated, improved data/model comparisons remain to be performed. These depend on careful measurements of the sediment parameters which are by being made by a number of different researchers. These include sediment interface roughness measurements made by stereo cameras and other systems which are essential to the penetration analysis as well as porosity and permeability measurements to properly apply Biot theory.

Despite the absence of ripple at the STMS1 site, several manipulations were performed on the sediment interface at the end of the deployment to examine the influence of ripple. This data remains to be analyzed as well as manipulations involving distributions of scatterers on the sediment interface.

Acknowledgements

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References


Section 2

SAX04 Scatter Studies
THE EFFECTS OF SEAFLOOR ROUGHNESS ON ACOUSTIC SCATTERING: MANIPULATIVE EXPERIMENTS

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Deliberate manipulations of the seafloor during SAX04 (Sediment Acoustics Experiment-2004) in the form of quasi-periodic ripple features were carried out to examine the effects of interface roughness on high-frequency acoustic scattering. Manipulative experiments were conducted in the field of view of a bottom-mounted acoustic tower (40 kHz) and in the field of view of acoustic transducers (30-90 kHz) attached to a mobile rail system. The center wavelength of ripple-like features varied between 2 and 3 cm and the strike of the ripples was oriented parallel, perpendicular and at 30° to the axis of propagation of the incident acoustic waves. Backscattering strength was greatest when the ripple spacing was close to one-half the acoustic wavelength and the strike of the ripples was perpendicular to the incident acoustic propagation path. Preliminary analysis suggests agreement between measured and modeled backscatter strength.

1 Introduction

High-frequency acoustic scattering and penetration experiments were conducted on shallow-water sandy sediments in the northeastern Gulf of Mexico, as part of two Sediment Acoustics Experiments in 1999 (SAX99) [1,2] and in 2004 (SAX04) [3,4]. During the SAX99 experiments, the seafloor was raked in the acoustic field of view of the Benthic Acoustic Measurement System (BAMS) [5,6]. This bottom-mounted tower allowed acoustic scattering measurements (40 kHz) to be made within a 30-m radius circle that included several 4-m² areas modified by divers. The tine spacing (ripple wavelength) of the artificial roughness was approximately equal to the acoustic “Bragg wavelength” (approximately half the acoustic wavelength) at the incident grazing angle appropriate for 40-kHz backscattering measurements. Values of acoustic backscattering strength increased by 12-18 dB immediately after raking; then decayed to background levels within 24 hours due to biological modification of seafloor roughness (Fig. 1).

The high rate of decay of man-made ripples and the related change in backscatter strength provided considerable insight into temporal dependence of high-frequency
scattering from surface roughness features. Modelled scattering strengths (1\textsuperscript{st} order perturbation theory) were about the same as measured scattering strengths for the natural environment (before and 24 hours after manipulations). However, the model results for raking orthogonal to the incident ensonification (+0.7 dB) were almost 20 dB higher than values of backscatter strength measured immediately after raking (-20 dB). The discrepancy between measured and modeled values of acoustic backscatter strength from artificial bottom roughness features created during SAX99 provided the motivation for additional manipulative experiments during SAX04.

Figure 1. Decay of acoustic scattering after raking orthogonal to the incident acoustic energy during SAX99.

2 Methods

2.1 Acoustic Methods

Acoustic backscattering measurements were made at 40 kHz using BAMS during SAX99 [5] and SAX04 and between 30-90 kHz during SAX04 using piston transducers mounted on a moveable tower affixed to a bottom mounted rail system [7]. BAMS is an autonomous system, which allows acoustic scattering measurements to be made within a 30-m radius circle around the bottom-mounted tower. The 40-kHz transducer is mounted 3.2 m above the seafloor at the apex of the BAMS tripod. The transducer has a horizontal beam width of 5º and uses a FM pulse to obtain a 0.4-m range resolution. BAMS rotates in 5º increments with about 6 minutes required for a full 360º rotation. This resolution allows 9 values of scattered intensity to be calculated within each 4-m\textsuperscript{2} manipulation area from which average scattering strengths are determined. During SAX99, experimental quadrates were placed 10-12 m distance from BAMS producing a mean grazing angle of 16º. During the SAX04 measurements the quadrates were slightly closer (8-10 m) with a mean grazing angle of 20º. The transducers on the rail tower were mounted at a fixed orientation 4.8 m above the seafloor. For many of the acoustic measurements, the tower translated over the entire 27-m length of the rail; however, for these manipulative experiments, six rail tower locations separated by 30 cm were used to obtain average scattering strengths. Divers conducted manipulations in a single 4-m\textsuperscript{2} quadrate 8-10 m from the base of the platform yielding a 28º mean grazing angle.
2.2 Sediment Physical Properties

In situ and laboratory methods were used to characterize surficial sediment physical properties during SAX99 and SAX04 [1,3,8-10]. Both sites consisted of well sorted medium quartz sand with slightly larger mean grain size (420 µm) at the more offshore, deeper (19-m water depth) site of SAX99 compared to the more inshore, shallower (17-m water depth) site of SAX04 (350 µm). Values of sediment sound speed (at 400 kHz) measured in cores from SAX04 (mean sediment-to-seawater sound speed ratio = 1.162) were slightly higher than those measured at the SAX99 site (mean sound speed ratio = 1.155), whereas values of attenuation measured during SAX99 (173 dB·m⁻¹) were significantly higher than those measured during SAX04 (92 dB·m⁻¹). Values of sound speed show no significant dispersion over the frequency range of 20-400 kHz [8,9] justifying the use of the sound speed measured at 400 kHz for modelling scattering strengths at 20-90 kHz. Values of sediment porosity and bulk density were not significantly different between the two sites with ranges of 35-38% for porosity and 2000-2100 kg·m⁻³ for bulk density. These values of sound speed, attenuation and sediment physical properties are typical for medium sized sands. For modelling acoustic scattering (section 3.2), mean values of sound speed ratio (1.16), density ratio (2.0) and attenuation (0.31 dB·m⁻¹kHz⁻¹) are used for both SAX99 and SAX04.

2.3 Seafloor Roughness

Considerable effort was made to characterize seafloor roughness during both SAX99 and SAX04 using a variety of manual, optical, laser, and electrical techniques [1,11]. For the purposes of this paper, digital stereo photographs collected during SAX99 will be used to characterize two-dimensional (2-D) seafloor roughness for the manipulative experiments. Photographs were made before, immediately after, and for periods up to 24 hours after raking (4-7 November 1999) in order to document the decay of roughness previously observed by divers. The stereo-correlation of digital images using area-based matching was performed to create a 2-D height field, or digital elevation model, from which the full 2-D roughness power spectrum was estimated. The effective resolution of the system is on the order of a millimeter in both the horizontal and vertical [12]. The images along with values of spectral strength and spectral exponent for 2-D spectra estimated from the digital images were presented in [5]. Given the similarity in sediment properties it is assumed that the initial 2-D spectra for all surfaces raked during both SAX99 and SAX04 are nearly identical when using rakes with the same tine spacing. In the future, when visibility improves 2-D roughness measurements will be made for fresh ripples at the site of the SAX04 manipulations.

2.4 Seafloor Manipulations

Rakes with tine spacing of 1.95 and 3.0 cm were used to create quasi-periodic roughness features on the seafloor in the acoustic field of view of both BAMS and the mobile rail system [7]. Quadrates (4-m² area) were staked out between 8 and 12 m from the base of BAMS. During SAX99 raking, ripples with a tine spacing of 1.95 cm were created near BAMS both parallel and perpendicular to the direction of acoustic propagation. During SAX04, ripples with tine spacing of 1.95 cm and 3.0 cm were created parallel, perpendicular and at 30° to the direction of acoustic propagation. Acoustic scattering
measurements were made each hour for at least 24 hours after manipulations during both experiments. Manipulative experiments at the rail tower did not attempt to measure temporal changes in backscatter strength due to decay of ripples, but instead concentrated on scattering from fresh ripples over a range of acoustic frequencies. Acoustic measurements were limited to two, 3-hour periods on October 18-19, 2004. Divers raked the entire 4-m$^2$ quadrate at angles parallel, at 30º, and perpendicular to the path of the incident acoustic energy (Fig. 2). This was repeated 8 times with divers smoothing the surface between each treatment.

3 Results

3.1 Acoustic Scattering Measurements at BAMS

Scattering measurements made during SAX99 were summarized in the introduction, have been previously published [5], and consequently will not be repeated herein. As reported elsewhere [4], hurricanes during SAX04 changed experimental plans, especially during the early part of the experiment when diver operations were severely hampered by poor visibility. Divers not only had problems establishing 4-m$^2$ quadrates but could not assess the quality of the manipulations. In addition, the backwash from Hurricane Ivan deposited fine-grained, clayey, lagoonal sediments throughout the experimental site changing the sediment impedance and roughness characteristics [3]. Often, raked quadrates around BAMS exhibited both sand and mud interfaces. Both the poor visibility and variable seafloor impedance restrict presentation of the backscatter strength measured during BAMS manipulative experiments to qualitative observations.

![Figure 2. Photograph of the sediment surface raked with a 1.95-cm tine spacing during the SAX99 experiments. The rake had triangular teeth cut at 45º but raking was accomplished with the rake held at an angle roughly 30º to the sediment surface. The resultant ripple amplitude (0.57 cm) was approximately equal to amplitude for a ripple given the measured angle of repose (28º) of the sediment.](image)
As in SAX99 experiments, the values of scattering strength rapidly diminished over time, generally returning to background levels with 24 hours. Values of backscattering strength were greatest when the ripple spacing was close to one-half the acoustic wavelength (1.95-cm versus 3.0-cm tine spacing) and when the strike of the ripples was perpendicular to the incident acoustic propagation path.

3.2 Acoustic Scattering Measurement at the Rail Tower

The manipulative experiments that were conducted later in SAX04 (18-19 October) and within the field of view of the acoustic rail had the benefit of good visibility, and a 4-m$^2$ quadrate that was free of surface mud deposits. This allowed the following quantitative analysis of the backscattering data (30-90 kHz) and a comparison to model simulations. Backscattering strength (Fig. 3) versus grazing angle shows a strong peak in scattering strength at 45 kHz for the grazing angles between 25º and 30º. These grazing angles correspond geometrically to backscattering from the raked quadrate (8-10 m from the base of the tower). Moreover, the tine spacing, and thus the ripple spacing of the raked sediment surface, is very close to the “Bragg wavelength” given by $\lambda/(2\cos\theta)$ for the acoustic wavelength ($\lambda$) at 45 kHz, where $\theta$ is the incident angle.

![Figure 3. Backscattering strength (dB) vs. grazing angle measured over the frequency range of 20-90 kHz. Measurements were made within 10 minutes of raking the seafloor using a tine spacing of 1.95 cm.](image)
3.3 Environmental Model

For the anthropogenic roughness a two-dimensional roughness spectrum measured during SAX99 was used. This spectrum was obtained from digital stereo camera data collected by A.P. Lyons [5]. This spectrum is composed of two power-law forms, and when properly symmetrized is expressed as the sum of four terms:

\[ W(K) = W_1(K) + W_1(-K) + W_2(K) + W_2(-K) \]

where

\[ W_n(K) = \frac{w_{2n}/2}{[a_n^2 K_n^2 + (K_x - K_n)^2 + (1/L_n)^2]^{\gamma_{2n}/2}}. \]

(It should be noted that due to a typographical error, the spectrum given by Eq. (1) in [5] was not properly symmetrized. However, the proper symmetrized form was used for the model results described in [5].) The parameters \( K_n \), \( n = 1, 2 \), allow introduction of spectral peaks. The parameters \( a_1 \) and \( a_2 \) control the anisotropy between the \( x \) and \( y \) directions in wavenumber space, \( K = (K_x, K_y) \). In matching the spectral data, the low-wavenumber behavior of the spectrum was set via \( W_1 \) with \( K_1 \) set to zero. Parameters \( a_1, L_1, w_{21}, \) and \( \gamma_{21} \) were set to 2, 3 cm, 0.05 cm\(^{-1}\) and 5, respectively, to match the low-frequency behavior of the measured spectrum. \( K_2 \) was set to the wavenumber of the anthropogenic roughness, \( 2\pi/(0.0195 \text{ m}) \). The parameters \( a_2, L_2, w_{22}, \) and \( \gamma_{22} \) were set to 0.7, 7 cm, 0.002 cm\(^{-1}\), and 2.5, respectively, to match the width of the measured peak due to the anthropogenic roughness and the spectral behavior at high wavenumbers. The mean-square ripple height is equal to the integral of the ripple spectrum over all \( K \), and yields an RMS roughness of \( h = 0.0031 \text{ m} \). Similarly, the RMS roughness due to the low-wavenumber portion of the spectrum is 0.012 m.

There is considerable uncertainty in applying this spectrum to the SAX04 data, as it was not determined contemporaneously. Further, there are substantial statistical errors in this spectral estimate, which is based upon a single stereo photo pair. Nevertheless, this spectrum is a reasonable starting point, as it was central to the attempted model-data comparison reported in [5] and was obtained using the same raking procedure as in SAX04. The acoustic modeling and simulations to be described employ the mean values of sediment parameters given in Section 2.2 and a water sound speed of 1530 m\( \cdot \)s\(^{-1}\). Changing the attenuation from the SAX99 to SAX04 value makes no discernable difference in the modeling results presented in the next section.

3.4 Acoustic Modeling

First-order, small-roughness perturbation theory was used to model the scattering strength as a function of grazing angle and frequency. The applicability of perturbation theory to a given rough interface is usually judged by the size of the dimensionless number, \( kh \), where \( k \) is the acoustic wavenumber and \( h \) is the RMS roughness defined above. At 45 kHz, the frequency of primary interest in this data set, \( kh = 0.57 \). This is sufficiently small that perturbation theory should be valid [13]. As a check, exact 2-D Monte Carlo simulations using randomly-generated 1-D ripple realizations were
compared with perturbation theory. For 45 kHz with an RMS roughness \( h = 0.004 \) m, the exact result was approximately 3 dB below the perturbation result at a grazing angle of 28°. Given the smaller roughness estimate (0.0031 m) used in the model-data comparisons, the simulations should have little error due to the use of perturbation theory. Even though the low-wavenumber part of the spectrum has \( kh = 2.2 \), this is not a concern with regard to accuracy of perturbation theory at 45 kHz, as the wavelengths responsible for most of this roughness are longer than the acoustic wavelength and do not contribute appreciably to scattering.

Figure 4 shows the modeled scattering strengths versus grazing angle at each of the measurement frequencies. The measured and modeled backscattering strengths show a large peak for 45 kHz at the grazing angle corresponding to the treatment location. This peak is about 20 dB above the scattering strength levels at frequencies removed from the Bragg resonant frequency. As the data have essentially the same behavior, it can be concluded that roughness scattering is dominant in the raked location.

The simulated scattering strength at 45 kHz matches the measured value satisfactorily, given that the measured value is subject to a statistical fluctuation of about ±2 dB due to finite sample size. In [5], the measured scattering strength was about 20 dB below the model prediction. It appears that the measurement errors listed in [5] were responsible for the lack of agreement. Detailed model-data comparisons are hampered by uncertainties in the roughness spectrum. In particular, uncertainty in the width of the spectral peak representing the ripple does not allow a serious discussion of frequency dependence.
Acknowledgements

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BISTATIC SCATTERING BY SEDIMENT RIPPLE FIELDS

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Multi-static sonar systems have the potential to increase detectability of targets. If the seafloor has prominent ripples, however, Bragg scattering from the ripples may generate target-like clutter. While Bragg scattering by a bottom ripple field has been investigated both theoretically and experimentally for the cases of backscatter into the water column and forward scatter into sediments, general bistatic scattering has received less attention. In this paper, 3 kHz bistatic scattering data, generated using a mobile source (part of a bottom-mounted SAS system) and recorded on a single hydrophone are analyzed. The analysis is aided by the use of contemporaneous bottom ripple measurements. Through simulations, we find that the measured acoustic field is indeed largely the result of bistatic scattering from the bottom ripple field, and the scattering strength is greater by about 10 dB than that in the absence of a ripple field. It is interesting that the observed bistatic Bragg scattering is strong, even though it is caused by a poorly defined ripple field, with a broad spectrum of spatial wavelengths. Synthetic-aperture beamforming was performed on both real and simulated data and resulted in spatially localized, target-like features. These features could appear as false targets or could mask real targets.

1 Introduction

Multi-static sonar offers the promise of improved detection of targets through increased target echo level. At the same time, one must consider the implications of bistatic scattering for interfering reverberation. In particular, Bragg scattering by sand ripples may lead to high levels of seafloor reverberation [1, 2]. Such reverberation may have unusual character, being localized spatially (target-like) even when the ripple is not localized. In order to study these issues, bistatic seafloor scattering measurements were carried out during SAX04 [3] in shallow water near Ft. Walton Beach, Florida. The acoustic source was moved along a 27 m track, which was part of a bottom-mounted synthetic-aperture sonar (SAS) measurement system. The receiver was moored at a perpendicular distance of 10 m from the track at a position 6.5 m down the track. Both source and receiver were calibrated, allowing absolute measurement of scattering levels. Synthetic transmit beamforming was used to map seafloor scattering in terms of target strength. Extensive geoacoustic measurements made as part of SAX04 support these acoustic measurements, and the ripple field was quantified using two methods, an in-situ sediment probe and SAS imagery. The experimental data are compared with a scattering model based upon small-roughness perturbation theory. This model provides time series given a realization of the seafloor relief and can be used to obtain simulated SAS images.
2 Properties of Measurement Site

The water depth at the site was 16.7 m, and the water sound speed at the seafloor was 1534 m/s with a slight depth dependence that can be neglected at the ranges of interest here. The sediment at the SAX04 site was a well-sorted sand with mean grain size 0.35 mm, sediment/water sound speed ratio 1.16, and density ratio 2.0 [M. Richardson, private communication]. An in-situ probe system (IMP2) [4] measured resistivity profiles along tracks of length 4 m, providing information on both the ripple field and the spectrum of non-directional roughness.

![Synthetic-aperture sonar image of the seafloor](image)

For simulations to be described below, the mean direction and amplitude of the ripple field were estimated from the SAS image shown in Fig. 1 and from IMP2 data. The power spectral density was assumed to have a Gaussian dependence upon the wave vector \( \mathbf{K} = (K_x, K_y) \) and centered on the mean ripple wave vector, \( \mathbf{K}_r \):

\[
W_h(K_x, K_y) = \frac{h^2}{4\pi\sigma_h^2} \{ \exp[-|\mathbf{K} - \mathbf{K}_r|^2/(2\sigma_h^2)] + \exp[-|\mathbf{K} + \mathbf{K}_r|^2/(2\sigma_h^2)] \}.
\]  

(1)

The RMS relief, \( h \), is assigned a value 1 cm based upon IMP data. The mean ripple wave vector was determined from the spectrum of the SAS image, with mean wavelength 40 cm and with the direction of average ripple crests at an angle of 10° with respect to...
the SAS track. The spectral standard deviation was not perfectly constrained by the rather noisy spectrum of the SAS image of the ripple field, and its value, \( \sigma_s = 0.3 K_r \), was determined by a fit of the broad features of simulated data to real data. Thus, the modeling involves one fitted parameter.

Equation (1) does not represent the random, isotropic background roughness, which is better described by a power-law spectrum of the form

\[
W_j(K_x, K_y) = \frac{w_2}{(K_x^2 + 1/a^2)^{\gamma_2/2}},
\]

with \( \gamma_2 = 3.8 \), \( w_2 = 0.001 \text{ m}^{-2} \), and \( a = 0.04 \text{ m} \), and determined from IMP2 data. The complete roughness spectrum is given by the sum of Eqs. (1) and (2).

3 Acoustic Measurements

Figure 2 shows the geometry of the experiment. The acoustic source transducer was a planar array of dimensions 0.20 x 0.97 m, with the shorter dimension being in the horizontal direction. The array was mounted on a movable tower on a 27-meter track intended for SAS measurements. The center of the source array was 4 m above the seafloor and the normal to the array face was tilted downward at an angle of 20° from the horizontal. The transmitted waveform was a pure tone consisting of five cycles at the center frequency of 3 kHz, multiplied by a Hann window function. During the measurement, the source moved along the track at a speed of 0.05 m/s, and pings were transmitted at a 0.5 s interval with a source level (at the waveform peak) of 184.4 dB re 1 \( \mu \text{Pa} \) @ 1 m. The receiver was an autonomously recording Bioprobe (Bioacoustics Probe by Greeneridge Sciences, Inc.) unit with sampling frequency 13.173 kHz, moored 6 m above the seafloor at a position \((x, y) = (6.5 \text{ m}, 10 \text{ m})\). This horizontal coordinate system has its origin at the starting source location, the \( x \)-coordinate is parallel to the track, increasing in the direction the source moves, and the \( y \)-coordinate is perpendicular to the track, increasing in the direction of the acoustic transmission.

![Figure 2](image_url)

Figure 2. Geometry of the bistatic reverberation measurement. The source was moved along the rail at an altitude of 4 m above the seafloor.
Figure 3 displays the output of the receiver as a false-color image formed from the signal envelope, aligned in the time domain using the leading edge of the direct arrival. The direct arrival follows a nearly horizontal path from source to receiver that is very near a null in the transmitter beam pattern. This accounts for the peculiar form of the direct arrival when the source x-coordinate is nearly equal to the receiver x-coordinate. The prominent arrival following the direct arrival is the seafloor reflection, followed by random seafloor scattering. The surface-bounce arrival is less distinct than the bottom reflection, but is clearly visible in the figure.

Synthetic aperture beamforming can be used to determine the directionality of the scattered energy. With a stationary receiver and moving source, the only option is to synthetically form directive transmitter beams. The aperture can be chosen to be any desired section of the 27-meter track. Shorter apertures have the advantage of providing a more well-defined incident direction, facilitating comparison with the simpler scattering strength models. Use of the full aperture better simulates actual SAS practice and provides better cross-range resolution than the shorter aperture. Figure 4 shows the result of using a 4 m aperture centered at a track coordinate of 15 m. A Hann weighting function was used to reduce sidelobe levels. The color scale is target strength in dB re 1 m². In forming images, the direct and bottom-reflected arrivals were eliminated by time
gating, as they produce extremely strong features in the region between source and receiver. The beamformed image shows one localized feature having target strength -16 dB re 1 m², as well as a few weaker, scattered features.

Figure 4. Image formed using synthetic aperture transmit beamforming with the aperture indicated by the heavy black line at the top edge. The y-coordinate is measured perpendicularly from the SAS rail and is zero at the rail. The receiver location is marked by a small black circle. The color scale is target strength in dB re 1 m².

Figure 5. Image formed using simulated data and synthetic aperture transmit beamforming. All parameters are as in Fig. 4.
Figure 5 shows a synthetic aperture image formed using simulated data. The simulated image compares well in character and target strength with the data image considering the random fluctuations inherent in reverberation and the fact that the simulation does not include surface-scattered energy. The elliptical “hole” in the data image is caused by time gating to remove the direct- and seafloor-reflected signals. The simulation technique and simulated data are discussed in the following section.

4 Simulations

The simulations employed first-order small-roughness perturbation theory to generate pressure time series, \( p(t) \), given by an expression of the form

\[
p(t) = \frac{2\pi f_0}{c_w^2} \int \int dx \, dy \, f(x, y) B(x, y) \tau(x, y) \frac{1}{r_s r_r} s(t - t_d).
\]

In this expression, \( f_0 \) is the acoustic center frequency, \( c_w \) is the water sound speed, \( f(x, y) \) is the function specifying the seafloor relief, the dimensionless function \( B(x, y) \) contains the source and receiver directivity functions, and \( \tau(x, y) \), also dimensionless, includes the seafloor parameters (density, sound speed, and attenuation) that appear in the fluid-fluid boundary condition as well as angular variables. Spreading loss is given by the reciprocal ranges from the source and receiver to the integration point \((x, y)\), and \( s(t)/r_0 \) is the far-field pressure at range \( r_0 \) on the maximum-response axis of the source. The time delay taken from a source position to the seafloor at \((x, y)\) and then to the receiver is denoted \( t_d \). The small roughness perturbation approximation is expected to be accurate for the conditions of this experiment, as the dimensionless product of the RMS relief (0.01 m) and the acoustic wavenumber is \( kh = 0.12 \). The first step in the simulations was generation of realizations of \( f(x, y) \) using the spectra of Eqs. (1) and (2) under the assumption of Gaussian statistics. The ripple realizations compare reasonably with the SAS image of Fig. 1. Time series were generated by performing the double integral in Eq. (3). This was done multiple times, once for each position of the source along the rail, with 10 cm steps. Note that the transmitter and receiver coordinates are not shown explicitly in Eq. (3), although both enter through the range and angular variables.

Figure 6 shows simulated data in the format of Fig. 3 for three cases: a pure sinusoidal ripple having wavelength 40 cm, RMS relief 1 cm, and oriented 10 degrees from parallel to the source track; a random ripple field having the spectrum of Eq. (1); and isotropic roughness having the spectrum of Eq. (2). In comparing these with Fig. 3, note that, in the simulations, the first arrival, seafloor reflection, and surface reflection are not shown. The random ripple case clearly provides the best match to the experimental data, both in spatial and temporal structure and in absolute level. Also notice that the isotropic case, as expected, shows a lower scattered amplitude, about 10 dB below the random ripple case.
The three different cases exhibit quite different responses to beamforming. The pure sinusoid has the best-localized image, and the isotropic roughness gives essentially no localization (Fig. 7) and has a peak target strength about 13 dB below that of the simulated random ripple. As noted above, the random ripple field gives an image (Fig. 5) that resembles the real-data image of Fig. 4 both in localization and target strength.

![Figure 6. Images formed from envelopes of synthesized receiver output, aligned in the time domain using the leading edge of the first (direct) arrival. The three cases are: upper left, pure sinusoid; upper right, random ripple field; lower, isotropic roughness. The color scale is in dB re 1 µPa.](image)

5 Discussion

Bistatic reverberation from ripple fields shows character unlike normal reverberation if the acoustic and ripple wavelengths are comparable. In this case, scattering levels are significantly higher than for typical isotropic seafloor roughness, and beamforming will show "hot spots" that might be mistaken for real targets or might mask real targets. In the case studied here, the ripple field was rather irregular, yet it increased scattering levels by about 10 dB relative to the background isotropic roughness existing at the experiment site. This picture is supported by simulations, but more work is needed to better understand this phenomenon and its consequences for bistatic sonar performance.
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Figure 7. Images formed using synthetic aperture transmit beamforming for simulated data with the aperture indicated by the heavy line at the top edge. The two cases are: upper, pure sinusoid; lower, isotropic roughness. The color scale is target strength in dB re 1 m$^2$. Note that the color scale of each image is different.

References


SYNTHETIC APERTURE SONAR (SAS) IMAGING AND ACOUSTIC SCATTERING STRENGTH MEASUREMENTS DURING SAX04 (SEDIMENT ACOUSTICS EXPERIMENT – 2004): EXPERIMENTAL RESULTS AND ASSOCIATED MODELING

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As part of SAX04, a bottom mounted rail/mobile tower system was deployed to carry out scattering strength and Synthetic Aperture Sonar (SAS) measurements. The goal of the scattering experiments was to acquire a large number of independent scattering measurements to reduce the statistical uncertainty for the estimates of backscattering and forward scattering strength. This reduction in uncertainty is necessary to discriminate between sediment acoustic models. The goals of the SAS measurements were (1) to examine buried target detections over a large frequency range in order to further understand the physical mechanisms involved in acoustic detection (using models tested by both the rail system scattering data and by other experiments carried out during SAX04), (2) to acquire both a backscattering and bistatic scattering database on mine-like objects and clutter for use in developing detection and classification methods. First, a brief description will be given of the rail/tower system. After this, we describe methods used to acquire data, present experimental results and compare experimental results to model predictions. Two preliminary conclusions from data/model comparisons are that the Biot model is an accurate predictor of the reflection coefficient derived from the forward scattering data and that a mud layer deposited during Hurricane Ivan affects measured backscattering levels. [Work supported by the US Office of Naval Research.]

1 Introduction

The system used in SAX04 was designed to carry out both scattering measurements to determine the basic acoustic properties of sediments and SAS measurements. This combination of measurements is quite natural given that SAS inherently requires the use of 10s to 100s of transmissions (from a moving source) in order to form an image and tests of statistical sediment acoustic models require use of the same numbers of transmissions over separate areas of the bottom in order to reduce the uncertainty in the determination of backscattering strength and the flat interface reflection coefficient.

Figure 1 shows engineering drawings of the system in SAS mode (Fig. 1a) and Backscattering/Forward Scattering (BFS) mode (Fig. 1b). The system is comprised of a bottom-mounted rail and a rail tower instrumented with acoustic and position-sensing transducers.
Each rail section is 7 m in length and rail sections can be connected and leveled to form longer rail lengths; during SAX04 four sections were used (Fig. 1 shows three sections). The electric motor-driven tower can traverse the rail at a constant speed from about 2 to 10 cm/s (used in SAS mode) or can be moved in a start/stop mode so that data can be taken at specified intervals (in BFS mode). The tower vertical mast has a pivot so that it can be rotated (by divers) between the two configurations shown in the figure. The configuration used in the BFS measurements allows temporal separation of forward scattering signals and scattering from rail and tower structure.

Further details of the rail, tower, transducers and electronics can be found in [1]. In the sections that follow we describe methods used to acquire data, present experimental results and compare experimental results to model results.

2 Forward Scattering, Backscattering and SAS Imaging

2.1 Forward Scattering

Experimental results at several frequencies (20, 30, 40, 60, 80, 100 kHz) were obtained during the latter part of SAX04. The experiments generating the results discussed here benefited from knowledge gained in on-site analysis of data acquired earlier in SAX04. In particular, identification of interfering tower structures in the initial experiments motivated a change to a simpler mounting apparatus.

The rail tower was used in the BFS mode shown in Fig. 1b. A source/receiver geometry was chosen and then implemented by divers. Results for 3 different grazing angles are given here as realized by the geometries chosen. For each source/receiver geometry the tower was moved to 80 positions along the rail separated by 30 cm. At each tower position, 250 µs pulses at the center frequencies given above were transmitted and the forward scattered signal recorded. Modeling [2] carried out before SAX04 had indicated that ensemble averages of the forward scattered energy could be used to estimate the reflection coefficient for a flat water/sand interface and that
averaging 80 positions would be sufficient to discriminate between Biot model and fluid model predictions for the sand.

The blue curves in the top panel of Fig. 2 show the signals recorded at each of the 80 positions. The dashed red curve is the intensity average of these signals. The first peak is the direct path, the second is scattering from a tower cross beam and the third is the forwarding scattering signal from the water/sand interface. Note the large variation in the forward scattering level as a function of tower position. Note also that this variation relative to the mean is not symmetric. This is consistent with a Gaussian quadrature process implying an exponential distribution for intensity [3].

The bottom panel of Fig. 2 shows model results for forward scattering from 80 independent realizations of a rippled interface with rms roughness (1 cm) and ripple wavelength (50 cm) of the type measured during SAX04. Again, the signal for each realization is in blue and the ensemble average is in red. The green curve is the ensemble average from the experiment. The model used Biot theory for the reflection coefficient with sediment parameters from the SAX99 experiment about 1 km from the SAX04 site. The full set of Biot parameters for the SAX04 site has not been determined at this point, however, using the parameters that have been determined indicates that the predicted reflection coefficients for both the Biot and fluid sediment models may be slightly larger (less than 0.5 dB larger at normal incidence) than for SAX99 parameters.
The slightly larger reflection coefficients would shift the model predictions (the red (Biot) and black (fluid) curves) in Fig. 3 up by a few tenths of a dB. Note that the model curves shown in Fig. 3 are for 50 kHz; in the 20 to 100 kHz range of the data the model results do not change significantly (with respect to the conclusion reached at the end of this section).

Figure 3 also shows reflection coefficients (vertical lines of various colours) calculated from the experimental ensemble results at three angles (38, 69 and 76 degrees). The data from different frequencies are offset in angle a small amount for clarity. The 100 kHz data (yellow vertical lines) are plotted at the experimentally realized angles. The vertical lines indicate the uncertainty in the measurements. The preliminary conclusion from the data/model comparison is that a Biot model is a better descriptor for the sand in this context.

2.2 Backscattering

Backscattering measurements were carried out using the tower in the BFS mode. As with forward scattering, the tower was moved to 80 positions along the rail. At each position 1 ms cw pulses with center frequencies within the range of 20 to 500 kHz were transmitted from a piston source and received on a separate piston receiver. At this point the backscattering levels in the 20 to 150 kHz range have been the primary focus of attention. In part, this is because the sensors used are the same ones used during the SAX99 experiment (Engineering Associates models EA33 and EA41). For the data shown here (30 and 130 kHz) the transmitter and receiver were set to a depression angle of 28°. Details of the analysis procedures for the data as well as the model used in data/model comparisons shown here can be found in [4].

It is instructive to compare SAX04 backscattering results with similar results from SAX99. Figure 4 is comprised of four panels. The top two panels show experiment (data points with error bars) and model (two curves indicating the model uncertainty
based on confidence limits of model inputs) results from SAX99 [4]. The bottom two panels show the results for SAX04.

For the experimental data, the uncertainties are a combination of both statistical uncertainty and uncertainty in the calibration of the transducers. The error bars in the SAX04 data are smaller due to the larger number of positions used in the ensemble results (20 positions in SAX99 vs. 80 in SAX04) but the transducer uncertainties limit the reduction achieved.

The model uncertainties shown for SAX04 are much smaller than for SAX99. The model used accounts only for surface roughness scattering and the model uncertainties are driven primarily by the knowledge of the surface roughness spectrum. For SAX99, roughness measurements were made in the general vicinity of the scattering measurements but not co-located. In SAX04 a goal was to reduce roughness uncertainty by making roughness measurements at the site of scattering measurements. The uncertainties are guided by the results in Ref. [5]. However, as with the forward scattering model, the entire parameter set needed for the model has yet to be determined. Thus, the model uncertainties shown in the bottom two panels are yet to be finalized.

With this caveat, comparison of the top panels in Fig. 4 to the bottom ones is revealing. Starting with the 130 kHz panels, the top (SAX99) panel indicates that roughness scattering can account for a majority of the scattering seen (though other data in [4] indicates that volume scattering above the critical angle at 30° may come into play above 50 kHz). The bottom 130 kHz panel (SAX04) indicates that below the critical angle surface scattering can account for the scattering but above it some volume scattering mechanism is presumably dominating.

![Figure 4](image-url)

Figure 4. Experiment scattering data and model comparison for SAX99 (top two panels) and SAX04 (bottom two panels).

Turning to the 30 kHz panels, the SAX99 results indicate that roughness scattering can account for all the scattering seen, including a drop in scattering strength above the
critical angle. For the SAX04 data roughness scattering seems to be playing only a minor role. The current hypothesis is that a near surface mud layer (and sand intrusions within that layer [5]) deposited as a result of Hurricane Ivan is responsible for both the above critical angle scattering in the 130 kHz SAX04 data and the scattering at all angles in the 30 kHz SAX04 data.

It is also interesting to note in Fig. 4 that, for SAX99, the model predicts a much higher backscattering strength at 130 kHz than at 30 kHz whereas, for SAX04, the model predictions are only slightly higher at 130 kHz than 30 kHz. This is a direct result of a difference in the surface roughness spectra in the two cases. The roughness spectra fall off faster at higher wavenumber for SAX04 than for SAX99.

2.3 SAS Imaging

SAS imaging of various proud, partially buried and buried objects was carried out throughout the SAX04 experiment. In order to obtain data sufficient for SAS imaging, the tower transited the rail at a speed of 5 cm/s (in the configuration shown in Fig. 1a). The tower sources transmitted 4 ms FM slides every 0.5 seconds (every 2.5 cm along the rail). For the results shown here a 12 to 28 kHz FM slide was used. The resulting 1080 sonar pings (over the 27 m length of the rail) were recorded for later processing. The transmitters and receivers and their geometry are described in [1].

Here we examine SAS imaging results for a 14 inch diameter focusing sphere. The silicon oil used in the sphere allows good focusing when it is buried in sand. This sphere offers a simple example for the type of imaging carried out and is currently being used in initial simulation efforts described below. The sphere examined here was flushed buried in the sediment approximately one week before the SAS data were acquired. The top two panels of Fig. 5 show experiment results. The envelope of the baseband, match filtered data for 10 meters of tower travel are shown in the top/left panel. The resulting SAS image is on the top/right. The bottom two panels in Fig. 5 show simulation results. At this point of simulation development only the buried sphere return has been modeled, i.e., reverberation from the sand/water interface was not included.

Simulation of the acoustic backscattering from a flush buried, fluid-filled, focusing sphere was carried out in four steps. First, a single rough surface realization was generated from a spectrum composed of a shifted-Gaussian ripple component and small-scale isotropic roughness with an algebraic cut-off corresponding to a 30 cm length scale. The spectrum is

$$W(K) = \frac{h^2}{2\pi \sigma_r} \left[ \exp(-|K - K_r|^2 / \sigma_r) + \exp(-|K + K_r|^2 / \sigma_r) \right] + \frac{w_2}{(K^2 + a^2)^{\gamma/2}}$$

where $\sigma_r = 2(\sigma K_r)^2$ and $K_r = 2\pi/\lambda_r$. The rms ripple height is $h$, the ripple fractional spectral width is $\sigma_r$ and $\lambda_r$ is the ripple wavelength. The components of the ripple wave vector in terms of the angle between the wave vector and x-axis (rail axis) are $K_x = K_r \sin(\beta)$ and $K_y = K_r \cos(\beta)$. For the simulation discussed here, the parameter values used were $h = 2$ cm, $\sigma = 0.1$, $\lambda_r = 50$ cm, $w_2 = 0.00166$ m$^{-5/2}$, $\beta = 6^\circ$, $\gamma = 3.8223$, and $a = 20.9$ m$^{-1}$. The rough surface is generated from this spectrum by methods described in [6].
The second step of the simulation implements the first-order perturbation model developed during analysis of SAX99 subcritical acoustic penetration data [7,8]. This model predicts the acoustic field at the center of the fluid-filled sphere as if the sphere were not present. The acoustic field includes the refracted and evanescent contributions and the first-order rough surface scattered field. Attenuation in the sediment is also included.

The third step convolves the penetration field with the backscattered form function for a fluid-filled, elastic spherical shell in a infinite medium [9]. The sphere’s shell is stainless steel 347, which has $\rho_e = 7890$ kg/m$^3$, $c_l = 5790$ m/s, and $c_t = 3100$ m/s for the density, compressional sound speed, and shear sound speeds, respectively. The shell’s thickness and radius are 0.0018 m and 0.1778 m. The internal fluid is a silicon oil with $\rho_i = 800$ kg/m$^3$ and $c_l = 1004$ m/s. The medium (sand) parameters used are $\rho_s = 2000$ kg/m$^3$ and $c_s = 1775$ m/s (losses in the sediment are ignored during this stage).

The fourth step propagates the field scattered from the spherical shell back through the sediment interface to the SAS receiver. This step again uses first-order perturbation theory (as in step 2) with the source contained in the water column and the field point within the sediment. Reciprocity is used to give the result for the source in the sediment and field point in the water. Steps 2 through 4 are applied for the 600 signals needed to populate the 15 m SAS aperture at a 2.5 cm spacing.

Figure 5. Top/left shows the baseband, match filtered experiment data for a flush buried focusing sphere. Top/right is the SAS image from that data. Bottom left and right panels are simulation results for backscattering from this buried sphere (All plots are in dB).
The experimental baseband data do not show as many returns (arcs) as the simulations. Some of this difference can be attributed to the fact that no reverberation from the sand/water interface is included in the simulations. Additionally, the simulation currently ignores attenuation within the silicon oil, which will cause preferential extinction of later arriving returns from inside the sphere as well as the elastic response of the shell. Having said this, the SAS images over an area that includes the brightest return are similar. The brightest signal in the SAS simulation comes from the focusing return of the sphere. This motivates identifying the brightest return in the SAS experiment result likewise. The return seen before the focusing return is the specular reflection off the sphere. The elastic nature of the return seen after the focusing return has not yet been determined. (Note that this return is better imaged in the SAS data than the simulations.) The next steps in our simulation development will include accounting for sand/water interface scattering (reverberation noise). After this, SAS imaging results for this same target, derived using data acquired on a towed array, will be simulated as will rail results obtained on a similar focusing sphere buried 85 cm below the interface.

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References

BISTATIC SYNTHETIC APERTURE SONAR MEASUREMENTS 
AND PRELIMINARY ANALYSIS

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As part of the sediment acoustics experiment-2004 (SAX04), bistatic synthetic aperture sonar (SAS) measurements were made. The Applied Physics Laboratory (APL-UW) rail/tower system was used to receive signals emitted by either the Naval Surface Warfare Center-Panama City (NSWC-PC) tower with a parametric source or a separate APL-UW tower with an omnidirectional source. For the parametric source, the relevant frequency bands are 1-5 and 60-65 kHz. The omnidirectional source emitted a short 20 kHz sine wave burst. A brief description of the measurement geometry will be given, and the time-domain imaging algorithm will be outlined. An important aspect of these measurements is the fixed location of the source towers relative to the rail/tower system removes possible problems with motion compensation of source and receiver arrays as could occur when the arrays are mounted on autonomous underwater vehicles. Various objects were placed in the field of view of the SAS system. Imaging results for one of these objects will be shown.

1 Introduction

A bistatic synthetic aperture sonar (SAS) scenario, which utilizes multiple autonomous underwater vehicles (AUV), has the desirable features of possible rapid high-area coverage, multiple aspect angle looks at an object (e.g., forward scattering), and covert operation. Unfortunately, these features are achieved at the expense of relative vehicle motion. Traditional towed SAS systems have implemented motion compensation schemes where the source and receiver are mounted on the same vehicle. In the multi-AUV, bistatic SAS scenario, not only is motion compensation for each AUV required, but each AUV must register its position with all other AUV positions. This is required because coherent processing of the recorded signals needs proper phase information to form images.

In this paper, the problems with the use of AUVs are removed, so that we can concentrate on the multiple aspect angle looks at an object. The APL-UW rail system [1] with its SAS array is used in a receive mode while the source is located on a distant, fixed, tower. The APL-UW mobile tower [2] and NSWC-PC parametric sonar tower [3] transmitters were used in a set of experiments during SAX04. This paper describes the measurements and demonstrates that the resulting pulse compressed baseband signals
and the bistatic SAS images made using these signals yield additional information for the detection and classification of targets.

2 Experimental Configuration

Figure 1 depicts the bistatic configuration of the SAX04 experiments. Several targets were placed on the seafloor 10 meters from the source tower. For the measurements with the NSWC-PC parametric source, the acoustic axis of the transmitter was aligned through (or nearly through) the proud target. The parametric source was driven with two linear frequency modulated (LFM) chirps where the primary carrier frequencies were nominally 61 and 64 kHz with a 2 kHz bandwidth and 4 ms duration. One chirp had a positive chirp rate while the chirp rate of the second was negative. The generated secondary field has an approximate frequency range of 1-5 kHz. A second set of LFM chirps generated a secondary field with a 5-16 kHz range where the carrier frequencies were nominally 57 and 67 kHz with a 7.5 kHz bandwidth.

For the measurements with the parametric source, the NSWC-PC tower’s location was \((x,y) = (10,13.5)\) m with the source approximately 4 m above the seafloor. The APL-UW mobile tower had a nominal location of \((x,y) = (28,15)\) m and its omnidirectional source was 4.33 m above the seafloor.

For the measurements that involved the NSWC-PC parametric source, only images of the target from the primary frequency band are shown. Images, based on the secondary field, have been formed, but the low signal-to-noise of the data tends to lower the quality of images. The strength of a parametrically generated field depends on the amplitude of the primary fields. During SAX04, it was found that the direct arrival of the primary field was sufficient to saturate the pre-amplifiers of the APL-UW receiving array. The APL-UW electronics were originally designed for a series of experiments that did not include the bistatic SAS measurement, so bandpass filtering prior to the pre-amplification stage was not needed. The addition of bandpass filtering during the bistatic SAS measurements was not possible. Thus, the amplitude of the primary fields had to be limited to avoid saturation of the pre-amplifiers. As a consequence, the strength of the secondary fields was also reduced.
3 Time Domain Imaging Algorithm

A time-domain image is constructed via a delay and sum algorithm. For a pixel located at $\mathbf{r}_{ij} = (x_i, y_j, 0)$, the complex image amplitude is

$$p_{ij} = p(\mathbf{r}_{ij}) = \sum_k A(\mathbf{r}_s, \mathbf{r}_{rk}, \mathbf{r}_{ij}) p(y_{rk}, t_k) \exp[-ik_0(R_s + R_{rk})]$$

where $t_k = (R_s + R_{rk}) / c$ is the time delay for propagation from the source to the pixel and then from the pixel to the receiver. The separation distances are $R_s = |\mathbf{r}_s - \mathbf{r}_{ij}|$ and $R_{rk} = |\mathbf{r}_{rk} - \mathbf{r}_{ij}|$ where $\mathbf{r}_s$ and $\mathbf{r}_{rk}$ are the source and receiver locations and $\mathbf{r}_{ij}$ is the pixel location on the mean sediment surface $z = 0$, and the speed of sound in the water is $c = 1538 \text{ m/s}$. The amplitude factor, $A(\mathbf{r}_s, \mathbf{r}_{rk}, \mathbf{r}_{ij})$, contains the beam patterns of the source and receiver as well as a time varying gain to enhance the contrast across an image. In the formation of the images in Sec. 4, contributions that occur outside of the $-6 \text{ dB}$ down points of the main lobe of the beam patterns are ignored (i.e., suppression of possible interference from side lobes). The complex, pulse-compressed, baseband pressure at the $k$th receiver location is $p(y_{rk}, t_k)$. The phase factor in Eq. (1), $\exp[-ik_0(R_s + R_{rk})]$, is phase compensation for a spherically diverging wave with the assumed time convention of $\exp(-i\omega t)$, where $\omega$ and $k_0$ are the angular carrier frequency and wavenumber in water, respectively. If the $y$-axis is aligned with the along-track direction, then the separation distances are

$$R_s = [x_i^2 + (y_j - y_{rk})^2 + z_{rk}^2]^{1/2}, \quad R_{rk} = [x_i^2 + (y_j - y_{rk})^2 + z_{rk}^2]^{1/2}$$

where the image plane is tacitly assumed to be at $z = 0$; however, this restriction is not necessary and other image planes can be defined by the obvious change to Eq. (2). It is also noted that Eq. (2) implies that only the receiver moves along the SAS track via the $k$ subscript. To form an image, the discrete representation of the spatial coordinates are

$$x_i = (x_0 - x_L / 2) + (i - 1) \Delta x, \quad (i = 1, \ldots, N_x)$$

$$y_j = (y_0 - y_L / 2) + (j - 1) \Delta y, \quad (j = 1, \ldots, N_y)$$

$$y_{rk} = y_{rk0} + (k - 1) \Delta y_r, \quad (k = 1, \ldots, N_r)$$

where the center of the image is at $(x_0, y_0)$, the length of the sides of the image are $x_L$ and $y_L$, and the initial receiver location is $y_{rk0}$.

Inspection of Eqs. (1)–(5) and the discrete nature of the sampled time signals $p(y_{rk}, t_k)$, $(n = 1, \ldots, N_t)$ suggests that $t_k$ seldom coincides with a discrete time point. Thus, the summation in Eq. (1) requires interpolation of the signals. The interpolation has been performed with 6, 12, 24, and 48 point cubic splines, which were constructed on a discrete time interval containing $t_k$. Although cubic spline interpolation permitted the construction of an image, a 4 point Lagrange interpolation algorithm was found to be sufficient for image formation and the Lagrange interpolation is more numerically efficient than cubic spline interpolation. For the results presented here, Lagrange interpolation was used. Additionally, the recorded signals were sampled at 1 MHz, and the use of the pulse-compressed baseband representation yields a finely sampled signal,
which significantly reduces the potential for numerical round-off errors in computing the interpolated complex pressure.

4 Discussion

Figure 2 shows the magnitude of the pulse-compressed, baseband scattered pressure and the image formed via the time domain algorithm described above. The target is an open-ended cement pipe, which is nominally 1.1 m in length and 0.42 m in diameter. The data were taken on 21 October 2005. In Fig. 2A, the time \( t = 0 \) ms corresponds to when the chirp is emitted by the transmitter and the parametric source is to the right of the image. The earliest arrival that forms a nearly parabolic arc is the direct arrival from the source to the receiver. The next parabolic arc is the first bottom bounce of the source. The bright, broad arc that appears after 13 ms is the scattering from the cement pipe. It is noted that the \( y = 13.5 \) and \(-13.5\) m locations are at approximately 45° and 150° with respect to backscattering to the source. As the receiver moves into the near forward scattering region, the direct arrival, bottom bounce, and scattered signal nearly

![Figure 2](image-url)

Figure 2. The orientation of the cement pipe gives an end-on ensonification. These images were formed from the LFM chirps of the primary frequencies and each image is normalized to its “hottest” pixel. A. Pulse-compressed baseband signals. B. Bistatic SAS image. The black rectangle represents the nominal dimensions and orientation of the cement pipe.

![Figure 3](image-url)

Figure 3. The cement pipe is oriented in a broadside configuration. A. Pulse-compressed baseband signals. B. Bistatic SAS image. The black rectangle represents the nominal dimensions and orientation of the cement pipe.
simultaneously reach the receiver. Figure 2B shows the image formed from the data in Fig. 2A. Note, the rail system is located below the bottom of Fig. 2B. One can identify the front and back ends of the pipe where the bright feature on the right is nearest the parametric source. The length and width of the pipe can be estimated from this image to be on the order of 1 m long and 0.5 m wide. The spread in the image may be due to multiple scattering of acoustic energy within the open ended pipe.

Figure 3 shows the magnitude of the complex, pulse-compressed, baseband pressure and the image formed from the data. The data were recorded on 22 October 2005. The ends of the pipe are again evident in Fig. 3B at ranges of 10 and 11 m, respectively. However, the brightest feature appears at the center of the pipe. The width of the pipe appears smaller than 0.25 m, which is partly due to the fact that neither end is directly illuminated with sound. As in Fig. 2A, Fig. 3A shows the direct arrival, bottom bounce, and the scattered acoustic signals.

The NSWC-PC parametric source was designed to have a narrow beamwidth for its secondary field, and hence, the primary field also has a narrow beamwidth (i.e., on the order of 5°) [5]. In a bistatic SAS scenario, it may be tempting to light up the underwater environment with an omnidirectional source to obtain high-area coverage. This was carried out with the APL-UW mobile tower on 16 October 2005. A three-cycle 20 kHz sine wave pulse was broadcast from an omnidirectional transducer on the mobile tower with the approximate position of (28,15,4.33) m.

Figure 4 depicts the magnitude of the complex, pulse-compressed, baseband pressure and the image formed from the data. The receiver was moved along the rail at an interval $\Delta y_r = 0.05$ m. The increased interval was due to limitations in the signal generation for the mobile tower source. The baseband pressure contains four broad parabolic features that span the cross range dimension. These are the direct arrival, the bottom bounce, the surface bounce, and the bottom-surface bounce. With a nominal water depth of 18 m and receiver location of (0,13.5,3.91) m, these arrivals should appear near 18.2, 19.0, 25.7, and 30.7 ms, respectively. The slight discrepancy of the computed arrival times and those observed in Fig. 4A can be attributed to uncertainties in mobile tower location and water depth.

The important features in Fig. 4A are the thin, crescent-shaped arrivals near 25 ms and cross range of 5 to 13.5 m and near 28 ms and cross range of 2 to 13 m. These
indicate objects are present, and Fig. 4B reveals at least two targets near (4,31) m and (8,31) m. A third target may be located near (9,30) m. These targets coincide with several proud targets placed on the seafloor for other SAS measurements.

5 Conclusions

The combination of a bistatic SAS image and an image of its pulse-compressed baseband data may provide additional information for classification and identification of a target that may not be present in data from conventional monostatic SAS systems. Targets with complex shapes may have low backscattering target strengths, but relatively high bistatic, and in particular, forward scattering cross sections. Inspection of Figs. 2A and 3A shows strong scattering from the cement pipe in the angular range of approximately 90° to 145° with respect to backscattering. The high signal-to-noise ratio provides the possibility of processing schemes to extract elastic responses of the target. Hence, alternative processing schemes may be able to extract this information.

Bistatic SAS images were constructed from data obtained during SAX04. The images in Figs. 2B and 3B clearly indicate the presence of a target and an estimate of its size can be achieved. Even though these images are substantially different due to the orientation of the cement pipe with respect to the source location and rail system, unambiguous identification of the cement pipe from these bistatic SAS images is unlikely. Bistatic SAS images alone may offer advantages over conventional monostatic SAS images for detection due to higher bistatic target strengths. Also, after a target has been detected, the same bistatic data can give important information on classification. Figures 2A and 3A show the magnitudes of the complex, pulse-compressed, baseband pressure. The parabolic arcs associated with scattering from the target in the two orientations are clearly different, and these may contain target information (e.g., elastic resonances) that is important to classification and identification of the target. SAS processing removes this information.

The complex, pulse-compressed, baseband scattered pressure shown in Fig. 4A for an omnidirectional source clearly demonstrates the need to resolve weak target scattering from multipath arrivals. Otherwise, the signal-to-noise ratio may be too low to adequately resolve a target. For example, a third target may be located at (9,30) m in Fig. 4B. One strategy to achieve high-area coverage would be to have broad horizontal and narrow vertical beams directed at a small depression angle to the surface.

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References


SUBCRITICAL DETECTION OF SPHERES AND ELONGATED TARGETS BURIED UNDER A RIPPLED INTERFACE: CALIBRATED LEVELS AND EFFECTS OF LARGE ROUGHNESS

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This paper describes results from modeling and highly controlled measurement efforts investigating shallow grazing angle acoustic detection of targets buried under a rippled sand bottom. The measurements were performed in a 13.7-m deep, 110-m long, 80-m wide test-pool with a 1.5-m layer of sand on the bottom. The bottom ripple contour was formed by scraping the sand with a machined rake. Broadband (10 to 50 kHz) transducers were placed onto the shaft of a tilting motor attached to an elevated rail that enabled this assembly to be translated horizontally. This permitted data to be processed using synthetic aperture sonar (SAS) techniques. Acoustic backscatter data were acquired at subcritical grazing angles for various ripple wavelengths, ripple heights, and ripple orientations. Two buried targets were used in the measurements: a silicone oil-filled sphere and a flat-endcapped, solid aluminum cylinder. In addition, the backscattered signals from a calibrated free-field sphere and the transmitted signals received with a free-field hydrophone were recorded. For each bottom configuration, the seabed roughness over the buried target was measured to determine the ripple parameters and to estimate the small-scale roughness spectrum. This roughness information is used in scattering models to calculate the backscattered signal levels from the target and bottom. By taking advantage of the backscattered data collected using the free-field sphere and of the transmitted data collected with the free-field hydrophone, measured buried target backscatter levels and bottom reverberation levels were calibrated and compared to predicted levels based on numerical modeling. Results of these efforts, including the impact of higher-order scattering effects on buried target detection, are presented.

1 Introduction

Sonar detection of completely buried underwater targets is a capability desired for missions such as mine countermeasure (MCM) and unexploded ordnance (UXO) cleanup. A critical component impacting sonar performance against a buried target is sediment sound penetration. This becomes significant when it is desired to search the
bottom at extended ranges in order to maintain a high search rate and/or a safe standoff distance from potentially active ordnance. At extended ranges the incident grazing angle on a sand bottom can be shallow enough (less than the critical grazing angle of about 25° to 30°) to result in negligible transmission of sound if the water/sand interface is flat. However, recent studies have shown that the environment can enhance detection at extended ranges if the target is buried in sediment with a rippled surface [1]. This happens by virtue of sound diffraction, which increases transmission into the bottom even at angles shallower than the critical grazing angle, where sound would normally be largely reflected back into the water column by a flat surface.

A simple diffraction model [1] that assumes a monochromatic plane wave incident on a sinusoidal surface can give important insight on subcritical penetration due to scattering from ripples. Using this simple analytical model, \( n^{th} \)-order perturbation theory predicts that the maximum depression angle (\( \beta_n \)) of the \( n^{th} \)-order field propagating in the sediment due to scattering from periodic ripples is given by

\[
\cos \beta_n = \frac{c_2}{c_1} \left( \cos^2 \theta - 2 \frac{n^2 \lambda}{\lambda_r} \cos \theta \cos \phi + \frac{n^2 \lambda^2}{\lambda_r^2} \right)^{1/2}.
\]

Here, \( c_1 \) is the water sound speed, \( c_2 \) is the sediment sound speed, \( \theta \) is the incident grazing angle, \( \lambda \) is the acoustic wavelength in water, \( \lambda_r \) is the ripple wavelength, and \( \phi \) is the angle between the ripple wave vector and the horizontal component of the incident field wave vector.

Field measurements have achieved mixed success in detecting targets buried at subcritical grazing angles when a rippled interface is present. In two measurements conducted in about 18 m water depth in the Gulf of Mexico, the Naval Surface Warfare Center - Panama City (NSWC-PC) Synthetic Aperture Sonar (SAS) system operating at a 20 kHz frequency was used to investigate subcritical buried target detection. In one measurement, the SAS system detected cylindrical targets buried 15 and 50 cm under the sediment at subcritical grazing angles of about 5° and 10° [2,3]. However, in a second measurement, the SAS system did not detect buried spherical targets at subcritical grazing angles [2,3]. Resolution of these discrepancies is an ongoing focus of research.

The objective of this work is to understand the field measurements through highly controlled measurements and modeling that take into account the roughness spectrum over the buried target. References 4-8 document the progress of this work. Presented in this paper are SAS generated images of a sphere and a cylinder buried under various bottom ripple profiles. In addition, calibrated backscatter intensity levels of signal and reverberation corresponding to several ripple wavelengths and heights are obtained and processed with SAS techniques. Results are compared to model predictions including first- and second-order effects and predictions based on resumming high-order perturbation corrections using a Padé approximant to ensure convergence.
2 Measurement Setup

The measurements were conducted in the NSWC-PC Facility 383 fresh water test pool, which is 13.7-m deep, 110-m long, and 80-m wide with approximately 1.5 m of sand covering the bottom. The basic measurement setup has been previously described and the reader is referred to reference 8 for a complete description. Below, a few details will be reviewed to clarify features relevant to the present measurements.

The water column of the test pool was well mixed by a filtration system that suppressed sound speed gradients. The water sound speed varied with water temperature from about 1460 m/s during the winter (~15°C) to around 1510 m/s in the summer (~30°C). The bottom sediment sound speed and attenuation were also measured using a buried transducer array. Assuming linear frequency dependence, the average attenuation over a 15 to 50 kHz band was 0.27 dB/kHz/m with a standard deviation of 0.09 dB/kHz/m. However, 0.33 dB/kHz/m was found to be a better fit to the attenuation data in the frequency range of 10 to 35 kHz, over which most of the data from buried targets were collected. The average sediment sound speed recorded during a six-week period prior to winter was found to be 1675 m/s with a standard deviation of 32 m/s (obtained using 70 kHz sinusoidal pulses). Because the variability in the measured sediment sound speed did not clearly correlate with temperature variability, we assume this sediment sound speed variability leads to a corresponding uncertainty in the sediment-to-water sound speed ratio. A sediment sound speed of 1668 m/s was recorded when the corresponding water sound speed was 1482 m/s, resulting in a critical angle of 27.3°.

Figure 1 depicts the target field as viewed from directly overhead. The target field contained a rippled bottom area, a buried target, a rail system with a sonar tower and an extender, broadband broad beam transducers, and a free-field hydrophone. In addition, a sand-scraping apparatus was used to create sinusoidal ripple profiles on the bottom sediment over the buried target, which was either a solid aluminum cylinder 30.5 cm in diameter and 1.52 m in length placed at a target aspect angle near broadside or a 35.6-cm diameter fluid-filled, focusing sphere which has a computed target strength from about −12 dB at 10 kHz to −7 dB at 50 kHz [9]. The sinusoidal profile of the scraped bottom patch and the superimposed fine-scale roughness were measured using the In-situ Measurement of Porosity 2 (IMP2) system [10].

![Figure 1. Target field.](image-url)
The rippled bottom area was a patch approximately 3.7 m in length by 3.7 m in width, and it started about 8.4 m from the rail system. The contour of this bottom was formed with the aid of the sand scraper. Seven different sinusoidal profiles were formed. For each profile formed, the bottom roughness over the buried target was measured with IMP2, and divers measured the burial depth and location of the buried target. Table 1 in reference 8 summarizes the designed and IMP2 measured ripple wavelength and RMS height as well as the corresponding target type, location, and burial depth. This table also lists the measured spectral exponent, $\gamma_2$, and spectral strength [11], $w_2$, for the fine-scale features superimposed on each ripple configuration. In addition to these profiles, data were also collected with a flattened bottom, created by divers dragging a weighted bar over the surface of the 3.7-m by 3.7-m bottom patch.

A 12.2-m long rail system placed on the bottom sediment was also used in the measurements. The rail system consisted of a motorized platform onto which a sonar tower was attached. The sonar tower supported two broadband beamwidth transducers and scanning (horizontal pan and vertical tilt) motors. A conical 10-cm-diameter transducer was used to project acoustics signals in the 10 to 50 kHz frequency range, and a 10-cm high by 15-cm long transducer was employed to record the backscattered signals. These transducers were oriented such that their main response axes were perpendicular to the rail. This system permitted data acquisition from a given part of the target field at many aspects so SAS processing can be applied. The sonar tower stood 1.76 m above the bottom. A 2.13-m tall extender could be inserted between the platform and sonar tower to increase its height to 3.89 m, permitting insonification of the buried target at two different grazing angles.

A free-field hydrophone and a free-field sphere were deployed in the target field to allow for a robust data calibration. The free-field hydrophone, an International Transducer Corporation (ITC) 1089D transducer, was attached to a small tripod that positioned it approximately 0.6 m above the bottom and about 14 m from the rail system. This hydrophone was used to record each transmitted signal as the transducers were translated along the rail system. Thus, it provided knowledge of the transmitted levels and of the locations of the transducers attached to the rail as they moved along the rail.

A 20.32-cm diameter free-field sphere was also utilized in the measurement. Divers deployed this sphere after the buried target data were collected. It was located 3.89 m above the bottom sediment and placed directly over the buried sphere. Backscattered signals from the free-field sphere were used to determine calibrated levels for the SAS processed data.

Buried target data were obtained by translating the sonar along the rail platform and taking data in approximately 2.5-cm increments. Data were obtained for the various bottom configurations (rippled and flat) for 1.76- and 3.89-m transducer heights above the bottom corresponding to grazing angles of 10° and 20°, respectively, which are both below the critical grazing angle. The free-field sphere data were acquired when the source transducer was 3.89 m above the bottom and directed horizontally.

Transmitted pulses were 0.2-ms sinusoidal signals that had a 0.04-ms taper on the leading and trailing edges to minimize ringing in the waveforms generated by the source. The received signals were amplified and filtered to include frequencies within ±5 kHz of the source center frequency, then digitized at a sample frequency of at least 500 kHz.
3 Results and Discussion

3.1 Data Reduction

The acquired data were processed using a $\omega$-k (wavenumber) algorithm as described by Hawkins [12]. The processed data, which are proportional to voltage, were mapped to the appropriate range and cross-range and used to generate a SAS image. Here range and cross-range are measured parallel and perpendicular to the direction of the acoustic beam, respectively.

The processed data were further analyzed to determine calibrated backscatter levels from the rippled bottom region and from the buried target. An estimate of the reverberation level was determined by averaging of the reverberation intensities in a patch 2 m wide in cross-range by 0.5 m long in range in a location near the target. The calibrated backscatter level, $EL$ in dB (re 1 $\mu$Pa for incident field at the sediment surface), was determined using,

$$EL = EL_{SAS} - G_{SAS} - SPL_{INTERFACE}.$$  \hfill (2)

Here $EL_{SAS}$ is the backscattered level in dB re 1 $\mu$Pa obtained after SAS processing, $G_{SAS}$ is the gain in dB due to SAS processing, and $SPL_{INTERFACE}$ is the sound pressure level in dB re 1 $\mu$Pa incident on the water-sediment interface directly above the buried target. $G_{SAS}$ was obtained using the free-field sphere data by comparing the echo level from a single ping (obtained with the transducers on the rail at the position of closest approach) with the level obtained using the rail system and SAS processing techniques. $SPL_{INTERFACE}$ was obtained by using the level measured with the free-field hydrophone and accounting for the difference in propagation loss to the location directly over the buried sphere.

3.2 SAS Images

Typical SAS processed backscattered intensity images at a 20° grazing angle are shown in Figs. 2(a), 2(b), 2(c), and 2(d), corresponding to data collected at 10, 20, 30, and 40 kHz, respectively. The intensity is scaled relative to the maximum in each image and displayed in color over a 30 dB range. Here, the cylinder is buried 10.8 cm below the mean surface level of a ripple with 75-cm wavelength, 2.7-cm root-mean-square (RMS) height, and oriented at $\phi = 0^\circ$. The cylinder is easily seen at 10, 20, and 30 kHz, showing a length of about 1.5 m and an orientation of about 7° between the cylinder axis and the ripple crests. These observations compare well with expected values. At 40 kHz, the target length is more difficult to assess because the target signal level is closer to the background reverberation level.

Table 1 lists the measured SNRs obtained with the buried cylinder at various frequencies for three different ripple orientations. In all cases the grazing angle of the incident beam is 20°. With the simple analytic model, perturbation theory predicts the cutoff frequency for subcritical penetration (where $\beta_n=0^\circ$ in Eq. (1) and the penetrating field becomes evanescent) decreases with increasing ripple orientation angle, which is consistent with the measured SNR results. Also, for the conditions in this measurement, the simple analytic model with first-order perturbation theory predicts a cutoff frequency
of approximately 39 kHz for a 20° grazing angle and a ripple orientation of $\phi = 0^\circ$. However, full simulations show a smooth roll-off in penetration near the cut-off frequency [1], consistent with measurements at 40 kHz that indicate an SNR = 14 dB. This behavior is also observed in some of the buried sphere data discussed below.

![Figure 2. SAS intensity images of the buried cylinder. Ripple wavelength is 75 cm and ripple orientation of $\phi = 0^\circ$.](image)

Table 1. Measured SNRs for the buried cylinder with ripple orientations of $\phi = 0^\circ$, 17°, and 31°.

<table>
<thead>
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<th>f (kHz)</th>
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Figures 3 and 4 correspond to buried sphere data collected with a 50-cm wavelength sinusoidal ripple with a 1.6 cm RMS height oriented at $\phi = 0^\circ$ and with a flat bottom, respectively. In both of these figures, the sphere is buried 5 cm below the mean ripple height. The color scale of each image in Fig. 3 corresponds to a logarithmic scaling of the backscatter intensity relative to the image maximum over a 15 dB range. To facilitate comparison with Fig. 3, Fig. 4(a) is plotted on the same color scale as Fig. 3(b) and Fig 4(b) is plotted on the same color scale as Fig. 3(d). Between 10.5 m to 11.0
m range, a well-focused acoustic return from the buried sphere appears in each image in Fig. 3 with a cross-range resolution of about 10 to 13 cm and a range resolution of about 22 cm. On the other hand, the buried sphere was not detected in the images of Fig. 4. The images in these three figures demonstrate the effectiveness of ripple scattering for enhancing subcritical detection of buried targets.

As further evidence of ripple scattering, note that the location of the maximum level from the buried sphere seen in each image in Fig. 3 exhibits a systematic change in range with changing frequency. For example, the maximum level occurred at a range of about 10.9 m for a frequency of 10 kHz, while it was 10.7 m at 50 kHz. The low frequency (10 kHz) variation may be affected by systematic measurement error (e.g., reverberant contamination of the target backscatter as discussed shortly) but, even with this accounted for, a subtler trend remains over the entire band. A plausible explanation for the subtler trend arises from inspection of Eq. (1) with $\phi = 0^\circ$, which predicts a change with frequency in the first-order diffracted grazing angle $\beta_1$ that illuminates the target. The diffracted angle $\beta_1$ ranges from $44^\circ$ at 10 kHz to $12^\circ$ at 50 kHz, corresponding to movement of the patch on the bottom that contributes to target illumination over an 80-cm range. This, in turn, impacts the overall two-way time associated with range.

Figure 5 demonstrates this with a plot of the two-way time versus frequency for the peak intensity. Unfilled circles represent times determined from data that may be unreliable. At 10 kHz there is some unavoidable data contamination by echoes from concrete blocks deployed near the test area. The open circle point at 50 kHz has a SNR of less than 15 dB, which could result in a time shift. The filled circles all have SNR greater than 15 dB and are believed to be unaffected by contamination from concrete block echoes. The black line in Fig. 5 represents travel time calculations based on the measurement geometry and Eq. (1) assuming the diffraction is predominantly first order. Furthermore, the red line corresponds to travel times determined from a high-fidelity simulation of the scattering by the buried sphere via transition (T-) matrix calculations carried out to second order in perturbation theory. Good agreement between these comparisons is a strong indication that, except at the low frequency end, the observed range shifts are not due to systematic measurement error but are driven by target illumination via ripple scattering.
3.3 Calibrated Backscatter Levels

Model predicted (solid and dotted lines) and measured (filled circles and open triangles) calibrated backscatter intensity levels corresponding to the sphere buried under the 75 cm ripple wavelength cases (see Table 1 in reference 8) are compared in Figs. 6-8. The model predictions assume a 1 µPa RMS amplitude monochromatic plane wave is incident on the bottom and use perturbation theory [13] in calculating both penetration into and scattering from the rippled interface. Sound speeds of 1482 m/s and 1668 m/s in water and sediment, respectively, and a sediment attenuation of 0.33 dB/kHz/m were assumed.

In all figures, four dotted curves are plotted corresponding to reverberation predictions based on the four sets of small-scale roughness parameters deduced from the IMP2 measurements associated with the buried sphere. The noise level estimates for these four sets of small-scale roughness measurements are included as a means of obtaining a more robust noise estimate. This is motivated by two factors. First, the small-scale roughness was measured by IMP2 along a single 1-D track, while a measurement over a 2-D region would be needed to fully characterize the small-scale roughness. Second, there is no apparent basis for assuming that small-scale roughness would be created during ripple formation with statistical uniformity over the ripple patch, while extrapolation of roughness measurements from 1-D to 2-D implicitly assumes such uniformity. Also, while biological processes under natural conditions at sea may bring the small-scale roughness close to statistical uniformity, such processes are nearly absent in the test pond environment. The four small-scale roughness measurements provide at least some measure of the roughness range that can be expected within the ripple patch.

The overall level of the reverberation curves depends on the area of the effective (SAS-processed) bottom patch contributing to the detected reverberation. This area is given by the product of the range and cross-range resolutions. For the 0.2 ms source pulse incident on the bottom at 10° and 20° grazing angles, the range resolution was 22 cm and 23 cm, respectively. The cross-range resolution, \( CRR \), was determined at each frequency according to [12,14].
Figure 6. Target and surface backscatter intensities for an oil-filled sphere buried 5 cm below the mean height of a sinusoidal surface of 75-cm wavelength and 1.7-cm RMS height with a 0° ripple orientation. The sphere is located under a crest.

Figure 7. Target and surface backscatter intensities for an oil-filled sphere buried 17 cm below the mean height of a sinusoidal surface of 75-cm wavelength and 2.5-cm RMS height with a 0° ripple orientation. The sphere is located under a trough.

Figure 8. Target and surface backscatter intensities for an oil-filled sphere buried 8.5 cm below the mean height of a sinusoidal surface of 75-cm wavelength and 2.5-cm RMS height with a 0° ripple orientation. The sphere is located under a crest.
where \( d \) is the physical source aperture, \( R \) is the slant range to the target, \( \lambda \) is the acoustic wavelength, and \( L \) is the synthesized array length. An extra factor of 1.46 is included in this expression to account for the use of a Hamming window to reduce side lobes around image features in SAS processed data.

Calibrated and spatially averaged reverberation measurements are represented by open triangles in the backscatter intensity image plots in Figs. 6-8. These points are determined by averaging the reverberation intensity from several patches of area taken from a region 2 m wide in cross-range by 0.5 m long in range located near the buried sphere. The error range for the measured data points, indicated by vertical bars, is based on the sum of (a) an estimated transducer calibration uncertainty of \( \pm 0.7 \, \text{dB} \) and (b) the statistical uncertainty in the mean reverberation intensity estimate which is taken to be \( \pm \sigma / \sqrt{N} \), where \( \sigma \) is the standard deviation of reverberation intensity, and \( N \) is the number of independent resolution cells in the region used to obtain the mean background noise level. The spatially averaged noise levels in all figures appear in reasonable agreement with the ensemble-averaged predictions.

Comparisons between the measured buried target signal level and target scattering models that include ripple-diffraction effects are made in Figs. 6-8 by solid curves and the filled circles; the latter represent properly calibrated peak target amplitudes in SAS-processed image spaces like those shown in Fig. 3. The target amplitudes include a background reverberation component. The error range for these data points is indicated by vertical bars and is again based on the sum of two terms: (a) the apparent target level uncertainty due to background reverberation interfering with the true target level and (b) the estimated transducer calibration uncertainty (\( \pm 0.7 \, \text{dB} \)). The reverberant uncertainty is estimated by \( 20 \log(|p_t| \pm |p_r|/p_0) \), where the measured target-plus-reverberation level is \( 20 \log(|p_t|/p_0) \), with \( p_0 = 1 \, \mu \text{Pa} \), and where the mean (intensity averaged) reverberation level is \( 20 \log(|p_r|/p_0) \).

The solid line representing the first-order penetrating field prediction uses a model (to be referred to as TM1) that yields target scattering via a T-matrix formalism [13] adapted to account for the specified sinusoidal bottom roughness. The solid line representing the second-order prediction uses a higher-order version of TM1 (to be referred to as TM2) to calculate smoothed target scattering levels, which are seen to depart from the TM1 levels at higher frequencies. For most of the cases considered in Figs. 6-8, agreement between the models and measurements is good. The basic trends predicted as a function of incident grazing angle, target burial depth, and ripple height appear to be followed well in Figs. 6, 7 and 8(a). The second-order refinements in TM2 appear to produce slightly better agreement with the data at the upper frequency range of Figs. 6(b) and 7(b) and significantly better agreement in Fig. 8(a). Nevertheless, first-order perturbation theory captures most of the relevant trends in target scattering level in these cases, when the scattering level lies above the reverberation level, even at a fairly high ripple height (2.5 cm RMS). These results provide substantial confirmation of the ripple scattering mechanism for enhanced detection of buried targets using sonar at subcritical grazing angles.

The exception to the good agreement is seen in Fig. 8(b) where a mismatch is seen beginning at around 25 kHz. This discrepancy may be due to two reasons. One
possibility is the inadequacy of second-order perturbation theory as developed in TM2. For this case, the perturbation parameter (wavenumber times the RMS height) at 20 kHz is already 2.1, high enough to cause concern for low-order perturbation theory. Interestingly, this is not seen to be a significant problem in Fig. 8(a) for a shallower grazing angle or in Fig. 7(b) for the same grazing angle and ripple height but a deeper target burial depth; also in Fig. 7(b) the target placement is near a trough of the ripple rather than a crest. A second possible explanation is that the parameters used as input for the calculations are not sufficiently accurate. During the bottom parameter measurements, the sediment sound speed varied over a range of ±2% of the mean, and the bottom attenuation varied over ±33% on a dB/kHz/m scale [6,8]. Such fluctuations can lead to significant differences in the predicted backscatter.

An attempt to resolve the exceptions seen in Fig. 8(b) was made recently by extending model predictions beyond second order with a recursive routine for generating high-order corrections [5] to the generalized transmission coefficient. While these predictions bear further checking against numerical benchmarks, they suggest that the second possibility noted above is the most likely cause of the discrepancies observed. This is illustrated in Figs. 9(a) and 9(b), where the backscatter measurements in Figs. 8(a) and 8(b), respectively, are compared against predictions of the buried sphere backscatter correct to 18th order in perturbation theory. These predictions are made by summing the perturbation corrections as a Padé approximant to ensure convergence. With this approach, numerical checks indicate convergence of backscatter predictions to within a line width when 18 orders of perturbation theory are used.

![Figure 9. Comparison of high-order backscatter predictions with the buried sphere measurements and predictions from Fig. 8.](image)

In addition to the dotted lines, which represent the original second-order model predictions, 3 additional predictions are shown as solid lines. The black line is the 18th-order backscatter prediction for the buried sphere calculated with the same input parameters used to obtain the second-order predictions. In both the 10° and 20° cases, it is seen that the original second-order prediction generally overestimates the converged backscatter result. This makes agreement between the data points and the converged predictions worse, although it is notable that, despite the magnitude of the perturbation parameter, the second-order prediction is seen to remain a reasonable estimate (i.e., within a few dB) of the converged result except beyond 35 kHz for the 20° case.
Nevertheless, better agreement with data is found when the sediment input parameters are adjusted within the measured ranges as specified above. The original input parameters used a complex wave speed of (1668, -16.8) m/s, where the imaginary component is added to account for an attenuation of 0.33 dB/kHz/m. For comparison the complex wave speed is lowered to (1650, -12.0) m/s and (1650, -10.0) m/s corresponding to an attenuation of 0.24 dB/kHz/m and 0.20 dB/kHz/m, respectively. 18th-order backscatter predictions represented by the blue (0.24 dB/kHz/m) and red (0.20 dB/kHz/m) lines are obtained. At 10° grazing the agreement is acceptable, without being significantly affected by the change in sediment parameters but at 20° grazing the agreement is much improved. While the actual parameters can no longer be verified, this at least provides a possible explanation for the original discrepancy. Notably, when 18th-order predictions are calculated for the cases shown in Figs. 6 and 7, we find that acceptable agreement is still retained with the original input parameters. In fact, the need to lower the real part of the sediment sound speed to 1650 m/s to achieve agreement in Fig. 8(b) is found to result in poorer agreement with the data in Figs. 6 and 7. Given the sensitivity to sediment parameters seen in the predictions, variations in sediment properties introduced during measurement set up could impact data/model agreement.

4 Summary

Controlled test pool measurements were conducted to investigate subcritical detection of targets buried under a rippled interface. Acoustic backscatter data were acquired at 10° and 20° incident grazing angles (well below the critical angle of the sand) for various ripple wavelengths, ripple heights, and ripple orientations. Two buried targets were used in the measurements: a silicone oil-filled sphere and a flat-endcapped, solid aluminum cylinder. The results show that the buried cylinder can be detected at subcritical grazing angles via ripple scattering. SAS generated backscatter intensity images of the buried cylinder indicated a target size and orientation comparable with the expected values. In addition, scattering data with the 50-cm wavelength ripple was further analyzed to explain the range shift in the SAS-processed backscatter intensity images of the buried sphere as a function of frequency. It was found that the range shift could be explained as a consequence of a frequency-dependent shift in the surface patch that contributes to the illumination of the target. Predictions for this shift are shown to be consistent with a first-order-perturbation diffraction law.

Calibrated backscatter intensity levels from the buried sphere corresponding to the 75-cm ripple wavelength measurements were compared to acoustic scattering models that incorporate diffraction effects into the bottom by the sinusoidal sand ripples. Most of the data-model comparisons exhibited good agreement in the trends across the experimental bandwidth, even when compared against models based on first-order perturbation theory only. These results confirm that ripple diffraction is a valid mechanism for enhancing the detection of buried targets at shallow sonar grazing angles. However, exceptions to this agreement with low-order perturbation theory appear when the ripple amplitude is high, suggesting that either perturbation theory beyond second order is required, or more accurate environmental parameters (such as sediment sound speed and attenuation) are needed. Preliminary comparisons with high-order perturbation
theory predictions indicate a significant sensitivity to bottom parameters that would explain discrepancies observed so far. However, further tests of these predictions are warranted before conclusions can be drawn.

Future work includes the following: (a) completing analysis of the data already obtained, including determination of calibrated backscatter intensity levels from the cylindrical target, (b) comparing measured SNR and backscattered intensity images to predictions of the Shallow Water Acoustic Toolset (SWAT) code [15], and (c) conducting additional measurements to investigate detection performance under more realistic conditions, such as using ripple profiles similar to those found in coastal areas and using differently shaped/extended buried targets.

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STATISTICAL ANALYSIS OF SYNTHETIC APERTURE SONAR REVERBERATION

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Synthetic aperture sonar (SAS) produces high-resolution imagery that often resembles a map of a seafloor region of interest. Because returns from the seafloor for SAS systems can sometimes exhibit large pixel to pixel intensity fluctuations, robust target detection still requires a thorough understanding of the reverberation environment which surrounds potential targets. Models of the reverberation envelope probability distribution function (PDF) based on the $K$ distribution have been found to well describe the reverberation environment for systems with lower resolutions than possible with broadband SAS systems. As part of the SAX04 experiment, broadband acoustic data suitable for SAS processing were collected over a range of center frequencies using a bottom mounted rail system off the coast of Florida in the Gulf of Mexico in October, 2004. This unique data set has been used to explore several important analyses on the statistics of SAS reverberation including: the usefulness of statistical models, such as the $K$ distribution, in describing the envelope PDFs; the dependence of reverberation statistics on physical resolution; the dependence of reverberation statistics on frequency and grazing angle. [Work performed under ONR Grant N00014-04-1-0013]

1 Introduction

High resolution synthetic aperture sonar (SAS) systems have been developed to improve detection of targets sitting on or beneath the seafloor. Unfortunately, the high-resolution achieved by these systems can have the adverse effect of producing backscatter with a statistical distribution that is significantly more heavy-tailed than the traditionally assumed Rayleigh distribution, leading to an increase in the probability of false alarm ($P_{fa}$). The Rayleigh distribution is obtained by assuming that there are enough scatterers or scattering patches contributing to the returns from a given resolution cell (after matched filtering and synthetic aperture beamforming) so that the central limit theorem holds and the received signal is Gaussian, resulting in a Rayleigh distributed envelope. Non-Rayleigh scattered envelope distributions, in particular distributions with tails heavier than Rayleigh, can occur when the conditions of the central limit theorem are violated. For example, there may be too few scatterer patches in the resolution cell or the scatterers may not be identically distributed.
An alternative to the Rayleigh distribution is the well known $K$ distribution [1, 2], a standard model for radar clutter which has also been shown to represent sonar reverberation well [3, 4]. The $K$ distribution is traditionally derived in the limit by assuming that the number of scatterers in a resolution cell follows a negative binomial distribution with a mean that tends to infinity. Statistical models for radar clutter based on the $K$ distribution have been extensively used for synthetic aperture radar (SAR) imagery [5], although the usefulness of the $K$ distribution for SAS imagery has just started to receive attention [6]. The $K$ distribution has also been described as a compound process arising from the modulation of Rayleigh backscatter by an intensity that varies slowly in time (or space) and is well modeled by the gamma distribution [7].

A major aim of this work was to assess the extent to which the $K$ distribution can be used to represent SAS image statistics over a broad range of frequencies, grazing angles and bandwidths using suitable statistical tests. The assessment of the suitability of the $K$ distribution for describing SAS data, described in Section 3.1, entailed fitting observed SAS image data to the $K$ distribution statistical model to determine goodness of fit. The SAS data, covering a wide frequency range, was collected off the Florida coast by the Applied Physics Laboratory of the University of Washington (APL-UW) in the Fall of 2004 during the Office of Naval Research (ONR) sponsored SAX04 sediment acoustics experiment [8]. Given the efficacy of the $K$ distribution for describing SAS image data, the shape parameter of the $K$ distribution can be used as a proxy for examining the APL-UW rail-collected broadband SAS data in greater detail. The scintillation index (or normalized intensity variance) can also used in a similar fashion. The shape parameter and scintillation index determined from the SAS image data are used in Section 3.2 to explore the dependence of image statistics on system and geometric parameters such as frequency, grazing angle and bandwidth (physical resolution). Results of this type of analysis show strong grazing angle dependence of the image statistics with data from further out in range showing a tendency toward Rayleigh (larger shape parameter or scintillation index closer to 1). The reverberation statistics also show that the $K$ distribution shape parameter is, as predicted by the model of Abraham and Lyons [4], inversely proportional to the bandwidth of the transmitted signal.

2 Background

Lyons and Abraham [9] discuss a theoretical model for scattered envelope distributions resulting from scattering from a seafloor comprised of patches of differing scattering properties. Diffuse scattering from the interface produces a Gaussian distributed return from each patch by virtue of the central limit theorem, with power proportional to the patch area and backscattering coefficient. Assuming $n$ patches within a resolution cell of the sonar system, the complex envelope of the received signal in this resolution cell (i.e., after matched filtering and beamforming) may be represented as

$$Z = \sum_{i=1}^{n} \sqrt{B_i} Z_i$$

where $B_i$ is the area of the $i^{th}$ patch and $Z_i$ is a zero-mean, complex, Gaussian random variable with variance $\sigma^2$. The resultant sum is non-Gaussian owing to the random
power of each component even though each patch produces a Gaussian response. Assuming that the patches are characterized as having an exponentially distributed area, with average patch area $\mu$, and assuming that $B_i$ and $Z_i$ are independent of each other and the responses of the other patches, the resulting matched filter envelope $Y = |Z|$ is $K$ distributed with PDF [10]:

$$f_Y(y) = \frac{4}{\sqrt{2\pi}(\alpha)} \left(\frac{y}{\sqrt{2\alpha}}\right)^{\alpha} K_{\alpha-1}\left(\frac{2y}{\sqrt{2\alpha}}\right)$$

where $K_{\alpha-1}$ is the Basset function (i.e., a modified Bessel function of the third kind) with order $\alpha-1$, $\lambda$ is the scale parameter, $\alpha$ is the shape parameter, and the power is $E[Y^2] = \alpha \lambda$. As the shape parameter of the $K$ distribution increases, the envelope PDF tends toward the Rayleigh PDF, while smaller values of $\alpha$ are representative of a distribution with heavier tails than a Rayleigh. In Abraham and Lyons [4] the shape parameter was related to the number of scattering patches in the resolution cell according to $\alpha = n$, the number of patches in a resolution cell, and the scale parameter was related to the average patch size through $\lambda = \mu \sigma^2$, average area of each patch times the backscattered power per unit area of each patch.

In addition to the shape parameter of the $K$ distribution, a useful indicator of the non-Rayleigh behavior of scattering which will be used later is the scintillation index or variance of the intensity fluctuation which is given by

$$\sigma^2 = \frac{\mu_2 - \mu_1^2}{\mu_1^2}$$

where $\mu_1$ and $\mu_2$ are the first and second moments of $I = |Z|^2$. Assuming that the form of the complex matched filter output is described by (1), the first and second moments can easily be derived as $\mu_1 = \alpha \lambda$ and $\mu_2 = \mu_1^2 + 2 \alpha \lambda^2$ yielding the scintillation index for normalized data

$$\sigma^2 = 1 + \frac{2}{\alpha}$$

Experimentally determined values of scintillation index for SAS images as a function of frequency and grazing angle will be compared later to shape parameter estimates. A large shape parameter would result in Rayleigh data and a scintillation index of 1.

3 Analysis of SAX04 SAS Image Data

As part of 2004 U.S. Office of Naval Research sponsored SAX04, SAS experiments took place about 1 km offshore in water about 17 m (55 ft) deep in the Gulf of Mexico south of Walton Beach, Florida. A bottom mounted rail/mobile tower system was deployed by Applied Physics Laboratory scientists to carry out scattering strength and SAS measurements. A description of the rail/tower system and the methods used to obtain and process the SAS data can be found in Williams et al., [8]. The SAS data examined in this paper were collected over five frequency bands spanning the range from 2 to 100 kHz. Figure 1 shows an example of the type of SAS image on which results in
this paper are based. Ripples on the sandy bottom can be seen in portions of the image formed from a 60-100 kHz transmitted waveform.

Figure 1. Example of synthetic aperture sonar image (60 – 100 kHz waveform). Ripples and possible targets can be seen in this image.

3.1 K-Distribution Goodness of Fit

Before evaluating the shape parameter and how it changes with system and geometric parameters, it is necessary to determine how well fit the data are by the K distribution. In order to quantify how much of the data are well fit by the Rayleigh and K distributions, the Kolmogorov-Smirnov (KS) test [11] is applied to normalized SAS data to test the ability of the models to represent the observed data. A mean power level normalizer [e.g., a cell-averaging constant false alarm rate (CFAR) normalizer] is applied to the original complex image data, which results in an image with nearly unit power. The KS test evaluates the maximum difference between the sample cumulative distribution function (CDF) generated by the data and a test CDF which is, in this case, either the Rayleigh or K distribution with their parameters estimated from the data being tested. The Rayleigh distribution only depends on its power, which is estimated by the sample intensity (i.e., the average of the matched filter intensity over the window being tested). As the data have already been normalized to have unit power, this should be near one. Estimation of the K distribution parameters is more involved and employs a method of moments estimator, described in detail in Abraham and Lyons [4].

For the SAS image data under consideration, windows 1024 samples long (all the along-rail data at a single range) are used to estimate the model parameters and then form the KS test statistic. Using the asymptotic p-value (the probability that a data sample would be rejected when it should be accepted as being well fit by the model under consideration) of the KS test statistic [11], the data are either accepted as being well fit by the Rayleigh or K distribution or rejected. Table 1 contains the results for various p-
values for the different transmit bands studied. For example, at the $p=0.05$ level, 33% of the 60–100 kHz data are well fit by the Rayleigh distribution and 91% are well fit by the $K$ distribution. Based on the acceptance percentages shown in Table 1, the $K$ distribution is accepted as a good model for these data. It should also be noted that portions of the data collected and analyzed, however, were well fit by the Rayleigh distribution. As the $K$-distribution has the Rayleigh distribution as a sub-member, the $K$-distribution will fit these data well too.

Table 1. Percent of Data Accepted as Rayleigh or $K$ distribution Based on the K-S Test at Various Levels of False Rejection.

<table>
<thead>
<tr>
<th>Frequency (kHz)</th>
<th>Rayleigh</th>
<th>$p$-value=0.01</th>
<th>$p$-value = 0.05</th>
<th>$K$ distribution</th>
<th>$p$-value=0.01</th>
<th>$p$-value=0.05</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 – 4</td>
<td>90.7</td>
<td>79.0</td>
<td></td>
<td>90.9</td>
<td>87.7</td>
<td></td>
</tr>
<tr>
<td>6 – 10</td>
<td>92.6</td>
<td>83.3</td>
<td></td>
<td>94.2</td>
<td>92.3</td>
<td></td>
</tr>
<tr>
<td>12 – 28</td>
<td>84.9</td>
<td>75.8</td>
<td></td>
<td>96.0</td>
<td>94.7</td>
<td></td>
</tr>
<tr>
<td>30 – 50</td>
<td>71.0</td>
<td>60.1</td>
<td></td>
<td>94.2</td>
<td>91.5</td>
<td></td>
</tr>
<tr>
<td>60 – 100</td>
<td>47.3</td>
<td>33.3</td>
<td></td>
<td>95.8</td>
<td>91.0</td>
<td></td>
</tr>
</tbody>
</table>

### 3.2 Dependence of Statistics on System and Geometric Parameters

An example of estimates of the $K$ distribution shape parameter versus range for the 60-100 kHz waveform along with linear fits to the shape parameter estimates for all the transmit bands studied are displayed in Fig. 2. In the same manner, Fig. 3 shows trends for the scintillation index as well as agreement with Eq. (4) on the relationship between the shape parameter and the scintillation index. The linear fits shown in Figs. 2 and 3 display strong frequency dependence, which are likely dominated by the bandwidth of the transmitted signals and not to any frequency dependent scattering properties of the seafloor. The shape parameter estimates shown in Fig. 2 are approximately linear functions of $1/$bandwidth. In order to show this more clearly, ratios of shape parameter estimates at a given range were formed for each bandwidth ratio (i.e. at bandwidth ratios of 2 kHz/4 kHz, 2 kHz/16 kHz, etc.). The means of these ratios at each bandwidth ratio are plotted in Fig. 4. In this figure an inverse dependence of shape parameter on bandwidth is clearly evident. The model discussed in Section 2, based on a finite number of scatterers, gives insight into how the PDF of the SAS image data changes as a function of sonar system parameters such as transmit waveform bandwidth or synthetic array beamwidth. Because the shape parameter can be related to the number of contributing scatterers, it will be linearly related to the sonar system resolution (shown as the solid line on Fig 4).

A trend toward higher shape parameters (i.e., toward a Rayleigh distribution) can be also be seen with increasing range (or grazing angle) in Figure 2. Although this effect is not yet understood, one might initially suspect that the larger number of along-track pings required to keep a constant cross-range resolution at greater ranges would induce more Rayleigh-like reverberation statistics. However, a preliminary analysis based on the results of [12] indicates that, with respect to array processing, the statistics are most strongly dependent on the beamwidth of the array. Thus, when SAS processing results in constant cross-range resolution with range, the beamforming is not expected to
significantly alter the statistics even though many more pings are used at longer ranges. A more likely explanation may be found in accounting for the effects of multipath propagation [13]. The earlier travel-times have less or no multipath arrivals while the later travel-times do, leading to more scatterers contributing to reverberation and therefore a higher $K$-distribution shape parameter.

Figure 2. Linear fits to the estimated $K$ distribution shape parameter as a function of range (solid line) along with an example of data for the 60-10 kHz waveform (symbols).

Figure 3. Linear fits to the scintillation index as a function of range (solid line) along with an example of data for the 2-4 kHz waveform (symbols).
4 Conclusions

In this paper the statistical distribution of SAS image data has been examined in terms of the shape parameter of the $K$ distribution and scintillation index as a function of bandwidth and grazing angle (after showing the efficacy of the $K$ distribution for SAS image data). The analysis showed that for the SAS data analyzed the shape parameter of the $K$ distribution (as well as the scintillation index) was proportional to the transmit waveform bandwidth, even when the data were well described by the Rayleigh distribution [i.e., a large number of scatterers in each image pixel (or resolution cell)] as predicted by the finite-number-of-scatterers model of Abraham and Lyons [4]. A logical and feasible next step with this data set is to examine changes in the image statistics as resolution is changed by adjusting both the size of the synthetic aperture and the bandwidth used in the image formation. Other issues that remain to be addressed include: (1) understanding of the grazing angle dependence seen in the distributions; (2) the development of optimal normalization schemes and detectors; (3) understanding and modeling of correlation structure of SAS reverberation in scattering environments with periodic structures (i.e., scattering from ripple fields); and (4) system performance evaluations that account for non-Rayleigh reverberation such as evaluating the trade-offs between improved imaging capabilities derived from an increase in the SAS resolution and the concomitant increase in false alarms resulting from heavier reverberation distribution tails.

Figure 4. Mean of shape parameter ratio estimates at a given bandwidth ratio (symbols) along with a line indicating the inverse relationship between shape parameter and bandwidth.
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References

BANDWIDTH DEPENDENCE OF HIGH-FREQUENCY SEAFLOOR BACKSCATTER STATISTICS

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A key element of successful sonar based object detection algorithms is an understanding of the operating environment, and an accurate prediction of its reverberation. High resolution sonar systems operated in shallow water environments often exhibit background reverberation that differs from the traditional Rayleigh reverberation assumption, with heavier tails than a Rayleigh distribution. This owes in part to the heterogeneous nature of the seafloor in shallow water areas, which is further exacerbated by high-resolution sonar. In this paper, seafloor back-scattering statistics from LFM signals (37-65 kHz) have been analyzed for various types of seafloors. By varying the bandwidth of the received signal, the resolution cell size of the responding seafloor can be altered. Correlations between bandwidth and the shape parameter of a matching $K$ distribution have been observed. For low bandwidths a large area of the seafloor responds, and the statistics tend to Rayleigh as anticipated. However for high bandwidths, a much smaller area is ensonified and an envelope distribution that is heavier tailed than Rayleigh is observed. Data analyzed in this paper were collected by the NATO Undersea Research Centre off of Elba Island, Italy in May 2003. [Research performed under ONR Grant # N00014-03-1-0245]

1 Introduction

Shallow water environments are often characterized by reverberation statistics having heavier tails than Rayleigh owing to the heterogeneous composition of the seafloor. The $K$ distribution has been shown to provide a better fit for the reverberation in shallow water areas [1, 2]. The heavier tails can be exacerbated when high resolution sonar is used, because of the finite number of scattering patches contained in the resolution cell [2]. This differs from the traditional assumption of infinite scatterers producing Rayleigh reverberation, and is a violation of a condition of the central limit theorem. It has been shown previously in low-frequency studies that a doubling of bandwidth resulting in a smaller ensonified resolution cell, tends towards a halving of the shape parameter of a matched $K$ distribution [3]. In this paper, this phenomenon will be investigated with high-frequency reverberation from several different types of seafloors using linear frequency modulated (LFM) chirps.
2 Experimental measurements and data analysis

2.1 Data Collection

Reverberation data analyzed for this paper were collected by the NATO Undersea Research Centre off of Elba Island, Italy in May 2003. A Reson 4026 mono-static sonar was deployed from the R/V Leonardo to record backscattered acoustic data. Three areas with different bottom types have been analyzed: Posidonia Oceanica sea grass, rock, and rippled medium sand with possible patches of immature seagrass (Figure 1). Each data set consists of reverberation resulting from 37-65 kHz LFM chirps of 2 ms duration, at a grazing angle of 20 degrees. The data were basebanded and sampled at 48 kHz during reception. A minimum signal to noise ratio of 6 dB was specified for processing in this paper.

![Figure 1. Images and scattered responses from three types of seafloors studied: Posidonia Oceanica (seagrass), Rock, and Sand (ping number from 1 to 500 along the y-axis; time along the x-axis).](image)

2.2 Processing

The processing performed on the data presented here has been outlined by Abraham and Lyons [3], with several adjustments made for use with this particular data set, which will be outlined.

- **Matched filter** – convolution with a time-reversed transmit waveform resulting in correlation of the received data with the transmitted signal
- **Normalization** – Normalization for this type of signal required a unique approach owing to the varying power of the signal as a function of frequency, range, and time. Ensonified area changes resulting from platform motion proved to be un-correctible from the telemetry measurements recorded during the experiment. To compensate for these power changes, a time domain transmit/receive response was calculated directly from the envelope data by first applying a two-dimensional smoothing filter (ping number by time), and then computing a
polynomial fit response for each ping. This time domain transmit/receive response was then removed from the original reverberation data to achieve normalized data with near unit power.

![Figure 2. Normalization Process (from left to right: original data, 2-d filter, polynomial fit, normalized data).](image)

- **Decimate at the bandwidth** – Data were then resampled to the bandwidth of the chirp (28 kHz) to avoid oversampling in frequency.
- **n-point DFT sub-banding** – By calculating integer n-point DFTs on the time series data, n time series frequency sub-bands can be produced. For this data, a 1-point DFT resulted in a single 28 kHz band; and a 100 point DFT resulted in one hundred 280 Hz bands.
- **Band Normalization** – Data were then renormalized using a typical CFAR normalizer to remove any changes in spectral level between sub-bands.
- **Shape parameter estimation** – The reverberation was matched to a corresponding $K$ distribution using the method of moments. The first two moments were matched for this processing.
- **Scintillation calculation** – Intensity scintillation (normalized intensity variance) was calculated to compare trends towards Rayleigh observed in the shape parameter estimation.

### 3 Statistical results

#### 3.1 Probability of False Alarm (PFA) vs. Bandwidth

Trends shown by Abraham and Lyons [3] for low-frequency reverberation also exist for the high-frequency reverberation discussed here. Generally, as the bandwidth of the chirp increases, a smaller resolution cell is ensonified on the seafloor resulting in a heavier tailed than Rayleigh envelope distribution. This is easily seen in PFA plots; six of which are shown for a *Posidonia* covered seafloor for various bandwidths (Figure 3). It is currently believed that the trend back towards Rayleigh for very high bandwidths is the result of over-resolving scattering patches in the range dimension as compared to the cross-range dimension [3], and will be investigated in further studies. All three bottom types showed similar results, with the trend towards this over-resolution condition occurring for bandwidths approximately greater than 7 kHz; however owing to the limitation of using integer values in the n-point DFT frequency sub-banding process, it is difficult to see exactly when the trend back towards a Rayleigh-like distribution occurs.
3.2 Shape Parameter Analysis

The data is segmented into small blocks, and the shape parameter of each of these blocks is calculated. The reason for this blocking is that the seafloor is expected to vary with range and between pings, and also minimally as a function of grazing angle [4]. Computing shape parameters of small samples of the seafloor and recording the median
value helps to minimize these deviations. No scaling or normalizing of the shape parameter for each bandwidth is used here, as in Abraham and Lyons [3].

Previous work has shown an inverse proportionality between bandwidth and shape parameter of a matched $K$ distribution [3]. Each of the three bottom types considered demonstrated this behavior for bandwidths ranging from approximately 600 Hz to 7 kHz (Figure 4). The higher than expected shape parameters at low bandwidths are possibly caused by estimates being biased high for high shape parameters. In Figure 4 clear separation is evident between the shape parameter estimates for the three different seafloor types. This may be caused by differences in the average number of scattering elements per unit area for these three seafloor types, with the rock seafloor having the fewest and the seagrass covered seafloor the most scatterers per area.

![Figure 4. Median Shape Parameter vs. Bandwidth for Posidonia, rock, and sand seabottoms. The inverse proportionality between Shape Parameter and Bandwidth predicted by [3] is represented by straight lines on this plot.](image)

3.3 Shape Parameter and Scintillation Index vs. Frequency

In an effort to ascertain the underlying mechanisms causing the trends associated with the shape parameter change as a function of bandwidth, the shape parameter for individual frequency sub-bands has been estimated. Estimation of the shape parameter is conducted as before, except that the blocks of data are restricted to contain data from a single frequency sub-band (Figure 5). These sub-bands again arise from the integer n-point
DFT sub-banding method. These plots contain a single value of the full-bandwidth signal at the top (one 28kHz bin), and a value for each of the 100 individual sub-bands at the bottom (one hundred 280 Hz bins). Striations seen in the figures originating at the upper left corner correspond to constant center frequencies, and these frequencies can be identified by the corresponding label on the bottom of the figure. It is expected that as the bandwidth decreases, the distributions will tend to Rayleigh and the shape parameter will increase. In light of this, it is evident that there are areas of much lower shape parameters corresponding to particular center frequencies.

Figure 5. Shape parameter as a function of bandwidth. Each pixel represents a single “bin” of frequency. For a single sub-band (top row), the single pixel represents the entire 28 kHz band. For 100 divisions (bottom row), each pixel represents a single 280 Hz band. Lines of constant center frequency can be identified by a line from top left to the corresponding label on the bottom.
To confirm that the presence of this observed frequency dependant effect is not an artifact of the method of moments estimator, the scintillation index was also calculated (Figure 6). Scintillation index calculations require less data, so any deviation owing to a small data sample size should be minimal, unlike the method of moments estimator used for the $K$ distribution. Scintillation indices of one are considered Rayleigh, and values higher are considered non-Rayleigh. Thus areas of low shape parameter should have higher scintillation values and areas of high shape parameter should have scintillation values close to one. The color axis has been compressed to make the frequency dependant structure more evident. The frequency dependant structures in the shape parameter estimate and scintillation calculation plots occur in the same locations, indicating that there is indeed a frequency dependant effect on the reverberation distribution from each of these seafloor types. Figure 7 shows shape parameter vs. bandwidth for two center frequencies for a rock seafloor. The center frequencies for 37.8 and 41.2 kHz were chosen to correspond to observed areas of low and high shape parameters respectively, and deviations in shape parameter are seen throughout the 500 Hz to 10 kHz range shown.

Figure 6. Scintillation index as a function of bandwidth. Light color indicates a non-Rayleigh envelope distribution, and dark color indicates a trend towards Rayleigh.

4 Discussion and conclusions

The cause of the frequency dependant nature of the deviations in shape parameter is not entirely understood. The frequencies correspond to lengths on the order of centimeters, while the structures of the bottom are tens of centimeters. Since the structures vary between seafloor types, the impact of residual errors from signal processing, or noise in the original system, can be considered negligible. The presence of this structure necessitates the careful use of this type of reverberation data, since even for a fixed bandwidth the choice of center frequency can result in a significant deviation in estimated shape parameter. Further work is required to understand the importance of symmetric changes of the resolution cell size (range vs. cross range). Additionally, an understanding of the frequency dependant nature will also need to be investigated for accurate design of high-resolution object detection algorithms.
Figure 7. Shape parameter for reverberation from a rock covered seafloor at 37.8 kHz and 41.2 kHz center frequencies.

Acknowledgements

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References

HIGH FREQUENCY MEASUREMENTS OF BOTTOM BACKSCATTERING STRENGTH IN THE NORTH SEA: CORRELATION WITH GRAIN SIZE, SHELL CONTENT AND GRAVEL CONTENT

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Measurements of the sound scattered from the seabed are presented for a 10 x 10 nautical mile region of the North Sea. The area is characterised by a variety of bottom types, including mud, sand and gravel. Backscatter measurements at 100 kHz are made by a forward-looking sonar, tilted at an angle of 30º from the horizontal. The measured signals are compared with signals predicted by a model. Values for the backscatter strength at 30º are determined as a function of position by maximizing the match between measured and modelled signals. Approximately 50 bottom grab samples, representative of the uppermost 20 cm, were taken and analysed for gravel content, shell content and grain size distribution. The 30º backscatter strength values are correlated with the gravel percentage, shell percentage and median grain size, showing positive correlation with the gravel and shell content. A small positive correlation is also observed with the median grain size of the remaining sand and mud.

1 Introduction

Scattering of sound from the seafloor is important for two reasons. Firstly, bottom backscattering can limit the performance of a sonar system. Secondly, scattering can provide a means for remotely measuring the bottom properties.

This paper deals with scattering at grazing angles of roughly 25º to 35º. We consider data at a frequency of 100 kHz. The area for which the data were collected is in the North Sea, which is well documented from a geological point of view. Moreover, a large number of additional bottom grabs was taken during the experiments.

Marine geologists classify sediments in terms of their mud, sand and gravel content, resulting in bottom identifiers such as sM (‘sandy mud’) and (g)S (‘slightly gravelly sand’), i.e., the so-called Folk class [1]. Geographical maps providing this type of information are widely available from geological institutes. It would be useful, for e.g. sonar performance modelling, if the bottom backscattering strength could be related to this relatively simple bottom information.
In this paper the backscatter strength at 30°, denoted $BS$ in the remainder of this article and obtained by optimizing the match between measured and modelled backscattered signals, is correlated with measured bottom properties, such as gravel and shell percentages.

In section 2 we present an overview of the experiments carried out. Also, the acoustic equipment used is briefly described here, together with a description of the bottom grab equipment and the results of the bottom grab analysis. For retrieving the backscattering strength, a simple model for the received sonar signal was used. This model and the method of deriving the backscattering strength are presented in section 3. The results are given in section 4. Also in this section the correlation of the obtained $BS$ values with the geo-technical bottom grab data is investigated.

2 The North Sea experiments

2.1 Trial area, logistics and oceanographic conditions

The experiments were conducted in the North Sea. The geology of the surface sediment of part of the North Sea is given in Figure 1 [2]. The information contained in this geological map is explained in section 2.3. The selected area (size 10x10 nautical miles), indicated by the square and shown in the inset of Figure 1 in more detail, includes a variety of sediment types from soft and smooth (‘sandy mud’) to hard and rough (‘sandy gravel’). The water depth ranges from 30 m in the gravel area to 60 m in the mud area.

The experiments were carried out in October 2000 and in May 2001. The ships used were equipped with a forward-looking sonar operating at a frequency around 100 kHz. The track sailed in October 2000 is indicated in the inset of Figure 1 and consists of 10 parallel horizontal legs. The track was sailed twice: once for collecting acoustic data and once for taking bottom grabs. The bottom grab positions are also indicated in the figure. As the acoustic data turned out to be corrupt, the collection of the forward-looking sonar data was repeated in May 2001. As measurement time was limited, only legs 1, 3, 5, 7 and 9 could be sailed in this case.

Sound speed profiles were measured immediately before and after the acoustic legs using a sound velocimeter. The sound speed value decreases from a maximum of 1482 m/s at the surface to 1478.5 m/s at a depth of 40 m. The wind speed varied during the course of the experiment between force 3 and force 4 on the Beaufort scale.

2.2 Acoustic equipment

The forward-looking sonar operates at a frequency of 100 kHz. The tilt of the transmitter is adjustable from 5° to 40°, measured from the horizontal. The sonar was operated at a tilt angle of 30°. The beam pattern of the transmitter is such that it has a 3 dB full width at half maximum (fwhm) of 11° in the vertical direction. It is omni-directional in the horizontal. The received signal is beamformed in the horizontal. The horizontal fwhm is 1.5° and the number of beams is 20.

The ensonified area (footprint) of the most forward-looking horizontal beam at 30° tilt is given in Figure 2. The acoustic signal backscattered from this ensonified area is used for determining the backscattering strength at an average grazing angle of 30° at the bottom.
Figure 1. Surface sediment type or Folk class [1]. The square indicates the trial area. The inset at the right shows the track sailed in October 2000. The track was sailed a second time for collecting bottom grabs, the positions of which are indicated. The numbering of the horizontal legs is also indicated. In May 2001 legs 1, 3, 5, 7 and 9 were repeated for collecting acoustic data again.

The analogue outputs for a few beams of the (horizontal) beamformer are fed into a dedicated data acquisition system. The signals are amplified and subsequently digitised at a sampling rate of 300 kHz. The data acquisition is triggered with the sonar pulse transmission. The acoustic data are stored together with the corresponding time and position as measured with a DGPS system. Only results for the most forward-looking beam are presented in this paper.

The received acoustic signals are expressed in Pa units after a careful calibration of the electronics (preamplifiers and beamformer) and using the known sensitivity of the receiving transducer elements. The remaining uncertainty in the calibration is estimated to be 2 dB.

Figure 2. Sonar footprint (-3 dB) for 30° tilt and a water depth of 50 m.
2.3 Bottom grabs

For obtaining up-to-date information of the surface sediment of the sea bottom, 50 bottom grabs were taken in the trial area. Five grabs per leg were taken at regular distances of about 2 nautical miles. Use was made of a so-called ‘Hamon happener’ and a ‘Van Veen happener’. For both devices the sampling depth in the sea bottom amounts to approximately 20 cm, which is large compared to the acoustic wavelengths of the sonar system used (1.5 cm in water at 100 kHz). With the Hamon happener the bottom sample is well preserved during transportation from the sea bottom to the deck of the ship. Because of the better sealing of the sampling system, the quality of the sediment samples taken with the Hamon happener is higher than that taken with the Van Veen happener. As the ship is relatively small and the Hamon device quite heavy and large, it can only be used under good weather conditions.

During the experiments 24 out of 50 bottom grabs could be done with the Hamon happener. The remaining grabs were carried out with the smaller Van Veen happener. The latter are somewhat less representative of the sediment.

The laboratory analysis of the bottom samples comprised the following steps. First the samples were dried. Next the samples were sieved with a mesh of 2 mm, thereby separating the gravel and shells from the sand and mud. Both the gravel and shell weight percentage were subsequently determined.

The sediment classification according to Folk [1] was assigned to each bottom grab. The Folk class is based on the relative amount of gravel, sand and mud (mud being silt or clay). The distinction between mud and sand is made on the basis of the grain size (diameter). All grains smaller than 62.5 µm are assigned to the mud content of the bottom grab. We note that here no distinction is made between silt and clay, where clay particles have a diameter less than 4 µm. The resulting Folk class for each bottom grab is given in Figure 3. Note that for nearly half of the bottom grabs the derived Folk class deviates from those given in the map of Figure 1, which originates from 1987.

The precise grain size distribution of the sediment samples (after the gravel was removed) was determined by optical microscopy. Based on this grain size distribution, a further distinction can be made for bottom type ‘sand’ (see Table 1). The median values \(d_{50}\) of the grain size distributions are given in Figure 4. This parameter is defined such that 50 % of the grains, by weight, are smaller than \(d_{50}\) (and 50 % are larger).

Table 1. Bottom type and corresponding grain sizes \((M_z=-\log_{2}[\text{grain size in mm}])\)

<table>
<thead>
<tr>
<th>Bottom type</th>
<th>Grain size range (mm)</th>
<th>(M_z) range (φ units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mud</td>
<td>&lt; 0.0625</td>
<td>&gt; 4</td>
</tr>
<tr>
<td>Very fine sand</td>
<td>0.0625 – 0.125</td>
<td>4 → 3</td>
</tr>
<tr>
<td>Fine sand</td>
<td>0.125 – 0.25</td>
<td>3 → 2</td>
</tr>
<tr>
<td>Medium sand</td>
<td>0.25 – 0.5</td>
<td>2 → 1</td>
</tr>
<tr>
<td>Coarse sand</td>
<td>0.5 – 1</td>
<td>1 → 0</td>
</tr>
<tr>
<td>Very coarse sand</td>
<td>1 – 2</td>
<td>0 → 1</td>
</tr>
<tr>
<td>Gravel</td>
<td>&gt; 2</td>
<td>&lt;-1</td>
</tr>
</tbody>
</table>
HIGH FREQUENCY BOTTOM BACKSCATTERING STRENGTH

3 Modeling the received sonar signals

For retrieving the bottom backscattering strength from the data, a simple model for the received acoustic signal is used. Several assumptions are assumed to be valid. These comprise, among other things, straight-line propagation paths and a homogeneous distribution of scatterers throughout the area producing the reverberation at any one instant in time.

We consider the sound path launched at the source with vertical angle $\phi$, see Figure 5. The corresponding rms pressure as received at the sonar due to direct backscattering at incidence angle $\phi$ from the bottom can be approximated by

$$ p_b(\phi) = \left( \frac{e^{-\alpha r_1}}{r_1} \right)^2 B(\phi) 10^{\frac{BS(\phi)}{20}} \sqrt{\rho c_m I_s r_1 \Delta x_1 \Delta \psi} $$

with $I_s$ the intensity at 1 m of the source (i.e. the source level of the sonar), $\rho$ the density and $c_m$ the average sound speed in the water. $B(\phi)$ is the vertical beam pattern of the transducer, $r_1$ the slant range of the sound path, $\alpha$ (Np/m) the absorption coefficient in the water, $\Delta x_1$ the horizontal distance of the sound path, $\Delta \psi$ the length of the elemental scattering area (with area $r_1 \Delta x_1 \Delta \psi$). $\Delta \psi$ is the opening angle of the horizontal beams of the receiver (being 1.5°). BS is the bottom backscattering strength in dB.

For the limited grazing angles of interest here we take Lambert’s rule for BS

$$ BS(\phi) = \mu + 10 \log_{10} (\cos^2 \phi) $$

Figure 3. Folk class for each bottom grab. The sandy mud ('sM') and sandy gravel ('sG') boundaries, see Fig. 1, are also indicated.

Figure 4. The $d_{50}$ value (median) in $\mu$m of the grain size distribution measured for each of the bottom grabs.
with $\mu$, the Lambert parameter, in dB.

Arrival time versus $\phi$ is easily obtained from the geometry, see Figure 5.

Now Lambert’s parameter $\mu$ is retrieved from the backscattered data by minimizing the deviation between the measured received sonar signal and the calculated signal, see Figure 6. For this one-dimensional minimization use is made of the ‘golden section search’, alternated with parabolic interpolation. The algorithm is capable of finding the optimum $\mu$ value within 5 to 10 iterations for a tolerance of 0.5 dB set on $\mu$.

The $\mu$ values thus obtained are used for determining $BS$ at $30^\circ$ by employing Eq. 2 and taking $\phi$ is 60°.

4 Results

In Figure 7 we plot the derived $BS$ values ($\phi$=60°) as a function of longitude for legs 1, 3, 5, 7 and 9. It is observed that the derived $BS$ parameter is a remarkably stable parameter.

From a comparison of the obtained $BS$ values with the geological map of Figure 1 it can be concluded that for areas where bottom type is not changing the error or statistical fluctuation in $BS$ is of order 0.5 dB, i.e. equal to the tolerance set on $\mu$ in the optimization process. Changes of $BS$ exceeding 0.5 dB must represent genuine changes in local scattering strength.

In Figure 8 we compare the Folk class of the bottom grabs with the corresponding $BS$ value. This result seems consistent with the expectation of an increasing $BS$ when going from muddy to the more sandy and gravelly sediments. However, from a closer look at this figure we can perhaps only conclude that sediments without gravel (or shell) (sM, mS and S) have some 11 dB lower backscattering strength than sediments with gravel (gS, msG, sG). Although useful, this analysis is too simple, as Folk class is a classification based on mud, sand and gravel content only, as explained in section 2.3. It does not account for other grab parameters, such as grain size and shell content.

Figure 9 shows $BS$ versus $d_{50}$ as derived from the corresponding grabs for sediments without gravel. Also indicated in the figure are the model results given in [3]. The predicted slight increase in $BS$ with increasing $d_{50}$ is driven by the roughness parameter.
‘spectral strength’ used as input to the model (spectral strength increases with increasing grain size). On the other hand, the absolute values of BS are in good agreement with all measured data.

Figure 10 and Figure 11 show BS plotted against gravel percentage and shell percentage. BS is seen to be positively correlated with all three variables, i.e., d_{50}, gravel percentage and shell percentage.

Figure 7. BS at ϕ=60° as a function of longitude derived for legs 1, 3, 5, 7 and 9.

5 Conclusions
The obtained BS-values are positively correlated with the gravel and shell content of the corresponding bottom grabs. Also, a small but positive correlation is observed between BS and the median grain size.
It is expected that a detailed canonical correlation analysis will provide more insight in the correlation between BS and the geo-technical parameters. In this canonical correlation analysis linear combinations of the geo-technical parameters are sought for which the correlation of this linear combination with BS is largest. If possible, this analysis will provide useful relations between the geo-technical parameters and BS.

Figure 8. BS plotted against the Folk class for each bottom grab position.

Figure 9. BS plotted against the median grain size for each bottom grab position.

Figure 10. BS plotted against gravel percentage for each bottom grab position.

Figure 11. BS plotted against shell percentage for each bottom grab position.

References
HIGH FREQUENCY SCATTERING FROM SANDY SEDIMENTS: ROUGHNESS VS DISCRETE INCLUSIONS

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Environmental data obtained at SAX99 site, including the sediment particle size-depth distribution and the water-sediment interface roughness spectra, were used to compare contributions of volume and roughness components of the seafloor scattering. It is shown, in particular, that contribution of gravel and shell inclusions and coarse sand fraction in total scattering at SAX99 site can be dominating (over roughness) at very high frequencies (about 100 kHz and higher) and grazing angles above critical (about 30 degrees) while roughness is likely a dominating mechanism of bottom scattering at lower frequencies and grazing angles below critical.

1 Introduction

Models for seabed scattering based on realistic assumptions about scattering mechanisms in the sediment provide relationships between various seabed properties and characteristics of the scattered field and are required for solution of various practical problems such as prediction of bottom reverberation given seabed properties or/and inversion of various seabed parameters from acoustic scattering data. There are different mechanisms of seabed scattering which are due to different types of seabed medium irregularities: continuous volume fluctuations of the sediment acoustic parameters and discrete volume inclusions (rock, shell hash, etc), roughness of the seabed interfaces, as well as volume-roughness interactions. Testing various models and mechanisms of high frequency seabed scattering was one of primary goals of recent major experiments in sediment acoustics, SAX99 and SAX04 [1-4].

Analysis and model/data comparisons for SAX99 show that scattering from continuous volume fluctuations and their contribution to total scattering at SAX99 site is much lower than that of roughness and, therefore, can be neglected [3]. On the other hand, extensive measurements of roughness spectra allow estimation of the level of roughness scattering, which shows, within a reasonable uncertainty, that roughness scattering models provide a good description of bottom scattering at frequencies below 100 kHz [3]. However, at higher frequencies, there is a significant discrepancy between observed level of scattering and predicted by roughness scattering theories because the level of roughness spatial spectrum is too low at the corresponding spatial frequencies.

Preliminary analysis shows that SAX04 scattering is also very complicated and that there is a significant discrepancy, even in a more wide frequency range than for SAX99, between backscattering data and results predicted by models taking into account only
roughness scattering. Therefore, other mechanisms of scattering must be considered and other approaches are required for understanding SAX99 and SAX04 data.

In this paper, a model of volume scattering in the sediment is presented, generalizing results of previous models [5-9]. The model, in particular, considers the case of stratified discrete inclusions in the sediment. Environmental data set obtained at SAX99 site, including the sediment particle size-depth distribution and the water-sediment interface roughness spectra, is used to compare contributions of volume and roughness components of the seafloor scattering.

2 Seabed roughness scattering model/data comparison

Extensive measurements of roughness spectra and other sediment parameters at SAX99 allow, using various models of roughness scattering, prediction of frequency-angular dependencies of seabed roughness scattering strength and their comparisons with observed bottom scattering [3]. Results of such comparison are illustrated in Figure 1, where various symbols show frequency dependence of bottom backscattering strength at two fixed grazing angles, 35 and 20 degrees, representing angles above (a) and below (b) the critical grazing angle, which is about 30 degrees for sandy sediments considered here. Solid and dash-dot curves show roughness scattering prediction and bounds of uncertainty correspondingly. The comparison shows, within a reasonable uncertainty, that roughness scattering mechanism can be dominating at frequencies below 100 kHz. However, at higher frequencies, predicted roughness scattering is substantially lower than observed level of scattering because the level of roughness spatial spectrum was found to be too low at the corresponding spatial frequencies at SAX99 site [3].

![Figure 1: Roughness scattering model comparison with data for frequency dependence of SAX99 seabed backscattering strength at a fixed grazing angle above (a) and below (b) critical.](image)

Preliminary analysis shows that SAX04 scattering is also very complicated and that there is a significant discrepancy, even in a more wide frequency range than for SAX99, between backscattering data and results predicted by models taking into account only roughness scattering. Therefore, other mechanisms of scattering must be considered and other approaches are required for understanding SAX99 and SAX04 data as well.
3 Seabed volume scattering

Let us assume that the seabed scattering is due to volume heterogeneity of the sediment layer with the average acoustical parameters, sound speed and density, independent from the depth. Between water and this heterogeneous scattering layer, an arbitrarily stratified transition layer is allowed. The volume backscattering coefficient in the sediment, or the cross section per unit sediment volume, $m_v$, can be treated generally as dependent on the depth. In this case, the seabed backscattering coefficient, or scattering cross section per unit area of seabed surface, $s_m$, can be presented in the form

$$m_v = |W| \left[ (\mu)^{-2} \int_{0}^{\infty} m_v(z) \exp(-z/h_p) dz \right].$$

Here, $W$ is the sound transmission coefficient of the water-sediment transition layer (or interface), $\mu = \rho_w/\rho_s$ is the sediment/water density ratio; $h_p$ is the depth of sound penetration into the sediment (see, e.g., [5,6]).

In a particular case, where the volume backscattering coefficient of the sediment, $m_v$, is depth independent, we have a well known result [5-9]

$$m_v = |W| \left[ (\mu)^{-2} m_v h_p \right].$$

For the transmission coefficient, in a particular case of a flat water-sediment interface, we have $W = 1 + V$, where $V$ is the seabed reflection coefficient.

4 Incoherent discrete scattering model

Volume scattering in the sediment can be attributed to two different kinds of heterogeneity, continuous and discrete. Here, in this paper, we consider the case of scattering from discrete inclusions in an effective fluid sediment and assume incoherent summation of the scattered intensities for different scatterers [6,7]. Some considerations of possible coherent effects can be found in [10] and omitted here. In the frame of incoherent scattering model, the scattering cross section per unit sediment volume can be presented as follows [6]

$$m_v = \frac{3}{4\pi} \int F(k, a) a^{-3} \psi_v(a) da,$$

where

$$\psi_v(a) = \frac{a^v \Delta v}{v \Delta a},$$

is a dimensionless volume size distribution function, $\Delta v / v$ is the relative part of volume occupied by particles of the size (equivalent radius, $a$) within the correspondent interval $\Delta a$; $k$ is the wave number in the sediment and $F$ is a dimensionless individual scattering function related to the individual scattering cross section $\sigma$ as follows

$$\sigma = a^2 F(k, a).$$

Equations (1)-(5) provide a solution for the seabed backscattering coefficient given an arbitrary depth-size distribution of arbitrary discrete inclusions in the sediment. In the calculations below, a simple case is considered. Assume that inclusions are spherical, homogeneous and have the same material properties. Also, here we ignore possible shear
effects within inclusions and surrounding sediments. The exact solution for the backscattering cross section and the scattering function in this case can be found, e.g., in [11]. A reasonable approximation represents a solution with smoothed interferential oscillations at $ka \geq 1$ [6] and used in the following sections for numerical calculations of the integral in Eq. (3).

5 Size distribution at SAX99

An environmental data set obtained at SAX99 site (near Walton Beach, Florida) [1] provides depth-size distribution histograms for a wide range of grain and inclusions sizes. Using the histograms (courtesy of K. Briggs) the volume size distribution function $\psi$, defined by (4) was analyzed and results are presented in Figure 2.

Figure 2. Volume size distribution for the SAX99 sediment at different depths (in-situ data). The solid line shows the best multi-power law fit to the environmental in-situ data. The dashed line shows the distribution that would provide the best fit for the acoustic scattering data.

Different symbols represent average within different layers of 2 cm thickness from the cores containing top 26 cm of the sediment. It is seen that shape of the size distribution is quite different for different depths and different size intervals. For example, concentration of shell fraction is low near the surface at 0-2 cm depth, while there is a remarkable shell layer at 20-22 cm depth. The solid line shows the best multi-power law fit to the environmental in-situ data [6]. The dashed line shows the distribution that will be used in model/data comparison below.

6 Volume scattering model/data comparison

Frequency dependence of the seabed backscattering strength, $10 \log m_s$, obtained at SAX99 [3] is shown in Figure 3 at a fixed grazing angle, $\chi = 35^\circ$, by various symbols. The curves show results of calculations for the model of discrete scattering described above, using Eqs. (1)-(5). Acoustic parameters of the sediment in the model correspond to environmental measurements at the SAX99 site [1]. The grain size distribution was taken as shown in Figure 2 (solid curve) and with changed location of the shell layer.
(dashed curve) to demonstrate an effect of the size distribution stratification. Model/data comparison shows that prediction of volume scattering using real size distribution is a few dB lower than observed bottom scattering at SAX99 at frequencies below about 100 kHz. However, this difference can be easily compensated, if the shell layer is located near the sediment surface (dashed curve).

Figure 3. Frequency dependence of the bottom backscattering strength at SAX99 at a fixed grazing angle (35 degrees). The solid line shows model prediction using in-situ size distribution data (see Figure 1). Comparison of the solid and dashed lines shows effect of the shell layer location. The shell layer is placed at the 20-22 cm depth (solid) and 0-2 cm depth (dashed) respectively.

Figure 4. Effect of a thin (3.5 mm) top homogeneous (transition) layer at high frequencies. The frequency dependence of the bottom backscattering strength at SAX99 shows a remarkable roll-off above 1000 kHz. The solid and dashed lines show results for a model of discrete scattering respectively with and without the transition layer.
In Figures 4, another example of model/data comparison is demonstrated, showing that the model provides both qualitative and quantitative explanation of some interesting experimental results obtained at SAX99 site for higher frequencies range 265-1850 kHz, including backscattering data roll-off above 1000 kHz (see Figure 4), which has not been explained adequately [12]. The model takes into account the fact that concentration of shell fraction is low near the surface at 0-2 cm depth (see Figure 2) which allows to consider a thin (3.5 mm) top homogeneous (transition) layer placed on a sediment half-space with depth independent size distribution, which here is taken as shown by dashed curve in Figure 2. The result is shown in Figure 4 by solid curve. The dashed line corresponds to the case without the transition layer and perfectly agrees with data below 300 kHz but fails at higher frequencies.

7 Volume vs roughness scattering at SAX99

Thus, the results presented above show that the model of scattering from discrete inclusions in the sediment can be a good descriptor of seabed scattering at high frequency (above 100 kHz) and grazing angles above critical, at least at SAX99. Moreover, a simple summation of the two mechanisms, roughness and discrete volume scatterers, provides a good model/data comparison for backscattering for all frequencies used in SAX99 at grazing angles above critical. This result is illustrated in Figure 5.

![Figure 5: Model-data comparison for frequency dependence of SAX99 seabed backscattering strength at a fixed grazing angle above critical.](image)

However, there is still a serious problem in understanding and modeling of backscattering for SAX99 at high frequencies (about 200 kHz and higher) at sub-critical grazing angles. This is demonstrated in Figure 6. Analogously to the case of grazing angles above critical, a simple summation of volume and roughness scattering was applied assuming no interaction between these two mechanisms. This means, that roughness scattering is being calculated for homogeneous sediment (with no inclusions) and discrete scattering is being considered assuming a flat sediment surface (no
roughness). This simplified approach, used successfully at higher grazing angles, as demonstrated in Figure 5, fails in attempts to explain high frequency data at sub-critical grazing angles (see Figure 6).

![Figure 6: Model-data comparison for frequency dependence of SAX99 seabed backscattering strength at a fixed grazing angle below critical.](image)

The discrepancy can be due to ignoring volume-roughness interaction. In the case of flat water-sediment interface, at grazing angles below critical, volume scattering is significantly reduced because of small depth of sound penetration into the sediment. In the case of randomly rough interface, there are always facets with local grazing angles above critical, which causes an enhancement of sound penetration and consequent enhancement of volume scattering in the sediment [13]. The effect can be very significant considering the fact that a slope of roughness at sub-cm scales at SAX99--SAX04 site is large and can be close to both angle of repose and critical angle (about 30 degrees).

8 Discussion

It is shown, in particular, that contribution of gravel and shell inclusions and coarse sand fraction in total scattering at SAX99 site can be dominating (over roughness) at very high frequencies (about 100 kHz and higher) and grazing angles above critical (about 30 degrees) while roughness is likely a dominating mechanism of bottom scattering at lower frequencies and grazing angles below critical. A simple summation of the two mechanisms, roughness and discrete volume scatterers, provides a good model/data comparison for backscattering for all frequencies used in SAX99 at grazing angles above critical.

However, there is a serious problem in modeling of backscattering for SAX99 at high frequencies (about 200 kHz and higher) at sub-critical grazing angles where there is a significant model/data discrepancy which can be due to ignoring volume-roughness
interaction. The effects of such interactions can be very significant and may require further theoretical considerations and other approaches.

One such approach, a unified approach to volume and roughness scattering [14,15], can be used to describe volume-roughness interactions in the sediments. It is exactly consistent with the small perturbation method, but it is not restricted by the smallness requirement for roughness height and slope, which makes it very appropriate tool for considering effects of non-small-slope roughness at SAX99-SAX04 conditions.

Acknowledgements

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References

SCATTERING FROM A ROUGH SEAFLOOR WITH STRATIFICATION

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A small-slope formulation for the bistatic scattering strength of a rough, realistically stratified seafloor is obtained by generalizing a previous result [Gragg et al., JASA 110 (2001)] that featured a general treatment of the scattering integral but considered everything below the rough water/sediment interface to be a homogeneous half-space. The essential steps are to realize that (i) the earlier result can be rearranged to make it clear that the bottom’s geoacoustic parameters enter through the complex reflection coefficient $R$ that would characterize the same bottom without roughness, and (ii) to include stratification, it is only necessary to introduce the appropriate layering into the form of $R$. This results in a small-slope expression for the scattering strength of a sea floor composed of a rough fluid sediment layer over an arbitrary stack of elastic strata. Successful numerical implementation requires only a reliable algorithm that can compute $R$ for sufficiently general environments. We demonstrate this formulation using Essen’s model environment (a uniform fluid sediment layer and a uniform elastic basement [JASA 95 (1994)]) and benchmark it using his first-order perturbation results.

1 Introduction

This work builds on the foundation established by the article that introduced Dashen’s symmetric formalism for the scattering amplitude [1]. That initial publication was followed by a series of articles in which Dashen and Wurmser investigated the implications for various cases involving Dirichlet, Neumann, and fluid-fluid boundary conditions [2–4], and finally by one in which Wurmsner extended the formalism to the fluid-solid and even solid-solid cases [5]. This theoretical development was followed up by an article by Gragg et al. that utilized the formalism’s expression for the small-slope acoustic scattering strength of a rough interface on a uniform seafloor and devised a general numerical implementation for the scattering integral [6], and then by an article in which Soukup and Gragg validated this formulation by using it to invert at-sea data for the geoacoustics and roughness parameters of a limestone seafloor [7]. The present work presents a simple way of expressing the sub-surface medium’s role in the scattering as a function of $R$, the complex reflection coefficient of the seafloor with its roughness neglected. Arbitrary bottom layering is then incorporated by simply using the appropriate $R$. This $R$-based approach constitutes a small-slope generalization to the perturbative formulation of Moe and Jackson [8]. It provides the surface scattering strength for any ocean bottom composed of a rough fluid sediment layer over an arbitrary stack of strata, any of which may involve depth profiles and/or elasticity.
The notation is continued from [6], with vectors in 3D indicated by arrows and their 2D projections onto the $z=0$ plane rendered in boldface [e.g., $\vec{x}=(x,z)$]. Wave-vectors in the water are: the incident vector $\vec{k}=(k_x,k_z)$ with $k_z<0$, the scattered vector $\vec{q}=(q_x,q_z)$ with $q_z>0$, and their difference $\vec{Q}=\vec{k}-\vec{q}=(Q_x,Q_z)$. The acoustic problem is formulated in terms of pressure (as opposed to potential) fields.

2 Theory

2.1 Deterministic Description: Scattering Amplitude

The Dashen-Wurmser small-slope scattering amplitude for the bottom relief $h(x)$ (with $\langle h(x) \rangle = 0$) is

$$T(\vec{q},\vec{k}) = \frac{i}{Q} \int d^2x e^{iQ(x)} A(x;\vec{q},\vec{k}) + O[(\frac{\lambda}{2h})^2, (\frac{\lambda}{2h})^3, \ldots]$$

(Eq. (2.6) of [3] with $h_0=0$), an expression correct to second order in the gradients of $h$ but to all orders in $h$ itself. Time-reversal invariance (equivalent to reciprocity in the present CW case) is manifest in the symmetry $A(x;\vec{q},\vec{k}) = A(x;\vec{k},-\vec{q})$. The kernel $A(x;\vec{q},\vec{k})$ relates to the corresponding “flat earth” problem for which the original physical boundary conditions remain in force at the water-bottom interface but that interface is artificially flattened into the $z=0$ plane. For that problem, an incident plane wave $e^{ik\cdot r}$ in the water would produce a total water-borne field

$$p(x;k) = e^{ik\cdot r} + R(k)e^{ik\cdot r}$$

in which $k = (k_x,k_z)$ is the reflected wave-vector and $R(k)$ is the plane-wave reflection coefficient for the flat bottom. Likewise, an incident plane wave $e^{i(-q)\cdot r}$, which corresponds to the time-reversed scattered wave, would produce a total field $p(x;-q) = e^{i(-q)\cdot r} + R(-q)e^{i(-q)\cdot r}$. The essence of Dashen’s approach is to weave reciprocity into the fabric of the formulation by expressing the scattering amplitude as a symmetric combination of both $p(x;k)$ and $p(x;-q)$. In any given problem, the expression for $A(x;\vec{q},\vec{k})$ that emerges is ultimately determined by the boundary conditions that these fields must satisfy at $z=0$. In general, this is a function of the water-borne fields $p(x;k)$ and $p(x;-q)$ (and their gradients) just above the $z=0$ plane together with these fields’ extensions into the bottom just below that plane.

For a seafloor whose top layer is a uniform fluid sediment, the result is

$$A(x;\vec{q},\vec{k}) = \lim_{z \to 0} \left[ \frac{1}{1-G} \frac{\partial p(x;\vec{k})}{\partial z} \frac{\partial p(x;\vec{-q})}{\partial z} - \left( \frac{\partial p(x;\vec{k})}{\partial x} \frac{\partial p(x;\vec{-q})}{\partial x} + \left( K_{xx}^2 - \frac{K_{zz}^2}{Q} \right) p(x;\vec{k})p(x;\vec{-q}) \right) \right]$$

(2)
The water is taken to be uniform \(^1\); however, except for its top layer, the bottom is not. The compressional wave-numbers \(K_p = \omega/c_p\) and \(K_w = \omega/c_w\) pertain to that top layer and to the water, respectively. The corresponding densities \(\rho_p\) and \(\rho_w\) appear only in the ratio \(\rho_p/\rho_w\). An important feature of Eq. (2) is that the field expressions are all evaluated in the limit as \(z \to 0\) from the water \((z > 0)\) side of the interface\(^2\).

The field \(p(\mathbf{x}; \mathbf{k})\) in the water has been expressed in terms of the complex reflection coefficient \(R(\mathbf{k})\) of the flat-earth seafloor: 

\[
\lim_{z \to 0} \begin{cases} 
  p(\mathbf{x}; \mathbf{k}), & \frac{\partial p(\mathbf{x}; \mathbf{k})}{\partial z}, \\
  \frac{\partial p(\mathbf{x}; \mathbf{k})}{\partial \mathbf{x}} & \end{cases} = \left\{ [1 + R(\mathbf{k})]i\mathbf{k}[1 - R(\mathbf{k})], i\mathbf{k}[1 + R(\mathbf{k})]\right\} \times e^{i\mathbf{k} \cdot \mathbf{x}} \quad (3)
\]

and similar expressions involving \(p(\mathbf{x}; -\mathbf{q})\) and its spatial derivatives (namely, Eq. (3) with \(\mathbf{k} \to -\mathbf{q}\)) allow Eq. (2) to be written as

\[
A(\mathbf{x}; \mathbf{q}, \mathbf{k}) = \beta(\mathbf{q}, \mathbf{k}) e^{Q \mathbf{x}} \quad (4)
\]

in which

\[
\beta(\mathbf{q}, \mathbf{k}) = (1 - \mathbf{q} \cdot \mathbf{k}) [1 - R(\mathbf{k})][1 - R(-\mathbf{q})] \\
- \{ (1 - \mathbf{q} \cdot \mathbf{k}) \mathbf{q} + [\mathbf{q} \cdot (\mathbf{k}^2_p - \mathbf{k}^2_w)] [1 + R(\mathbf{k})][1 + R(-\mathbf{q})] \} \quad (5)
\]

As a result, through first order in \(h\), the scattering amplitude acquires the form

\[
T(\mathbf{q}, \mathbf{k}) = \frac{i}{Q_c} \beta(\mathbf{q}, \mathbf{k}) \int d^3 \mathbf{x} \left\{ e^{i\mathbf{q} \cdot \mathbf{x}} \right\} \quad (6)
\]

in which the coefficient \(\beta(\mathbf{q}, \mathbf{k})\) involves nothing more than (a) the surficial values (i.e. \(z = \pm\varepsilon\)) for the density and sound speed and (b) the reflection coefficient of the seafloor with its roughness flattened out. The crucial point is that below the topmost sediment layer, which must be a uniform fluid, the seafloor may have any stratified structure at all—including layers and/or depth profiles involving fluid or elastic media. The flat-earth response of any such stratified seafloor is fully specified by its complex reflection coefficient \(R(\mathbf{k})\). The rapid, accurate computation of this quantity for various complex environments has been \([9–14]\) and continues to be \([15–18]\) an area of active research. Consequently, for most layered environments of practical interest in ocean acoustics, adequate methods already exist among the numerical codes that form the mainstay of propagation modeling in that field, so that \(R\) can be regarded as given.

\(^1\) As in most scattering analyses, the use of a uniform incident medium just simplifies the presentation. It is not essential \([2]\).

\(^2\) At an earlier stage in its derivation in \([2]\), Eq. (2) contained some quantities evaluated as limits from the \(z < 0\) side. But since \(p\) and \(\rho^{-1} \partial \rho/\partial z\) are continuous across \(z = 0\), these were easily swapped for values in the water, yielding the above form.
2.2 Stochastic Description: Scattering Strength

If the bottom relief \( h(x) \) is viewed as a stationary, isotropic, Gaussian stochastic process in two dimensions, then the non-specular part of this random rough surface’s incoherent scattering strength per unit solid angle—essentially \( \left\langle \frac{\Gamma}{4\pi} \right\rangle \) per unit area—assumes the separated form [6]

\[
\sigma_n = P \times I
\]

in which the bottom geoacoustics affects \( P \) and the interface roughness affects \( I \). For general bistatic scattering, \( \sigma_n \) depends on \( \hat{k} \) and \( \hat{q} \), whose directions may be specified by the spherical angles \((\theta_{\text{in}}, \varphi_{\text{in}})\) and \((\theta_{\text{out}}, \varphi_{\text{out}})\), respectively. Under the isotropic assumption, \( \sigma_n \) retains its functional dependence on the separate grazing angles \( \theta_{\text{in}}, \theta_{\text{out}} \) but only depends on the azimuth difference \( \Delta \varphi = \varphi_{\text{out}} - \varphi_{\text{in}} \). In this article, we restrict our numerical simulations to backscatter geometries \((\theta_{\text{out}} = \theta_{\text{in}} = 0)\), which allows us to disregard azimuth and drop the ‘in/out’ designation on the grazing angle.

The frequency-dependent factor \( I \) is a spectral integral involving \( S(k) \), the radial wave-number spectrum of \( h(x) \). Natural surfaces are often represented using a simple power-law form \( S(k) \propto k^{-\gamma} \) with \( 2 < \gamma_s < 4 \) (corresponding to a fractal dimension \( 1 + \gamma_s/2 \) between the 2 and 3 — limiting values that characterize classical Euclidean surfaces and space-filling fractal surfaces, respectively). But even with that simple spectrum, accurate evaluation of \( I \) has been surprisingly troublesome. Recently, however, an efficient numerical algorithm has emerged for computing it throughout the range \( 2.6 \leq \gamma_s \leq 3.9 \), which seems to cover most ocean acoustics situations [6,19].

The frequency-independent prefactor

\[
P = \frac{1}{8\pi} \left| \frac{\beta(\hat{q}, \hat{k})}{Q_1|Q|} \right|^2
\]

is a function of bottom geoacoustics only. Our efforts to date [6,7] have managed to incorporate elasticity in \( P \) but have been restricted to modeling the ocean bottom as a uniform half-space, exploiting explicit expressions for \( \beta \) that were valid only in that case (e.g. [6], Eq. (4)). That rudimentary view of the geophysics was a holdover from the theoretical scattering work [2–6] in which it was natural to de-emphasize the complexity of the target medium in order to focus on the feature directly responsible for the scattering, namely the interface roughness. Fortunately, as seen in the preceding section, it is actually a fairly simple matter to incorporate realistic bottom stratification. Assuming a fluid sediment layer on top, this can be done by just using Eq. (5) for \( \beta \) and including the stratification in \( R \).

The small-\( \theta \) asymptotic form of \( I \) yields the perturbation-theory expression [6],

\[
\sigma_n = \left| \frac{\beta(\hat{q}, \hat{k})}{2} \right|^2 \frac{S(|Q|)}{R}
\]

For small rms relief \( h_{\text{rms}} \), this can actually remain valid up to rather large \( \theta \). It is convenient and easy to interpret in terms of the roughness spectrum, but it can be
significantly less accurate than the small-slope expression when $h_{in}$ and/or $\theta$ grow large. The implementation reported in [6] operated in either “PT mode” or “SS mode”; i.e., it used the same $\beta$ to produce $\sigma_n$ by means of either Eq. (9) or the more accurate Eq. (7). This remains true of the improved implementation reported here, in which $\beta$ can include arbitrary bottom layering incorporated in $R$.

3 Modeling

We have validated the above formulation, in PT mode, against Essen’s published perturbative computations [20] for a model environment consisting of a fluid sediment layer and an elastic basement. Both were uniform in this case so, rather than invoking numerical codes for the reflection coefficient, we can simply exploit the analytic form

$$R(\tilde{k}) = \frac{V(\tilde{k}; \text{water/sediment}) + V(\tilde{k}_p; \text{sediment/basement})e^{-ik_p d}}{1 + V(\tilde{k}; \text{water/sediment})V(\tilde{k}_p; \text{sediment/basement})e^{-ik_p d}}. \quad (10)$$

In this, $d$ is the sediment thickness; $\tilde{k}_p = (\mathbf{k}, k_{p c})$, with $k_{p c} = -\sqrt{k^2_p - |\mathbf{k}|^2}$, is the continuation of $\tilde{k}$ into the sediment; and $V(\tilde{k}; \text{incident/target})$ represents the reflection coefficient of a uniform target half-space (fluid or elastic) relative to a uniform fluid incident half-space in which the incident wave-vector is $\tilde{k}$. Equation (10) corresponds to Eq. (2.10.7) of [21] and $V(\tilde{k}; \text{incident/target})$ is an implementation of Eq. (7.13) from [13].

Figure 1 presents computed scattering strengths for Essen’s environment. The basement is sedimentary rock, and the sediment is a layer of very fine sand one quarter-wavelength thick. The three broken curves were generated by the new $R$-based algorithm (PT mode). The solid one, digitized from Fig. 5a of [20], is the result of Essen’s perturbative formulation. Essen’s curve corresponds to a surface spectrum with $\gamma_z = 4$. We have had to be content with plotting results from the $R$-based formulation for $\gamma_z = 3.7, 3.8,$ and $3.9$ because the scattering integral formulation from [6] is not validated for $\gamma_z > 3.9$. Still, it seems clear from the figure that Essen’s results are recovered in the $\gamma_z \to 4$ limit, and this serves to validate the $R$-based algorithm.

Figure 2 illustrates the result of implementing the $R$-based formulation in the SS mode rather than the PT mode; i.e., the impact of using small-slope theory rather than perturbation theory in Essen’s environment. Note that

- PT $\to \infty$ as $\theta \to 90^\circ$. This is expected since $\theta = 90^\circ$ is the specular direction, where $S(lQ0)$ diverges. In contrast, SS is well behaved there.
- SS $\to$ PT as $\theta \to 0^\circ$. This trend is also expected because PT is the small-$\theta$ asymptotic form of SS.
- For this environment, PT and SS are at least 6 dB apart throughout the middle third of the grazing angle range, $30^\circ < \theta < 60^\circ$.

In brief, small slope theory provides numerical results that coincide with perturbation theory at small grazing angles and can be a considerable improvement elsewhere.
Fig. 1 – Perturbation result digitized from Essen’s Fig 5a [20] together with results from the $R$-based scattering formulation (PT mode) for the same environment. Vertical lines mark the critical angles: water/sediment p-wave, $\theta_p^{(w/s)}$; sediment/basement s- and p-wave, $\theta_s^{(s/b)}$ and $\theta_p^{(s/b)}$.

Fig. 2 – Results from the $R$-based scattering formulation, comparing the SS and PT modes in Essen’s environment. (The PT curve is repeated from Fig. 1.)
4 Summary

Our earlier formulation [6] expressed the bistatic scattering strength of a rough seafloor in the form of Eq. (7), i.e. $\sigma = P \times I$, and was capable of invoking either small-slope theory or its perturbative approximation to produce the scattering integral $I$. It was limited, however, by a need to generate the $P$ factor by representing the seafloor as a uniform half-space. The improved formulation presented here lifts that restriction and produces $P$ for any stratified seafloor whose top layer is a uniform fluid. The main contribution of this work is to allow small-slope scattering to exploit the reformulation of $P$ in terms of $R$, the layered seafloor’s complex reflection coefficient whose computation can be “outsourced” to existing algorithms.

Our $R$-based scattering algorithm agrees in the proper limit with the perturbative algorithm of Moe and Jackson [8], and makes a compatible small-slope enhancement available to those bottom interaction models where the latter is now used [22].

5 Future work

The $R$-based formulation presented here admits roughness only at the top of the sediment. For ocean acoustics applications, the logical next step would be to allow the top of the basement to be rough as well. This appears to be a relatively straightforward matter and is being pursued in the near term.

The present version of the formulation also requires the topmost sediment layer to be a fluid. Another possible generalization would be to allow elasticity there too. Although that may appear equally straightforward, there are subtleties involved. The simple approach, stepping the field values from the elastic sediment across into the water using the fluid-elastic boundary conditions to produce a more general version of Eq. (2), fails. Despite its attractiveness from the standpoint of theoretical completeness, the practical need for such a step seems relatively low, and it is being pursued as a lower priority.

Acknowledgement

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References


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3 Once notational differences are resolved, Eq. (33) of Ref. [9] is equivalent to Eq. (9), the PT-mode result obtained here.
VERIFICATION OF ROUGH SURFACE SCATTERING PREDICTIONS USING AN ELASTIC SCALE MODEL

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Quasi-monostatic scattering strength measurements in the 100-300 kHz band with a PVC scale model of a rough surface were collected in an acoustic tank facility at the Naval Research Laboratory under the Geoacoustic Physical Modeling project. The scale model was analogous to elastic ocean bottoms (e.g. limestone) in its large predicted dependence of scattering strength on roughness parameters and its compressional to shear speed ratio. The inputs to the BORIS-SSA scattering model (speeds, attenuations) were measured from material samples to allow direct comparison between the modeled and measured scattering strengths. Varying the positions of the source/receiver allowed the variability in the data at specific grazing angles to be minimized and approach the theoretical predictions with high accuracy. [Work supported by ONR and NURC]

1 Introduction

The Naval Research Laboratory (NRL) has recently performed experiments to verify the predictions of rough surface scattering theory with scale models of elastic ocean bottoms. The Geoacoustic Physical Modeling Rough Surface Scattering 2 (GPM RSS2) experiment, performed at the NRL Shallow Water Acoustic Laboratory in May 2004, was designed to begin the process of experimentally supporting the predicted dependence of scattering strength on roughness and geoacoustic parameters. To systematically address scattering issues relating to roughness, the most practical approach is to manufacture rough surfaces with the desired parameters and perform the acoustic measurements in a tank facility. For the GPM RSS2 experiment, a PVC sheet (4′ by 4′ by 2-4″) with a milled surface on one side was employed. A detailed description of the experiment, acoustic data files, material properties, and rough surface profilometry is given in [1].

PVC was selected as a material that provides a significant shear speed (roughly one-half of the compressional speed) and exhibits a large dependence of bottom backscatter on the surface roughness parameters for sub-critical grazing angles. This type of dependence is characteristic of rocky ocean bottoms (e.g. limestone), according to the NRL small slope model, which uses a power-law roughness spectrum [2]. Since the
milled surface for the GPM RSS2 experiment does not lend itself to a single power-law value in the wavenumber range of interest, we employ a model which predicts scattering strength for a deterministic rough surface, namely, Bottom Reverberation for Inhomogeneities and Surfaces-Small Slope Approximation (BORIS SSA) [3]. At the time of this writing, stylus profilometry data are available for approximately half of the sample. The completion of the profilometry is expected to take place before July 2005. NRL is also planning to fabricate surfaces that will more closely follow power-law models, following a methodology outlined in [4], so that both the NRL small-slope and BORIS-SSA models can be used to examine the dependence of the scattering strength on roughness spectral parameters.

2 Experimental Summary

For the GPM RSS2 experiment, the transmitted signal was an impulse with an approximate length of 20 $\mu$s, which produced a nearly flat spectrum in the band 100 kHz to 300 kHz. It is visually noticeable that PVC sheet has irregularities at millimeter length scales (due to the milling process) and is consequently not designed for characterizing acoustic scattering above 300 kHz. Compressional/shear speeds and attenuations were measured at the Houston Advanced Research Center (HARC) on a sample of the material. Details of the material analysis, which covered the band 300 kHz to 1 MHz, are given in [1]. A summary of the estimated results at 300 kHz is given in Table 1 – the values given in the table were extrapolated to the experimental frequency band. The error values for the geoacoustic parameters in Table 1 are derived from the following percentage errors for these measurements: 0.5 % for the speeds, 2 % for the p-wave attenuation and 4 % for the s-wave attenuation. Model predictions indicate that these measurement errors cannot produce a change of more than 2 dB for stochastic surfaces. The acoustic parameters of the deionized tank water are sound speed = 1482 m/s and density = 1.00 g/cc.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>1700 kg/m³</td>
</tr>
<tr>
<td>Compressional Speed</td>
<td>2381 ± 11 m/s</td>
</tr>
<tr>
<td>Compressional Attenuation</td>
<td>0.25 ± 0.005 dB/m/kHz</td>
</tr>
<tr>
<td>Shear Speed</td>
<td>1117 ± 6 m/s</td>
</tr>
<tr>
<td>Shear Attenuation</td>
<td>0.56 ± 0.02 dB/m/kHz</td>
</tr>
</tbody>
</table>

Table 1: Estimated properties of the PVC material at 300 kHz.
Figure 1: Geometry (not to scale) for the GPM RSS2 experiment backscatter measurements. The PVC sheet size was 4 ft x 4 ft (121.9 cm x 121.9 cm) with a thickness of 5-10 cm and an rms roughness of about 0.7 cm. The target position is taken to be zero at the center of the sample and is positive for the upper portion of the PVC sheet, where the stylus profilometry has been collected.

Figure 1 is a diagram of the experimental geometry. The PVC sheet was suspended vertically in the center of the tank, with the rough side facing the source and receiver. The boundaries of the tank (air/walls/bottom) are at least 3 m away in each direction, so that all direct path interactions with the rough surface take place before any reflections from the tank walls. Two data sets were taken, with the source and receiver positions varying for each. For the first data set, the spherical, omni-directional source was positioned at a distance of 40 cm and the receiver, of identical manufacture to the source, was moved in 2 mm increments from 20 to 35 cm. For the second data set, the source was positioned at 60 cm, and the receiver was moved in 2 mm increments from 30 to 50 cm. All these distances were measured from the flat side of the PVC sheet.

For each data set, nine target positions were taken. (We use the term “target position” to describe the vertical placement of the PVC sheet.) The horizontal center of the PVC sheet was initially aligned to the middle of the water tank (target position = 0, as shown in Figure 1), and the PVC sheet was then moved vertically so that target positions from -20 cm (the lowest source/receiver positions in Figure 1) to +20 cm (the uppermost source/receiver positions) in 5 cm increments were obtained. The time series were collected with a sampling interval of 0.3333 µs in sets of 100 at each source/receiver positions, and averages over these 100 time series were computed at each position. A reference measurement was made by positioning the source and receiver 1 m apart and measuring the pressure produced from the transmitted waveform.
3 Modeling of Grazing Angle Dependence

The reference time series of the transmitted acoustic signal, the surface topography from stylus measurements, and the information in Table 1 (except the shear attenuation) were used as inputs to the BORIS-SSA model. (Shear attenuation is not an input to the current BORIS-SSA model, and has been shown to be of minimal importance for PVC when using the NRL small slope model with stochastic surfaces.) The surface topography was collected in the form of a 1 mm by 1 mm grid, with the error in height being less than 1 mm. The reference measurement was used to obtain calibrated results for the acoustic time series, and the transmission loss along ray paths and the area ensonified by the signal were calculated to obtain the scattering strength as a function of grazing angle. The scattering strength plots use the mean of the incoming and outgoing grazing angle as the abscissa; in the grazing angle regime shown in the plots, the bottom-to-receiver grazing angle was approximately 9/10 of the source-to-bottom grazing angle. A deterministic ripple created by the milling process, with heights of 10-100 microns, separated by 1 mm, was modeled mathematically and added to the profilometry data. The BORIS-SSA model predicted the contribution of this ripple to be < 1 dB. The profilometry outside the measurement range was extrapolated to cover the lower half of the sample, using a repetition of the data from the upper half of the sample and a smoothed transition region between the actual and extrapolated profilometry.

As shown in Figure 1, the upper source/receiver positions are next to the region where the profilometry has collected. Since the area used to compute scattering strength is an annulus whose inner and outer radii increase as the time increases (and grazing angle decreases) and has a width of about 3 cm (based on the signal duration) we will encounter acoustic interactions with the part of the model for which we have no profilometry data. The scattering strength calculations for the data at target position = 0 use the least amount of actual profilometry (approximately 50% measured and 50% extrapolated), while the calculations for the uppermost source position in Figure 1 use the most actual profilometry (approximately 80% measured and 20% extrapolated at the lowest grazing angle, approaching 100% measured as the maximum grazing angles are approached). The data set for target position = 0 has the largest range of grazing angles due to the central location of the source and receiver, as shown in Figure 1. The BORIS-SSA predictions and data agree in a general sense, as they show a similar upward trend in the mean scattering strength and the same variability. The BORIS-SSA curve is valid down to 35 degrees, where the edge of the extrapolated profilometry is reached. When similar curves are created for the uppermost source/receiver positions (target positions = 15 or 20), individual features of the curves can be modeled. The variability of the curves can also be reduced by averaging curves from different target positions together for both the model prediction and the data, as shown in Figure 3. Here the results have been averaged over the set of model predictions and scattering strength curves for the five uppermost target positions in Figure 1.
Figure 2: Scattering strength (dB) vs. grazing angle (deg) at target location = 0. The broken (red) curve shows the data and the solid (blue) curve shows the BORIS-SSA model prediction. Given the amount of extrapolated profilometry in this case, there is only agreement in a limited sense.

Figure 3: Scattering strength (dB) vs. grazing angle (deg), averaged over the five uppermost target locations. The broken (red) curve shows the data and the solid (blue) curve shows the BORIS-SSA model prediction. With the averaging and inclusion of more real profilometry, individual features of the scattering curves can be modeled. Note that the x-axis has different limits from those in Figure 2.
Figure 4: Comparison of BORIS-SSA model predictions for target position = 0. The dashed (red) curve is the fourth order small slope prediction, the solid (blue) curve is the second order small slope prediction, and the dotted (black) curve is the second order small slope prediction with the input shear speed reduced from 1117 m/s to 100 m/s.

Given that the errors arising from using extrapolated profilometry will tend to average out when multiple positions are combined, the curves in Figure 3 show substantially improved agreement in comparison with Figure 2, especially at the highest grazing angles where there is a very limited amount of extrapolated profilometry.

In Figure 4, a set of BORIS-SSA model predictions for target position = 0 is shown. The fourth order small slope prediction is shown to be significantly higher than the second order small slope prediction at lower grazing angles, and this elevated level was shown to be necessary to model data in this grazing angle range. To assess the influence of the shear speed on backscatter, a model run with low shear speed (100 m/s instead of the measured 1117 m/s) was run. This “non shear” run produced similar levels overall, with the exception of some large dips in the curve (e.g. at 43 and 46 degrees grazing angle).

4 Discussion

The type of tank experiment described in this paper represents a practical way of verifying the predictions of scattering models, especially those relating to the dependence on roughness parameters. The geoacoustic parameters of a material such as PVC can be measured to a high degree of accuracy that nearly fixes their values and allows other phenomena to be examined in a controlled experiment. In the GPM RSS2 experiment, the variability of the physical model made a deterministic scattering model such as BORIS-SSA desirable. Given actual profilometry, we see that BORIS-SSA is capable of modeling the individual features on the scattering curves. In future experiments we plan to use both the BORIS-SSA and NRL small slope models: the former having the giving
information on the statistical behavior of the scattering for a limited number of realizations, and the latter allowing a rapid ensemble-average solution for physical models with power-law roughness. With the tools provided by the two models, we will be able to obtain a thorough characterization of the effect of roughness on acoustic backscatter. Experiments including forward scattering geometries and lower grazing angles are planned for 2005 and 2006.

Acknowledgements
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References


USE OF SCALED MODELS TO STUDY HIGH FREQUENCY SEA FLOOR BACKSCATTERING.

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In the last decades, many experiments on acoustical backscattering by the sea floor have been conducted in real environments and a lot of data have been recorded in many different conditions. If most of these data have been successfully processed and compared to theory, several unanswered questions remain. In this paper we present different experiments which can be performed in a water tank in order to help in the understanding of sound scattering by real sea bottoms. As an example we will show how volume and surface backscattering can be studied in a water tank. Finally, it will be given some indications on the influence of an external applied pressure on sediments cohesion.

1 Introduction

During the last twenty years a lot of experiments on acoustical bottom backscattering have been performed at sea and the results compared to theoretical models [1,2,3,4]. If in many cases a good agreement was observed, in some other cases experimental data could not be completely explained by these models. Indeed, real sea environments are in general very complex ones and most of usual theoretical models cannot completely describe this complexity; moreover, in a real sea experiment all the parameters cannot be controlled during the measurements and it is sometimes difficult to conclude to the agreement or not between theory and experiment. To solve this problem one solution could be to resort to tank experiment in order to work not only with perfectly controlled conditions but also with gradually more and more complex conditions [6]. In the following we will give few examples of what can be done in a water tank in order to understand the influence of both volume heterogeneities and surface roughness on the backscattered field and also the relation between sediment consolidation and measured physical parameters.

2 Volume Backscattering.

The objective was to study sound scattering by elastic particles inside a fluid absorbing medium simulating a sandy bottom with inclusions. In order to determine the influence of these particles on both the reflected and backscattered field, a tank experiment was performed in the Laboratory. Three plates (30cm x 30cm x 5.2cm) made of silicone in which spherical glass beads have been embedded were designed. Different concentrations (10% and 30%) and different sizes (φ=1mm and φ=3 mm) of beads were studied. During the manufacturing process, these
beads were embedded in the silicone, in such a way to obtain a homogeneous distribution inside the volume. We give in table 1 the properties of the 3 different plates.

Table I. Physical parameters of the different plates.

<table>
<thead>
<tr>
<th>Beads density (volume fraction)</th>
<th>Beads diameter (mm)</th>
<th>Density (kg/m³)</th>
<th>Mass (g)</th>
<th>Volume (m³)</th>
<th>Thickness of the plate (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plate 1 10%</td>
<td>1mm</td>
<td>1372.0</td>
<td>6613.5</td>
<td>4.81 10⁻³</td>
<td>51.4</td>
</tr>
<tr>
<td>Plate 2 30%</td>
<td>1mm</td>
<td>1535.2</td>
<td>7602.5</td>
<td>4.95 10⁻³</td>
<td>52.4</td>
</tr>
<tr>
<td>Plate 3 8.5%</td>
<td>3mm</td>
<td>1356.9</td>
<td>6685.5</td>
<td>4.93 10⁻³</td>
<td>52.3</td>
</tr>
<tr>
<td>Plate 4 No beads</td>
<td>----</td>
<td>1251.2</td>
<td>6085.5</td>
<td>4.86 10⁻³</td>
<td>51.9</td>
</tr>
</tbody>
</table>

2.1 Backscattering measurements.

We measured backscattered signals in the angular domain [-80°, 80°]. The mechanical system for transducer displacement was driven in such a way that the sensor was always looking at the same spot on the plate. In this experiment we used Panametrix transducers whose central frequency was 1 MHz. The angular aperture of the beam was: 2θ = 2.5°. Before doing any measurement the system was calibrated at the air-water interface (perfect reflection). Figure 1 gives the backscattered level for the reference plate (no beads). The backscattered level is maximum at normal incidence (-20 dB). For oblique incidence this level goes down to -80 dB at 50°. Four different points have been selected on the plate in order to make spatial averaging. Moreover, it must be noticed that curves have been corrected by an angular factor taking into account the insonified area. In the case of a cylindrical beam, this factor is cos (θ), θ being the incident angle.

Figure 1. Reverberation index for plate n°4 (reference).
Figures 2 and 3 give the backscattered level for plates 1 and 2 (particles of diameter 1mm). For these 2 plates only the concentration in volume was different (10% for plate 1 and 30% for plate 2). As before, 4 points on the plates were selected in order to make spatial averaging. This number is probably too low, but the time duration for one acquisition was approximately 2h and the total duration for more points would have been too long.

Observation of fig 2 and 3 shows that at normal incidence, the backscattered level is not very different from the level obtained with the reference plate. For other angles of incidence there is an increase of the level of about 20 dB. For a given size of beads, it seems that this behaviour does not depend very much on bead concentration.
2.2 Reflection measurements

For a better understanding of scattering by inhomogeneous media we also have studied reflection coefficient as a function of incident angle. We used effective medium theory [7, 8] to compute the equivalent parameters of the inhomogeneous medium and from this we could get the reflection coefficient of the plates. In order to compare theoretical results to real data, we performed reflection measurements between 5 and 75°. We give in table 2 the density and p wave velocity obtained with Waterman-Truell approach.

Table 2. Density and p-wave velocity obtained using Waterman-Truell’s theory

<table>
<thead>
<tr>
<th>P-wave velocity (m/s)</th>
<th>Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plate 1</td>
<td>1000</td>
</tr>
<tr>
<td>Plate 2</td>
<td>975</td>
</tr>
<tr>
<td>Plate 3</td>
<td>1010</td>
</tr>
<tr>
<td>Plate 1</td>
<td>1380</td>
</tr>
<tr>
<td>Plate 2</td>
<td>1630</td>
</tr>
<tr>
<td>Plate 3</td>
<td>1350</td>
</tr>
</tbody>
</table>

Density and sound speed were calculated using the following relations:

\[
\frac{1}{1 - \rho} = \phi + \frac{1 + \rho}{2} + \phi \rho_2 + \frac{1 + \rho}{2} + \rho_1 + \frac{1 + \rho}{2} + \rho_1
\]

\[
\frac{k}{k_1} = (1 + \frac{2\pi f(\theta)}{k_1})^2 - (\frac{2\pi f(\pi)}{k_1})^2
\]

In these relations, \( f(0) \) and \( f(\pi) \) are respectively the forward and backscattering form function of a sphere.

Measured reflection coefficients for the different plates are given on figure 4. Except for plate 2 there is quite no influence of volume heterogeneities on the reflection coefficient. This result can be confirmed by applying Waterman-Truell effective medium theory. This means that it would be probably very difficult to inverse the reflection coefficient in order to recover bottom characteristics (actually, different sorts of heterogeneities in the bottom give rise to the same reflection coefficient).

Fig 4 Reflection coefficient of the different plates: experimental data.
2.3 Discussion.

In the case where the matrix is a weak reflector (low impedance contrast with water), beads inclusions create a strong backscattering effect. This effect which is not very important at normal incidence can only be observed for oblique incidence. For the concentration of beads used in this experiment (10% and 30%), this backscattering effect was independent of beads density.

3 Backscattering by a rough bottom.

For this experiment we designed a thick plate made of RTV 585 (Room Temperature Vulcanizing) whose upper face was made rough during manufacturing. Because surface roughness was small enough, laser techniques could be used to measure the statistics of the surface. From these measurements, histogram of heights and 2D correlation function were obtained. It was verified that the roughness of the surface was isotropic and that the distribution of heights was Gaussian (mean size: 0.17mm, $\sigma$=0.06 mm); the correlation length was: 0.6mm. Moreover, the physical properties of the material (p-wave velocity, density, attenuation…) were measured in the laboratory. Because no shear wave was detected we concluded that the behaviour of this medium could be approximated by that of an absorbing fluid.

We give in figure 5 the backscattered level for the flat surface (no roughness) and on fig 6 the backscattered level for the rough surface. Measurements were performed at 500 kHz for incident angles ranging from 0° to 70°. As before, the system was calibrated at the air-water interface. For this frequency, roughness was very small compared to the wavelength and theoretical computations [9] were validated using these data and both the statistical and geophysical parameters measured for the plate.

![Fig 5. Backscattered level for flat bottom](image1)

![Fig 6. Backscattered level for rough plate](image2)

If this kind of experiment is very easy to perform in water tanks, the interest seems to be very limited except if it is used as a starting point to study more complex media. For example, the plate could be constructed with the same surface roughness but with a known distribution of elastic beads in order to check complex models taking into account both surface and volume reverberation.

Another example which has been studied in the Laboratory is the case of a very complex bottom made of an aggregate of gravels of different size covered by a fine layer...
effect of pressure on sediment parameters.

In this part, the objective was to find a relation between consolidation of sediment and geoacoustic parameters. Moreover, the aim of this work was to determine which of these parameters are most sensitive to consolidation. In our study we used a power press (axial loading) and measured the p-wave and s-wave sound speed as a function of applied pressure on sediment. In some cases, before applying the loading we used an electrical system vibrating at 50 Hz to shake the sediment and rearrange the grains. The horizontal movements transmitted to the sample made the sediment settle. Then we used a hydraulic press to apply a loading to the sample. The variations of both the sample thickness and the volume were available at any time. Table 3 gives the characteristics of the different samples of sand and the experimental conditions used during the tests.

Table 3. Experimental conditions.

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Shaking Duration</th>
<th>Thickness (cm)</th>
<th>Frequency (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>no Shaking</td>
<td>6.7 cm</td>
<td>250</td>
</tr>
<tr>
<td>4</td>
<td>30 seconds</td>
<td>3.9 cm</td>
<td>250</td>
</tr>
<tr>
<td>5</td>
<td>60 seconds</td>
<td>8.5 cm</td>
<td>100</td>
</tr>
<tr>
<td>6</td>
<td>30 seconds</td>
<td>3.8 cm</td>
<td>100</td>
</tr>
</tbody>
</table>

4.1 Experiment description

For most of the experiments discussed in this paper we used a calibrated fine sand (mean size: 200μm), but we also did a test with a marine sand with a large distribution of size grains (30 to 400 μm). The cell used to confine the sediment is described in fig 9.
A piston D1 was used to apply the loading to the sample. We used a PVC cap for the transducers in order to protect them. Two different frequencies (250 kHz and 100 kHz) were used. Our s-wave transducers could be used for both s-wave and p-wave excitation because we observed that P waves were automatically generated into the samples. After each loading, transmitted acoustical signals were recorded and time of flight measured. Velocities were calculated because at the same time we could measure the displacement of the piston and then the acoustical path in the sample.

Fig 9. Description of the cell for P-wave and S-wave velocity measurements.

For shear wave attenuation measurements, we used the same system, with two cells (8.5 cm for the first one and 4 cm for the second one). From the comparison of received amplitude in the cell1 and in the cell2 we could measure attenuation as a function of applied pressure. Results are given in figure 10 for s-wave velocity as a function of applied loading and fig 11 for attenuation.

Fig 10. Shear wave velocity in the calibrated sand as a function of the applied loading. (All the tests were done with calibrated fine sand, except test 10 which was done with marine sediment)

As a first conclusion, we could observe that s-wave sound speed increase with the applied loading. Moreover, the increase of shear wave sound speed depends strongly on the nature of the sediment (grain size has probably a major effect). It seems also that if the sediment has been shaken before applying the loading, the increase of sound speed is higher.
Fig 11. Attenuation as a function of applied loading (samples 5 and 6).

From these tank measurements, it can be concluded that shear wave transmission through sediments gives a good indication of the consolidation of the medium.

5 Conclusion.

Scaled tank experiments are a complementary approach to full scale experiments at sea. One of their main advantages is that they can be used to study separately different physical effects which cannot be separated during sea experiment. Moreover because all the parameters in a tank experiment can be controlled during the test, tank experiments offer an alternative way to check theoretical models. Finally, tank experiments could be used to design future sea surveys and new system of measurements at sea.

References

EXPERIMENTAL EVALUATION OF A MODEL FOR FADING DUE TO IRREGULAR MOVING BOUNDARIES, WITH APPLICATION TO ACOUSTIC COMMUNICATION IN SHALLOW SEA ENVIRONMENTS

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We present a predictive simulator modeling the acoustic Impulse Response (IR) in shallow sea-environments, adapted to underwater acoustic communications. It includes a physical description of scattering from surface waves and seabed irregularities, relying on the so-called "small slope approximation", combined with the JONSWAP model for the spectrum of wind-waves and swells. Extinction by sub-surface bubble clouds and a panel of several sub-models for bottom loss are used. The simulated IR features effects like Doppler effect, time spread as functions of delay after transmission (characterizing frequency-selectivity), fading (random fluctuations as functions of transmission time). Some experiments at sea demonstrate quite a satisfying qualitative and quantitative agreement of the model with observations. As complement to earlier experiments held within European MAST projects PROSIM and SWAN, the pertinence and validity of the simulator are tried against experimental data collected during a recent campaign organized by Thales-Safare (October 2004), testing communication with a moving ship (velocities up to 8 knots), in a shallow water environment (mean bottom depth from 80 to 100 m); transmitted signals involved combinations of BPSK and CW chirps, with frequencies spanning around 6 kHz, with a bandwidth of 2 kHz.

1 Introduction

Over the second half of the past century years, underwater activities involving sonar were dominated by problems like sonar detection of target-echo in deep waters, and required only rough models of sea-surface and bottom scattering. The detailed structure of distorted transmitted signals could be largely ignored, and global empirical reflection coefficients, simultaneously accounting for the mean specular part and the mean energy of the random part of the total acoustic field; the final deliveries from such modeling were loosely defined "mean levels", probably sufficient as input data for the Sonar equation in deep waters. Recent underwater activities massively turned to shallow waters,
where many interactions of transmitted signal with the moving rough sea surface and seabed necessarily occur. Moreover, applications like communications rely on more complex properties of the acoustic signals, like the detailed spatial correlation of wavefronts or the knowledge of transmitted waveform. For the factory assessment of the performances of a sonar or communication system, one may need more complex, explicitly stochastic models that model and compute statistical moments of the channel. We have developed such a numerical model, called NARCISSUS-2005 (standing for Nature Aléatoire de la Réflexion d’un Champ Incident sur une Surface Stochastique Uniforme Stationnaire), up-grading an earlier version NARCISSUS-2000 finalized throughout several projects, including the European MAST projects PROSIM and SWAN.

Effects to be numerically simulated are listed below and summarized on the Figure 1:
- Refraction by sound-speed profile and Earth curvature;
- Attenuation excess and sound-speed reduction induced subsurface background population of air micro-bubbles (using M.V.Hall’s model [7]), along with the “ordinary” volume visco-chemical absorption (François & Garrison model);
- ”Intrinsic fading” and spatial decorrelation of sound, due to reflections on the random moving rough sea-surface;
- ”Doppler fading” of sound-pressure arising from roughness and irregularities of seabed and surface, combined with movements of source and/or receiver;
- Doppler effect and more complex distortions due to source and/or receiver movements (horizontal stationary displacements, vertical sinusoidal oscillations);
- Stationary ambient noise (turbulence, shipping, surface, thermal).

Input data reduce to standard meteorological and environmental data (sound speed profile, etc.) Over the frequency band 300.Hz-40.kHz, the model tries to match modern standards of channel description in Herzian communications (standard COST 259). Different outputs are available: simulations of typical IR or transmitted waveforms,
statistical moments and scales corresponding to the existing standards in radio communications: the “Rice factor” (ratio of the energy of the mean coherent part of the response to the mean energy of the random scattered part of the response), the spectral broadening, the delay spread, the shape of the mean and random part of the response (decay as function of delay), etc.

2 Fading in shallow sea sound channels

Marine environments are time-varying acoustic channels, where transmitted pulses feature not only Doppler effect (global stretching or contraction of waveform) and time spread (multi-path as functions of delay after transmission), but also strong fading, i.e. random variability of the IR as a function of transmission time. The same pulse, transmitted at two different times, will result in different received signals, because the sea boundaries change with time: surface waves, bottom irregularities in relative motion if source or receiver is moving. Fading combine “intrinsic fading” due to reflections on stochastic moving sea-surface (like reflection on ionosphere in short-shave communication) and “Doppler fading” arising from roughness and irregularities of seabed and surface, combined with movements of source and/or receiver (similar to scattering from buildings, vegetation, topography in mobile communication).

A typical example of acoustic Impulse Response, collected in a shallow marine environment (October 2004, Thales-Safare experiment) is illustrated by the color mapping of Figure 2: the experimental IR’s level is estimated by filtering received signals with transmitted wave-form (central frequency about 6 kHz, bandwidth 2 kHz), and is displayed as a function of delay (horizontal variable) and transmission time (vertical axis). The IR clearly features delay-spread (individual multi-paths) as a function of delay (horizontal axis); but individual paths also display variations as functions of transmission time (vertical axis); these last fluctuations include not only “simple” variations of intensity, but may also be sudden appearances or disappearances of peaks. First arrivals are quite stable and fluctuate at a time rate similar to the scale of a typical swell (over the order of some 5 to 10 s); later arrivals, that know several bottom and surface interactions, are far more unstable and fluctuate more quickly with increasing delay.

Such random fluctuations as functions of transmission time are what the term “fading” refers to (random variability along transmission time), whereas more classical distortions like Doppler or time spread affect only the signal as function of delay. The IR can not be modeled only as a constant channel, independent on transmission time, but more generally as a function of delay and transmission time independently; moreover, the fading, due to scattering roughness and movements of sea-surface and sea-bed, is intrinsically stochastic and can be predicted only statistically.

3 Theoretical modeling and numerical implementation

We give a brief description of the physical assumptions and computational techniques involved in the model NARCISSUS-2005, in its actual operational form. This code relies on mutually connected or imbedded independent numerical ”tool-boxes”:
Geometrical Propagation Toolbox: after transmission from the source, between interactions with surface or bottom, the mean spectral and directional density of acoustic radiated power ("luminance") is conserved along paths that may be numerically computed, except for exponential decay due to attenuation from water absorption and air-bubbles. Elementary routines of ray acoustics are invoked, evaluating the related parameters (delays, angles, etc., as functions of horizontal range) are used.

Scattering from Boundaries: the acoustic power impinging a random boundary within some incident bundle of ray is split into the sum of two components:

- a coherent part, that behaves classically as if the boundary was flat except for a reflection loss
- a random scattered part, which features a certain directivity pattern, and a certain dispersion in scattered frequency (if the surface is moving).

A "Generalized Scattering Index" accounting for this "directivity" in space and frequency, is a kernel, appearing inside the integral linear relation that gives the second-order moments of the incident field, whereas the mean part (first-order moment of the field) behaves specularly and is fully modeled through a reflection coefficient. A model for the reflection coefficient and the kernel may be derived from the today classical "small-slope approximation" (see e.g. McDaniel [2], or Voronovitch [1], Ch.6, pp.191-194), finally resulting in two elements: an attenuation coefficient for the coherent specular part, and an integral expression for the scattering index (random non-specularly reflected part).

A Monte-Carlo technique is used for combining propagation and scattering (see Cristol [10], for more details about this procedure). Wilson & Tappert ([4]) applied such a procedure, historically introduced in the modeling of beams of particles, to a very similar problem: scattering of sound from random space variations of sound-speed, associated with internal waves in ocean environments. The results from the previous Monte-Carlo process is a collection of several first- and second-order statistical moments of the sound-field (averages, space- and time-correlation functions), both in time-frequency and space-direction spaces.

From the previously tabulated statistical moments, typical realizations of the IR may later be pseudo-randomly drawn, provided further statistical assumptions:

- the IR is assumed a normal process; this may be loosely justified, if considering that the random part of IR, at fixed delay, is the sum of contributions of many independent scattering irregularities. We otherwise checked this assumption experimentally in configurations where the source and receiver where motionless (see Cristol [8] and [9]).

- we assumed the classical "uncorrelated scattering" approximation (see e.g. p.706, in Proakis [7]), which states that the IR, taken at different delays, features uncorrelated random variations.
4 Experiment in an operational communication configuration

Validation of a complex model like NARCISSUS must be performed globally, against experimental data, for two reasons: firstly, the complete problem combines several layers of sub-models for propagation and scattering, each of them complex in itself; secondly, we nowadays know of no numerical model, which could be taken as a reliable reference for the considered complete problem.

We have reported in previous papers ([8], [9], [10]) favorable conclusions concerning the model-to-experiment agreement in experimental configurations, organized within European projects MAST and SWAN, in shallow and very shallow continental shelves. The validation procedures included investigations of several statistical properties of fading: the "Rice factor" (ratio of the energy of the mean coherent part of the response to the mean energy of the random scattered part of the response), the spectral broadening, the delay spread, the normality of the random part of the response, the shapes of the mean and random parts of the IR (peaks and decay as function of delay). Involved signals included FM chirps, pseudo-random sequences and CW pulses, with frequency spanning from 400 Hz to 6.5 kHz. Source-to-receiver ranges ranged from 500 m to 15 km.

In the aforementioned experiments, we took an important care in making the source and receivers as motionless as possible, so that the fading could certainly arise from surface wave alone. A three day experiment was organized by Thales-Safare in October 2004, on the Mediterranean continental shelf, near Toulon (France); this campaign, devoted to the testing of acoustic communication procedures, was an occasion for evaluating the model NARCISSUS in a realistic operational communication configuration, with a receiver moored from a moving ship (velocities up to 8 knots), in a shallow water environment (sandy bottom, with a depth from 80 to 100 m); transmitted signals involved combinations of BPSK and CW pulses, with frequencies spanning around 6 kHz, with a bandwidth of 2 kHz, transmitted at a rate of 8 per seconds, under strong sea conditions (sea state 4). Source-to-receiver range spanned from 500 m up to 10 km. Several CTD were launched, and gave profiles of temperature and salinity, featuring typical bottom-refracting summer sound-speed profiles.

The question to be answered when investigating the data was: is the numerical model able to reproduce "naturally" the main features of observed IR's, when introducing minimal environmental descriptive input data? This is a bit different from the investigations with the MAST and SWAN experiments, where the environmental and instrumental geometry were far more accurately controlled. The color map of Figure 2 displays a typical output from processed data from a sequence of this experiment, resulting in estimated IR as functions of delay and transmission time; the short-term distortions of the IR as a function of transmission time (vertical axis) are clearly visible. Playing the model directly gives simulations and statistical moments that are apparently very similar to observed orders of magnitude and shape. For instance, the decay rate of intensity (as function of delay) and the distribution of main peaks are very well reproduced (plot b) of Figure 2), close to observed IR (plot c) of Figure 2). The less classical plot at the bottom of the plate of Figure 2, gives correlation scales (along transmission time) for the fading, which appear as a dominant phenomenon.
The model makes possible to investigate the relative parts of loss due to air-bubbles and to roughness scattering in the resulting IR. As displayed on the upper plot of Figure 3, the pure loss from air-bubbles is not enough for simply explaining the observed decay rate, which can be fully understood only as a consequence of scattering from surface irregularities, and can be modeled only statistically.

Figure 2. Experimental estimation of IR as function of delay and transmission time (See caption of Figure 3 for details about the experimental configuration)
5 Conclusion

The fading due to scattering from the moving rough sea-surface and from the sea-bed in relative motion relatively to the source or receiver results in distortions and instabilities of the Impulse Response as a function of transmission-time, fully independently from delay spread (multi-path) and Doppler stretching, which affect the IR along time-delay as a second independent time-variable. Fading has two classes of practical consequences:

- **scintillations**, i.e. fluctuations of the received signals for successive transmissions of a same waveform, at different times;
- **distortions** of the received waveform, if the pulse length is longer compared with time scale over which the IR is stable; this will induce degradations in the properties of outputs from processing relying on knowledge of waveform.
Both types of effects require simulations or modeling of fading effects for factory or laboratory evaluation of system performance in the fields of sonar and communications, when the detailed shape of received waveform is exploited in the processing. The experiment presented in this paper clearly shows that, for operational applications like acoustic communications, the modeling of fading is not only useful, but also necessary for realistic simulations. Our model demonstrates that such realistic simulations are feasible.

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Section 4
Mapping
SINGLE BEAM SEABED CLASSIFICATION: DIRECT METHODS OF CLASSIFICATION AND THE PROBLEM OF SLOPE

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Generally, there are three categories of single beam acoustic seabed classification methods: acoustic impedance measurements, statistical segmentation of echo types and inversion of acoustic field data. The most commercially successful method is segmentation because of cost and robustness to different echosounder systems and seabed types. The disadvantage of segmentation compared to the other two categories is it requires extensive ground-truthing. The aim of our research is to create a method that has the advantages of segmentation without the need for ground-truthing. A possible way of accomplishing this is to relate features of echo time series to seabed properties. The first stage in this process is to overcome the two major non-seabed influences on echo time series data: depth and slope. In this paper an echo ray-trace model will be presented. It relates echo duration to depth, slope and seabed properties. It is useful for understanding the effect of slope on various aspects. Slope is the major cause of error in seabed classification and causes significant errors in echosounder bathymetry. Work on verifying the model with both field and simulated data is on-going. Analysis of field data from the North Coast of British Columbia will be presented in this paper.

1 Introduction

Research into using normal incidence echosounders for seabed classification has been ongoing for more than twenty years. Recently, research has been active in three categories: calibrated acoustic impedance measurements, inversion by forward modeling and segmentation by statistical or neural networks methods. Our research in this field is in developing a new category which can be described as directly relating echo features to geoacoustic properties. The methods we are working on use the same data that segmentation classification systems use. No calibration is needed as the features are based on time not absolute amplitude. The major advantage over the commercially successful statistical segmentation methods is elimination of the need for ground-truthing by grab-sample or video imagery. Seabed classification data from single-beam echosounders could then be combined with multi-beam data for more complete coverage, with the single-beam data acting as ‘acoustic ground-truthing’ for multi-beam classification. A recent paper has shown the benefits of combining multi-beam and side-
scan image analysis with seabed classification by segmentation of single-beam data [1]. Our research will clearly improve upon that approach.

The first stage in developing seabed classification methods for single-beam echosounders is to overcome the major non-seabed influences on the echoes, namely depth and slope. It is well known that echo time series scale linearly with depth. Compensation for depth by the reference depth approach [2] or by the standard echo length approach [3] is successful. However, no methods exist to correct single-beam echosounder data for angle of incidence, which is a function of transducer tilt and seabed slope.

The detrimental effect of seabed slope on echosounder seabed classification and bathymetry is known but has not been addressed in the literature. Many users of the QTCView™ system reported classification errors in areas of high seabed slope. Some astute users have observed different seabed classes depending on the direction of travel relative to slopes. This is due to subtle transducer tilt (due to the lay of the survey vessel underway) interacting with seabed slope [4]. In areas of significant slope, the QTCView™ system tends to classify by degree of slope instead of seabed type. This was also found by von Szalay and McConnaughey [5]. As will be shown in this paper, bathymetry measured by systems with effective beamwidths greater than 1-2 degrees is a function of slope.

The purpose of this paper is to introduce a ray-trace model useful to understand the effect of slope and to compensate bathymetry for slope. Although compensation of echo time series for slope is not possible, our new methods of direct seabed classification take slope into account via the echo ray-trace model. Since the new methods of direct seabed classification are at an early stage of research, they will not be presented. However, the first stage of this research, the verification of the echo ray-trace model, will be presented in this paper.

2 Echo Ray-trace Model

The following ray-trace model exists in various forms in many contexts. In this derivation it assumes a normal incidence echosounder interacting with a sloped seabed. It is a simplified version of the model by Preston used for depth compensation by standard echo length [3]. There are two cases based on when the specular reflection ray is inside the beam (case I) or when the ray is outside the beam (case II). Figure 1 shows the former, case I. The outside beam case, case II, is occurs for slopes greater than one-half the beamwidth and up to slopes at which the downslope ray (s) of the beam goes parallel to the seabed. Case I includes the normal incidence situation where there is no slope. Without slope, the expression for footprint diameter: \( 2d \tan(\theta/2) \) is accurate (where \( d \) is the distance to the seabed as measured by the echosounder and \( \theta \) is the beamwidth). Equations 1a and 2a for echo duration are derived for case I and II respectively. From figure 1, it is clear echo duration is the sum of pulse duration and travel time due to curvature, penetration and roughness. In this description, \( E_d \) is echo duration, \( P_L \) is the pulse length and. In the curvature term, \( \phi \) is the seabed slope and \( v_w \) is the sound speed in water. In the penetration and roughness term, \( P_D \) is the penetration depth, \( R_H \) is roughness height and \( v_s \) is the sound speed in sediment. Equations 1b and 2b are the expressions for the true or vertical depth \( D \), represented as the dashed line in figure 1.
The echo ray-trace makes several approximations of the real situation. First, slope is measured over distances longer than the acoustic footprint. Smaller-scale variation is approximated as roughness, which can be neglected in many cases with good bottom picking. The most constraining approximation is of a purely conical beam with equal sound intensity throughout and zero intensity outside the beam (as opposed to the true beampattern). A consequence of this approximation is penetration is equal across the footprint, even out to the edges where, physically, it must be less. Penetration depth approximated by the depth at which incident sound is attenuated by a fixed amount, generally 10 dB [6]. Determining the appropriate beamwidth which best corresponds to the conical approximation is another issue. The advantage of this approach is it allows us to readily calculate echo duration and true depth.

### 3 Verification of the Echo Ray-trace Model

There are two ways to verify the model. Field data can be used to compare measured echo duration to echo duration predicted by equations 1a and 2a. Simulated echo time series data by a model such as BORIS [7,8,9] can be used in a similar fashion or can be used to test the approximations of the echo ray-trace model directly. Pouliquen successfully used BORIS to test depth compensation by reference depth [2]. Work with BORIS is in its early stages at the time of this publication.
Figure 2 shows the comparison of measured versus calculated echo duration for field data from a survey of Eagle Bay on the North Coast of British Columbia, Canada. Eagle Bay is a small glacially-formed inlet with a high degree of slope (8° on average, with a maximum of 60°). Seabed classification of this bay correlates highly with slope and not with seabed type. The survey system was comprised of an Odom Hydrographic Systems 24 kHz echosounder with a -3 dB beamwidth of 20° (28° at -6 dB) and a QTCView™ series 5 acquisition system sampling at 0.5-1 MHz. Positioning obtained by a differential global positioning system was accurate to ±1 m. The survey line spacing was 50 m. Measured echo duration is the average from 5 echoes. Bottom and tail picking was done post-survey with a robust threshold technique. The overall $r^2$ correlation co-efficient between the measured and calculated echo duration is 0.70. Low correlation generally occurred in specific regions of Eagle Bay which have more gravel in the sediment than the overall seabed type which was found (by video and grab-sample) to be muddy sand (mS). Calculated echo duration was based on mS only. Although ground-truthing is limited, performance could be improved by including seabed type variation. Other sources of error include the accuracy of slope data as determined from bathymetry measured during the survey, ping-to-ping variability and picking errors.

![Figure 2. Measured and calculated echo duration for 1832 groups of 5 echoes throughout Eagle Bay, British Columbia. The error bounds are the standard deviation of each group.](image)

The beamwidth used for calculation of echo duration is known as the effective beamwidth. It is determined, by equations 1a and 2a, from the observed linear scaling of echo duration with depth over the entire survey. The effective beamwidth found to be 24.0 degrees.

### 4 Discussion

Preliminary work on verifying the echo ray-trace model shows the model to be accurate. Considering all of the sources of error, including assumptions and approximations, the model performs well and the errors are manageable. The model certainly represents the behavior of echoes in relation to slope and depth.

The effect of slope, like depth, is to increase echo duration. As shown in figure 3, the effect is approximately ten times that of depth. Using the echo ray-trace model, the maximum change in echo duration due to seabed type is about 4 times for most systems.
An approximately equal change in echo duration due to slope occurs at slopes equal to or slightly less than the beamwidth. Then, slopes greater then the beamwidth dominant the echo signal over seabed influences. However, significant change in echo character is observable with much less slope. At slopes equal to one-half beamwidth, the changeover criteria from case I to II, the specular reflection is lost. Interface scattering greatly diminishes with increasing incident angle and volume scattering becomes dominate at slopes of one-half to two beamwidths [6]. Von Szalay and McConnaughey observed classification accuracy breakdown at slopes of 5-8°, which is slightly less than the half beamwidth of their system [5]. Without compensation for slope, single-beam echosounder seabed classification is not possible for slopes greater than one-half beamwidth.

The effect of slope on the accuracy of bathymetry is also significant. Using equations 1b and 2b one can show that for slopes of 20° the vertical depth is 6.4%, 1.2% and 0.46% greater then the measured depth for beamwidths of 20°, 10° and 1.5° respectively. Fortunately, this correction can be applied to any data for which slopes can be calculated accurately. We made use of an iterative correction scheme in the Eagle Bay data. It is iterative since slope is calculated from corrected bathymetry. It takes 3-5 five iterations of slope and depth calculations for the bathymetry to converge.

Figure 3. Echo duration as functions of depth (right) and slope (left). Note the scale of the slope plot; it is ten times that of the depth plot to illustrate the approximately ten-fold influence of slope on echo duration over depth. Both plots are based on a muddy sand seabed and a pulse length of 0.3 ms. The depth plot has no slope while the slope plot is based on a depth of 100m.

5 Conclusion

Our work in this area of research is on-going with the use of the BORIS model. Preliminary results in testing the conical beam approximation show echo duration is the same between the effective beamwidth conical beam and the full beam pattern. The nature of the echo is changed, but the results show the accuracy of the echo ray-trace model for predicting echo duration and the influence of depth and slope on echoes. Work on the new classification methods will surely benefit from testing with BORIS as well.
Acknowledgements
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INVERSION OF GEO-ACOUSTIC PROPERTIES FROM HIGH FREQUENCY MULTIBEAM DATA.

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An algorithm for the determination of geo-acoustic properties critical to high frequency sonar performance is presented together with encouraging preliminary results. This study is motivated by the fact that geo-acoustic properties like impedance and roughness strongly influence seafloor reverberation, which in turn hinders object detection. Geo-acoustic inversion is performed using multibeam bathymetric sonar data that associate backscattering strength information with bathymetric data. This allows the segmentation of the seafloor into areas of similar homogenous geo-acoustic properties. We show here that processing multibeam data can provide a map of the seabed in terms of key seafloor geo-acoustic parameters such as impedance and roughness. The segmentation map is obtained using the SESAM algorithm while the estimation of seafloor properties and reverberation is obtained from BORIS-SSA simulations. Such detailed geo-acoustic maps may allow the prediction of seafloor reverberation for a different measurement setup in terms of frequency, geometry and footprint and subsequently provide performance prediction of detection sonars over the area of interest.

1 Introduction

The primary use of multibeam systems is measurement of bathymetry. Various systems operating at frequencies from 10kHz to 500kHz are available. The area coverage and bathymetric accuracy achieved depend on the system properties. The lowest frequency systems allow coverage of the order of tens of square miles/day with a vertical bathymetry assessment of a few tens of centimeters while the very high frequency systems provide a reduced area coverage but centimetric bathymetric accuracy. In addition to bathymetry measurement, the current generation of multibeam systems provides information on “reflectivity” from the seafloor patch impinged by each beam. This information, corrected for transmission loss and footprint size, has been the object of fruitful studies during the last decade [1,2,4,5,9,10]. Most effort has been directed at the automatic identification of areas having similar acoustic properties in order to provide a segmentation map. This map would be subsequently validated with the help of ground truth measurement (from cores, grabs, videos, etc.) The criteria for evaluating the degree of similarity between various patches of the seafloor are based on the shape and/or level of the angular response (AR) of the seafloor reflectivity collected at each ping (Fig. 3). The AR is rich in information as it depends on the intrinsic geological/biological nature and upper morphology of the seabed such as water/sediment interface roughness and the sediment volume structure. In parallel to the development of segmentation techniques from multibeam data, much work has been conducted in the
field of geo-acoustic inversion using various sensors such as vertical/horizontal arrays [8], normal incidence parametric sources [3], normal incidence echosounders [12], sub-bottom profilers etc. These inversion algorithms are usually model-based as they consist of establishing a best match between signals acquired at-sea and the output of a model that mimics the measurement setup. The geo-acoustic parameters used as input to the model are considered to be the most likely properties of the seafloor. A similar model-based approach has not yet been thoroughly applied to very high frequency multibeam data. The reasons for this are numerous: a) the calibration of multibeam data and the computation of backscattering strengths from each beam is difficult, b) in-situ ground-truth is also difficult as it requires the quantification of the 2D properties of the interface roughness and a good estimate of the upper sediment density, sound speed and structure, and c) the use of a model such as BORIS-SSA [6,7,11] capable of predicting backscattering strength at very high frequency for complex seafloors (e.g. with anisotropic interfaces, upper cm gradients, 3D volume heterogeneities) and for geometries encountered by multibeam systems was not available until recently. This study introduces a simple geo-acoustic inversion scheme to be applied on multibeam data. It uses BORIS-SSA for predicting AR in terms of backscattering strength. Data acquired on a rippled sandy seabed using a 300 kHz system are used for inversion following a segmentation procedure performed by SESAM [4,5].

2 Data processing

As a first attempt to invert geo-acoustic properties using multibeam data, the test site of Biodola Bay (Island of Elba, IT) was chosen. This site is often used by NURC scientists to conduct environmental acoustic experiments and is well-characterized. A survey using the EM3000 multibeam system was carried out in 2000 during a bistatic scattering experiment [6]. The EM3000 operates at 300 kHz and collects bathymetry and reflectivity from its 120 beams (1.5°x1.5°) spanning from normal incidence up to 60-70 degree incidence on both port and starboard. Fig. 1 shows a geo-referenced projection of the computed backscattering strength from each beam along a track at the Bay of Biodola over an area of medium sand and a few patches of sea grass (Posidonia Oceanica). On the medium sand, a stereo-photo shows the presence of a slightly anisotropic interface (Fig. 1) having a RMS height of 2 cm over the field of view of the stereo camera. The compressional sound speed and density were found to be 1720 m/s and 1.920 kg/m³, respectively. The NURC SESAM algorithm is applied to the multibeam data to provide a segmented map of the surveyed area. Using statistics, SESAM processes and classifies each measured BS value associated to a beam, and therefore to a local slope on the seabed, with the help of typical ARs (pre-selected by the operator). A spatial filtering step produces an outlier-free map of Biodola Bay as shown in Fig. 2. For each segmented area, the goal is to characterize the geo-acoustic properties such as impedance contrast and roughness properties. An attempt of model-based inversion using BORIS-SSA is made for the area marked by a rectangle in Fig. 1. The selected rectangle has a mean angular response (AR) displayed in Fig 3. This AR exhibits a slow decay as the incident angle increases which is typical for slightly rough sands at very high frequencies.
Figure 1. The top image is an example of the BS dataset from Biodola Bay after local-slope correction before computation of the AR data and subsequent segmentation maps. The rectangular region shows the data used in this paper; patches of *posidonia oceanica* are visible in the BS data (p) and are easily identified by SESAM. The photography is an image of the medium sand present at Biodola Bay.

3 Models description and Inversion Scheme

3.1 Boris-SSA

BORIS-SSA [6,7,11] is a model able to generate the acoustic signal received for a deterministic seabed (*e.g.* rough interface and heterogeneous volume matrix), detailed sonar properties (*e.g.* beam pattern, pulse shape) and pre-defined experimental setup (*e.g.* nominal incidence, distance from the seafloor, *etc.*) The rough interface contribution is calculated using the small slope approximation (SSA) by performing a coherent summation over the beam footprint of the elementary contribution of the pressure field. Similarly, the heterogeneous volume contribution is obtained by summing the elementary contribution of the volume located under the interface footprint, using the first order small perturbation theory. The deterministic properties of the seafloor (*i.e.* 2D rough interface and 3D substructure) are generated using the Fourier synthesis technique with
inputs of typical seabed properties measured at-sea or estimated, such as, power law spectral densities of the interface roughness.

Figure 2. Segmentation map of Biodola Bay produced by SESAM using five classes of seafloor. The red dot points to the geographical area treated in the inversion example.

Figure 3. AR of Biodola bay (thick line) on medium sand with the 50% confidence spread in dB around it (thin lines); the dots correspond to individual BSs measured for each beam within the selected area; the circles represent the BS values obtained by 10 runs of BORIS-SSA using the most likely geo-acoustic parameters, as a result of the inversion.
3.2 Inversion scheme

The first step as displayed in Fig. 4 consists of determining whether heterogeneous volume scattering is significant or not. In other words, this means determining whether the seabed is hard, soft or covered with highly scattering thick sea grass. This study concentrates on the “hard” seabed scenario, i.e., when the average normal incidence BS (BS\textsubscript{N}) is higher than –30 dB at 300 kHz, thus discarding the possibility of a significant volume contribution and considering only interface scattering. The second step of this scenario uses the AR slope as the criterion for estimating two roughness parameters, namely a combination of Gaussian and power-law spectra. This is done with the help of a lookup table of pre-computed BORIS-SSA ARs for various roughness values, having fixed the impedance to a nominal value. The AR having the closest shape/slope in comparison to the measured AR is selected. Then, the seafloor impedance contrast (Z=\rho_w c_w/\rho_s c_s) is adjusted by minimizing the distance between the measured BS\textsubscript{N} and the ones computed by BORIS-SSA. Since a saturated power-law spectrum \( W(k) = \beta(K^2 + K_L^2)^{\frac{\gamma}{2}} \) did not fit the measured AR of Biodola, a combination of a Gaussian (\( \eta \exp(-\frac{K^2}{4K_L^2}) \)) and a saturated power-law spectrum is used. The RMS values of Gaussian (\sigma_G) and power-law (\sigma_{PL}) fields are tuned with an exhaustive search until the distance between the measured AR and the simulated ones is lower than a given...
threshold $\varepsilon$. The inversion is carried out with a few fixed parameters such as, $K_L = 16.56$ rad/m, $\gamma = 3$, $K_S = 30$ rad/m. The outputs of the inversion scheme for the hard seafloor scenario are the impedance contrast $Z$, $\sigma_G$ and $\sigma_{PL}$. Fig. 3 shows the results of the simulations of BORIS-SSA for 10 different seafloor realisations once the "best-fit" parameters were found ($\sigma_G = 2$ cm and $\sigma_{PL} = 0.15$ cm). Simulations agree well with data in terms of the absolute level and also of spread around the absolute level. Figure 5 shows a corresponding comparison in the time domain between the measured and modeled envelopes at three different angles of incidence. These measured time series are obtained after beam forming the band-pass filtered signals recorded from each stave of the EM3000 antenna. The simulated time series are noise-free, unfiltered, amplified using the correct time variable gain and produced taking into account the $\pm 4$ degree aperture of the transmit/receive beam pattern of the EM3000. The geometrical setup of the simulation is equivalent to the one of the ELBA2000 survey at Biodola Bay. The shape and level of the time series are in good agreement, considering the deterministic nature of the measured and modeled signals.

4 Conclusion

The objective of this study is to propose an inversion scheme using reflectivity data from multibeam systems. The proposed approach is model-based and offers at the initial stage three inversion scenarios depending on the first guess on the impedance contrast of the seabed. The scenario suitable for “harder” seafloors is illustrated in this paper from data acquired on medium sand using the EM3000 multibeam system. The optimization of the model input parameters converges to inverted geo-acoustic parameters close to those measured in situ, such as the impedance contrast and RMS roughness using gravity cores and stereo-photography, respectively. The model used as a basis for the inversion is BORIS-SSA as it is able to handle seafloor interface anisotropy, specific beam patterns and measurement geometries and produces the actual deterministic time series which can be directly compared to signals acquired by multibeam systems at very high frequencies. Other models or pre-computed lookup tables valid at those frequencies could be employed. In the near future, it is intended to test the three inversion schemes on many different seafloors ranging from clays (with a significant volume scattering content) to rock and dense sea grass.

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Figure 5. A comparison, at different angles, between three snapshots of measured and simulated data. Measured data are affected by noise and are band-pass filtered. Simulation results are obtained using ±4 degree of transmitting and receiving beam pattern (to reduce simulation runtime).

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SEAFLOOR CHARACTERIZATION THROUGH THE APPLICATION OF AVO ANALYSIS TO MULTIBEAM SONAR DATA

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In the seismic reflection method, it is well known that seismic amplitude varies with the offset between the seismic source and detector and that this variation is a key to the direct determination of lithology and pore fluid content of subsurface strata. Based on this fundamental property, amplitude-versus-offset (AVO) analysis has been used successfully in the oil industry for the exploration and characterization of subsurface reservoirs. Multibeam sonars acquire acoustic backscatter over a wide range of incidence angles and the variation of the backscatter with the angle of incidence is an intrinsic property of the seafloor. Building on this analogy, we have adapted an AVO-like approach for the analysis of acoustic backscatter from multibeam sonar data. The analysis starts with the beam-by-beam time-series of acoustic backscatter provided by the multibeam sonar and then corrects the backscatter for seafloor slope (i.e. true incidence angle), time varying and angle varying gains, and area of insonification. Once the geometric and radiometric corrections are made, a series of “AVO attributes” (e.g. near, far, slope, gradient, fluid factor, product, etc.) are calculated from the stacking of consecutive time series over a spatial scale that approximates half of the swath width (both along track and across track).

Based on these calculated AVO attributes and the inversion of a modified Williams, K. L. (2001) acoustic backscatter model, we estimate the acoustic impedance, the roughness, and consequently the grain size of the insonified area on the seafloor. The inversion process is facilitated through the use of a simple, interactive graphical interface. In the process of this inversion, the relative behavior of the model parameters is constrained by established inter-property relationships. The approach has been tested using a 300 kHz Simrad EM3000 multibeam sonar in Little Bay, N.H., an area that we can easily access for ground-truth studies. AVO-derived impedance estimates are compared to in situ measurements of sound speed and AVO-derived grain-size estimates are compared to the direct measurement of grain size on grab samples. Both show a very good correlation indicating the potential of this approach for robust seafloor characterization.
Seafloor Characterization

Remote seafloor characterization by means of acoustic methods has practical applications in a broad range of disciplines, not only in traditional marine geological, geotechnical and hydrographic research but also in biological, environmental and fisheries studies (Hughes-Clarke et al., 1996). Examples of important seafloor acoustical and physical properties to be estimated are the gain size, the acoustic impedance (density x sound speed), acoustic attenuation and the roughness of the near-surface sediments. Unfortunately, these properties are not normally measured directly by remote sensing methods. We have to rely on the indirect measurements (the observations), and estimate the values of the seafloor properties (the observables), by means of a theoretical or empirical models.

The remote indirect observations of interest are the acoustic backscatter signals acquired by multibeam and sidescan sonars. These observations carry important information about the seafloor morphology and physical properties, providing valuable data to aid the difficult task of seafloor characterization. Once we establish a formal mathematical model that links the observables to the observations, we can attempt to invert the model and estimate the seafloor properties based on the remotely acquired acoustic backscatter.

Observations: Acoustic Backscatter

The acquisition of more reliable observations is the first requirement of any practical remote seafloor characterization method based on model inversion. Since the primary observation of an acoustic remote sensing method is the acoustic backscatter, it is necessary to radiometrically correct the backscatter intensities registered by these sonars, and to geometrically correct and position each acoustic sample in a projected coordinate system (Fonseca and Calder 2005). The processing sequence starts with the original acquisition data, so that all the logged parameters will be considered for the radiometric corrections. Each raw backscatter sample is corrected by removing the variable acquisition gains, power levels and pulse widths, according to the manufacture’s specifications. Additionally, a residual beam pattern correction is removed on a ping by ping basis.

If the detailed bathymetry is known, the effective incident angle is calculated from the scalar product of the beam vector (form the transducer to the footprint) and the normal to the bathymetric surface at the boresight of the footprint. As the backscatter strength is calculated per unit of area and per unit of solid angle, the actual footprint area of the incident beam should be taken into account for proper radiometric reduction. The effective area of insonification is calculated based on the bathymetric surface, the transmit and receive beamwidths, the pulse length and range to the transducer. The acoustic backscatter signal sampled at the transducer head is subject to stochastic fluctuations that produce a speckle noise in the registered backscatter data. The removal of the speckle noise improves considerably the interpretability of the data, and this aids in the process of seafloor characterization (Fonseca, 1996). The final result of this
processing is the best estimate for the actual backscatter cross-section returning from the seafloor, so that the acoustic backscatter values from different acquisition lines are reduced to a near-calibrated scale of scattering strength, and can be directly compared to a mathematical model.

**High-Frequency Acoustic Backscatter Model**

The next step towards the remote seafloor characterization is the definition of an acoustic backscatter model. This is an essential tool to link seafloor properties to angular signatures measured by multibeam sonars. Usually, high frequency backscatter cross-section models consider two different processes: interface scattering and volume scattering (Ivakin, 1998). The interface scattering occurs at the water-sediment interface, where the seafloor acts as a reflector and scatterer of the incident acoustic energy. A portion of the incident acoustic energy will be transmitted into the seafloor. This transmitted energy will be scattered by heterogeneities in the sediment structure, which are the source of the volume scatter (Novarini and Caruthers, 1998). In this work we used the effective density fluid model derived from the Biot theory (Williams, 2001), with some modifications for the calculation to the volume scattering contribution (Fonseca et al., 2002).

The acoustic backscatter is normally modeled as a complex function of many sediment acoustic and physical properties, but the three main parameters that control the model are the acoustic impedance, the seafloor roughness, and the sediment volume heterogeneities. As a result, the backscatter strength measured by multibeam sonars is not only controlled by the acoustic impedance contrast between the water and the sediment, which is the key for the seafloor characterization, but also responds to the seafloor roughness and to the sediment volume heterogeneities. This ambiguity between roughness, impedance and volume heterogeneities is the main difficulty in the direct determination of seafloor properties based on remotely acquired backscatter. The AVO analysis will address this problem by separating the portions of the acoustic backscatter due to impedance contrast, roughness and volume scatter.

**AVO Analysis – Model Inversion**

In our attempts to invert the backscatter model, it became clear that its direct inversion was an ill-posed problem. In order overcome this limitations, we applied a constrained iterative inversion of the model, imposing constraints based on Hamilton relations for sediment physical properties (Hamilton, 1974), and building parametric equations with the AVO (amplitude-versus-offset) parameters calculated from the backscatter angular response.

AVO analysis is normally applied to multichannel seismic reflection data and has been used successfully in the oil industry for the exploration and characterization of subsurface reservoirs. AVO analysis is based on the fundamental property that the seismic amplitude varies with the offset between the seismic source and detector, which translates to different angles on incidence, and that this variation is due to different
acoustic properties in the subsurface reflectors (Castagna 1993). Multibeam sonars acquire acoustic backscatter over wide range of incidence angles, and the variation of the backscatter with the angle of incidence is an intrinsic property of the seafloor. With appropriate alterations, a similar approach to seismic AVO analysis can be applied to the acoustic backscatter.

The variation of backscatter strength as a function of the grazing angle represents, for a certain frequency, an inherent property of the seafloor (Jackson and Briggs, 1992). Although this angular variation or angular signature reveals subtle differences in the backscatter response of different materials on the seafloor, this information is normally lost during a normal backscatter processing, after an angle varying gain equalization function is applied to the swath data in order to produce a backscatter mosaic. The AVO Analysis tries to rescue this angular signature, by preserving the full backscatter time series during the analysis.

A simple and practical way of preserving some angular information from multibeam data is the use of the partial stacking technique similar to the one used in seismic processing. For that, the near soundings, i.e. the soundings with grazing angle closer to the nadir, will be processed separately from the far soundings, i.e., the sounding with shallow grazing angles. Another technique used to preserve part of the angular signature is to compute the slope and the intercept of the angular response curve. The slope has a good correlation with the seafloor roughness, while the intercept has a good correlation with the impedance, although the actual relationship is complex and is described by the mathematical model for the acoustic backscatter.

The AVO Analysis is applied to a seafloor patch, which is defined as the stack of a certain number of consecutive sonar pings, normally between 20 and 30. Each stacked angular response defines two distinct seafloor patches, one for the port side and another starboard side. The stacking of consecutive pings reduces the speckle noise common to any acoustic method, and is the swath-sonar equivalent of the seismic stacking. After the stacking, the corrected backscatter angular response is divided to thee intervals: near, far and outer ranges.

The near range includes grazing angles from 90° to 65°, the far range form 65° to 35°, and the outer range 35° to 5°. In the near range, the mean backscatter, the slope, and the 80° intercept of the stacked backscatter are calculated and stored as AVO attributes (Figure 1). The near-intercept is calculated at 80° in order to avoid the nadir instability, very common in swath sonars. In the far range, the attributes of mean backscatter, slope and the intercept at 55° are calculated. In the outer range, only the mean backscatter is stored as an attribute, as it has a correlation to the critical angle of reflection defined by the sound-speed ration between the water and the sediment. One important AVO parameter used to characterize the backscatter angular response is the Fluid-Factor. According to the backscatter model, this attribute responds to volume heterogeneities, more specifically the amount of free fluid, normally gas, in the sediment structure (Fonseca et al 2005).
Figure 1 – Stacked backscatter angular response measured by a simrad EM3000 multibeam sonar, with some AVO parameters.

The Fluid-Factor is part of a series of parameters that can be extracted from a slope-intercept graph. For that, equations 1 and 2 are used to calculate the total gradient and the total intercept for each survey patch, and all the pairs (slope, intercept) of the survey are plotted in the Cartesian plane (Figure 2). Then, the background trend line for the survey is defined as the linear regression of all coordinate pairs (gradient, intercept) in the gradient-intercept plane (Equation 3). Finally, the fluid factor attribute (Equation 4) is calculated as the orthogonal distance of each coordinate pair to the background trend (Equation 4). The final parameter extracted from the plane is the product, defined as the multiplication of the gradient by the intercept.

Based on the calculated AVO attributes and the constrained iterative inversion of the acoustic backscatter model, it is possible to estimate the acoustic impedance, the seafloor roughness and volume backscatter of the insonified area on the seafloor.

\[
B = \frac{\text{Far} - \text{Near}}{\sin^2(\theta_{\text{far}}) - \sin^2(\theta_{\text{near}})} \quad \text{Equation 1}
\]

\[
A = \frac{\text{Far} + \text{Near}}{2} - B\left(\frac{\sin^2(\theta_{\text{far}}) + \sin^2(\theta_{\text{near}})}{2}\right) \quad \text{Equation 2}
\]

\[
\text{Background Trend} = g \times A + d \quad \text{Equation 3}
\]

\[
\text{Fluid Factor} = \frac{-gA + B - d}{\sqrt{g^2 + 1}} \quad \text{Equation 4}
\]
Where,
A: Total gradient of the angular response;
B: Total intercept of the angular response;
Near: Average backscatter in the near range;
Far: Average backscatter in the far range;
g: Slope of the background trend line (see Figure 2);
d: Intercept of the background trend line (see Figure 2);
θ_{far}: Average incident angle of the sounding in the far range;
θ_{near}: Average incident angle of the sounding in the near range;

Example from Little Bay, NH

AVO analysis was applied to an acoustic remote sensing dataset acquired in the summer of 2003 in Little Bay, NH (Figure 3). The equipment used was a Simrad EM3000 multibeam sonar, which is a shallow water system operating at 300kHz, forming 127 beams in an angular sector of 130 degrees. The survey mapped water depths from 6 to 24m, with bottom sediments ranging from gravel to clay. The analysis started with the backscatter time series stored in raw Simrad datagrams, which was then corrected for radiometric and geometric distortions. Radiometric corrections included the removal of the time varying and angle varying gains applied during acquisition, calculation of the true grazing angle with respect to a bathymetric model, and correction for footprint size. Additionally, it was necessary to remove the lambertian correction and the near nadir time-varying-gain compression that were applied to the backscatter time series during acquisition. The radiometrically and geometrically corrected backscatter was then compared to the predictions of the mathematical model.
A series of AVO attributes (near, far, slopes, gradients, fluid factor and product) were calculated from the stacking of 30 consecutive time series. The same AVO parameters calculated for the measured backscatter angular response were also calculated for a series of modeled backscatter angular response. The inversion of the model was done iteratively by adjusting the near-range slope, the near-range intercept, the far-range intercept, the far-range slope and the fluid-factor, with the model parameters constrained by Hamilton equations. The inversion is regularized by the adjustment of the AVO parameters and not by the adjustment of the model parameter, which showed to be a more robust approach. Based on the calculated AVO attributes and the constrained iterative inversion of the acoustic backscatter model we estimated the acoustic impedance, the roughness, and consequently the grain size of the insonified area on the seafloor (Figure 4).
In Little Bay, the estimated impedance and grain-size were compared to in-situ measurements of sound-speed taken from the R/V Gulf Challenger and to the direct analysis of grain size in grab samples. In October 2003 and April 2004, measurements of in-situ sound speed were completed in Little Bay, with two orthogonal matched pairs of transducer probes operating at frequencies of 40 and 65 kHz. (Kraft et al, 2004). In October 2003, sediment sampling with a Van grab sampler was also conducted from the R/V Coastal Surveyor. The comparison between in-situ and remotely estimated measurements showed a very good correlation, and the results are plotted in Figure 5.
Figure 5 – Remotely estimated acoustic impedance versus in-situ measurements of sound speed. Note the very good linear correlations ($R^2=0.876$).

Conclusions
AVO analysis of Multibeam data is a promising technique for remote acoustic seafloor characterization. This technique was successfully applied to the Simrad EM3000 multibeam sonar data from Little Bay, where the remotely estimated impedance was compared to the in-situ measurements of sound speed, indicating a strong correlation between these two acoustic parameters. More accurate results will be possible with better observations, specifically radiometrically calibrated and geometrically corrected acoustic backscatter. Additionally, the definition of more precise acoustic backscatter models is essential for understanding the acoustic signature of seafloor sediments.

Acknowledgments
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References


STATISTICAL AND CHANGE-DETECTION ANALYSES USING QUANTITATIVE SIDE-SCAN-SONAR SURVEY DATA

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This report discusses recent research in the sediment-classification project within the Hydrographic Science Research Center (HSRC) at The University of Southern Mississippi. Such work has a bearing on statistical analyses and bottom change detection relevant to the detection of mines and other naval warfare areas in the littoral. The research discussed here includes surveys made in 2003 and 2004 and current analyses of the resulting data and of data taken in a survey conducted in 2002. The primary contributions of this work are based on the use of probability density functions (PDFs) of the backscatter signals to specify the various regimes of bottom sediments and to detect spatial changes in these regimes based on chi-square tests applied to these PDFs. A simple, quantitative test for non-Rayleighness of a PDF was also applied. This work was supported by the ONR.

1 Introduction

The primary contributions of this work are based on the use of probability density functions (PDFs) of the backscatter signals to specify the various regimes of bottom sediments and to detect spatial changes in these regimes based on chi-square tests applied to these PDFs. A simple quantitative test for non-Rayleighness of a PDF was applied. The analyses were applied to several high-resolution, data sets from quantitative, dual-frequency, side-scan-sonar (SSS) surveys, notable, but not limited to KauaiEx and SAX04. The second major aspect of this work is the application of these PDFs for spatial change detection (sometimes called “segmentation”). The specifications of the modified SSS and details on the application of these techniques can be found in a series of reports [1-5].

This work is, in part, a collection and summary of recent work on statistical and change-detection analyses using quantitative side-scan-sonar survey data. The details of this work can be found in the references cited and the projects supporting this work are cited.

2 Analytical Techniques

2.1 Backscatter PDFs

The fundamental analytical techniques in this study are the calculation and analyses of PDFs of the backscattered signals of selected sub-regions of the seafloor and the delineation of changes in the seafloor based on these PDFs. A number of change-detection algorithms exist for detecting changes in bottom properties based on backscatter, but all are associated with textural analyses based on imagery rather than PDFs. Basing a change-detection algorithm
on PDFs is important because all signal-processing algorithms for detection of foreign objects (e.g., mines) are based on decision theory involving PDFs. And, in particular, these target-detection algorithms are based principally on an assumption of Rayleigh reverberation statistics, which often is not the prevailing statistics. Any change in the background PDF of a region fundamentally changes the detection decision and, therefore, for such applications seafloor changes should be monitored by quantitative algorithms based on PDFs such as those developed in this project rather than on textural analyses. Coupling change-detection algorithms to PDFs has added advantages in that, as regions are delineated, PDFs can be improved iteratively by their proper groupings by regions.

2.2 Change-Detection Algorithms

The analytical methods for change detection for the above-mentioned backscatter research were based on algorithms using (1) a modified Chi-Square goodness-of-fit Test (CST) and (2) Log Likelihood Ratio Cumulative Sum Tests (LLRCST) [6]. Both these tests are applied to a comparison of the PDF at hand to some ‘standard,’ which may be an overall PDF of the survey, some a priori known PDF, or a canonical PDF such as a Rayleigh distribution. Both the tests were developed in the late 1990s by one of the authors (jwc) while at NRL for application to data from the dual-angle, multi-frequency NRL backscatter system [7]. This paper will be limited to discussion of the CST based on SSS data collected by USM in 2002, 2003, and 2004.

The chi-square test is based on the algorithm

$$\chi^2(T) = \sum_{n=0}^{M} \left[ \frac{f(n) - \hat{f}(n)}{\hat{f}(n)} \right]^2 ; T = 0,1,2,...M$$

where $f(n)$ and $\hat{f}(n)$ are the reference distributions and an estimate of the distribution to be tested, respectively. The $T$ is an advancing threshold so that the resulting CST is a function of the threshold to emphasize the high end of the PDF in some cases. The importance of this modification is that the location of the threshold is critical in the process of rejecting false alarms and for heavy-tailed PDFs (which is often the case, particularly in high-clutter environments). This test was further developed and applied in this project to SSS work.

2.3 A Test for Rayleighness

Rayleigh statistics is important in the process of detection of targets. Its importance is fully discussed in twelve papers published in a “Special Issue on Non-Rayleigh Reverberation and Clutter” of the IEEE Journal of Oceanic Engineering in 2004 [8]. In the course of this work, a simple test for Rayleighness of the reverberation due to backscatter from the sediments was investigated. If the reverberation waveform is Gaussian distributed with zero mean, then the PDF is given by
CHANGE-DETECTION ANALYSES

\[ g(x) = \frac{1}{\sigma g \sqrt{2\pi}} \exp \left( -\frac{x^2}{2\sigma_g^2} \right) \]

where \( \sigma_g \) is the standard deviation of the Gaussian distribution. Then the detected signal – related to the root-mean pressure (\( y \) here) – is Rayleigh distributed given by

\[ f(y) = \frac{y}{\sigma_g^2} \exp \left( -\frac{y^2}{2\sigma_g^2} \right) \]

The Rayleigh distribution will have a mean, \( \mu \), and a standard deviation, \( \sigma \), given by

\[ \mu = \sigma_g \sqrt{\frac{\pi}{2}} \quad \text{and} \quad \sigma = \sigma_g \sqrt{\frac{4 - \pi}{4}}. \]

respectively. The ratio of the mean to standard deviation for a Rayleigh distribution is given by

\[ \frac{\mu}{\sigma} = \sqrt{\frac{\pi}{4 - \pi}} = 1.913058\ldots. \]

One reported use of this fact concerning a Rayleigh distribution, can be found in the literature for ultrasonic backscatter from biological tissues [9]. This simple test does not seem to have been previously reported in the ocean acoustics literature.

Although this test requires that the ratio of the mean to the standard deviation be 1.913... for the distribution to be Rayleigh, it is not a sufficient condition for Rayleighness. What can be known with certainty is that, if the ratio of mean to standard deviation is not 1.913..., the distribution is non-Rayleigh. We are exploring additional criteria that may provide the sufficient condition.

3 Summaries of Surveys and Data Analyses Conducted

Selected analyses of data from the following surveys will be discussed further:

3.1 Panama City Beach 2002 (PCB02)

The analyses of these data, as was the survey itself, were conducted jointly with NRL. NRL and the author (jwc, while at NRL) had previously conducted bottom scattering research in the area surveyed by this project and the combined results were published jointly by USM and NRL [5]. Initial results for the analysis of these data were reported in [7]. Additional analyses, including the use of the CST as revised for side-scan work, were published in [2,3].
(Reference [7] was supported by NRL, Ref. [5] was supported by an ONR/HSRC project, and Refs. [2-4] were supported by this current project.)

3.2 Kauai, HI 2003 (KH03)

This survey was conducted primarily as a research project for an ONR grant that was in support of the KauaiEx program [10-12], but a relatively small part of those cited papers addressed data taken on one day outside the KauaiEx range in support of this project. This latter data set was further analyzed and used in references [2-4], and is the subject of comments in this paper.

3.3 Ft. Walton Beach, FL 2004 (FWB04)

This survey was conducted primarily in support of the ONR/SAX04 project. This work, however, was partially supported by the ONR/HSRC project to the extent that it was used to support the thesis work of the ONR/HSRC Master’s student (vr). The results of the analyses of these data were reported in references [2-4].

4 Analysis of Panama City Beach, FL, Data, April 2002 (PCB02)

This project supported work that resulted in a paper, “Statistics of high-resolution seafloor backscatter and the detection of spatial changes,” presented at the 146th Meeting of the Acoustical Society of America in Austin, TX, in November, 2003 [4]. The paper addresses results from our recent analysis of SSS data taken off Panama City Beach, FL, in 2002 (PCB02) and comparisons with data taken by NRL in 1996 (PCB96) [5,7]. Data used in these analyses were collected using NRL’s dual-angle, multi-frequency, towed sonar array and using USM’s dual-frequency SSS discussed above.

The PCB02 area was chosen because of the pre-existing PCB96 data, for its very uniform characteristics and known sandy bottom, and for the expectation of only very subtle spatial changes. Frequencies used in the NRL system discussed in that paper are 200, 225, 250, and 275 kHz [7] which are bracketed by the SSS’s 150- and 300-kHz frequencies. Scattering patch sizes of the NRL system were of the order of a square meter, as compared to the 0.1 square meter patch sizes for the USM SSS data.

The side-scan data, labeled PCB02 and taken on 16 Apr 02, were compared to the PCB96 data taken near the same site. Several hurricanes and tropical storms occurred between the collections of those data sets, however, so no one-to-one correlation was attempted. Generally, however, both data sets showed small-scale fluctuations within larger isolated regions and both sets showed small regional variations based on the chord-detection algorithms applied. Nevertheless, the entire survey appeared to be fairly uniform in the visual images.

Example PCB02 (for data files 0416010 and 0416001, where the first four numbers indicated the month and day and the last three the digital-data file number) PDFs for the two frequencies can be seen in Fig. 1. The PDFs of the file 0416000 shown in Fig. 2 are compared to several standard PDFs. Based on the data in that figure, we have attempted to
find a standard form PDF that fits. A Weibull distribution appears to fit very well for the smaller values, but departs severely at the more extreme values. For those values a lognormal distribution probably fits best. Others have found that a combination of distributions is required and these data seem to confirm that conclusion.

An image for the data file 0416003 is shown in Fig. 3. This figure shows a series of change tests revealing some distinct changes in the character of the seafloor that are not visually obvious. PDF differences were that were apparent led to automatic detections of change based on the

Figure 1. PDFs for indicated SSS files show only slight differences between frequencies and regions off Panama City.

Figure 2. Fitting file 0416000 to selected PDFs. Weibull fits best for smaller values and Lognormal can be made to fit at larger values.

Figure 3. Processed image for file 0709015 (left) and several change detection tests as indicated.
mean, standard deviation, mean divided by standard deviation (the Rayleighness test, but remember the caveat expressed earlier) and the CST. (Colors and classes are arbitrary with exception of the Rayleighness test. For those quantitative values latter see Table I.) The “blockiness” in these diagrams is necessitated by a requirement to include enough data points (1560 pts) to form good PDFs. This can, however, be improved through the use of sliding regions for the PDF calculations [1,3].

An image for the data file 0416003 is shown in Fig. 3. This figure shows a series of change tests revealing some distinct changes in the character of the seafloor that are not visually obvious. PDF differences were that were apparent led to automatic detections of change based on the mean, standard deviation, mean divided by standard deviation (the Rayleighness test, but remember the caveat expressed earlier) and the CST. (Colors and classes are arbitrary with exception of the Rayleighness test. For those quantitative values latter see Table I.) The “blockiness” in these diagrams is necessitated by a requirement to include enough data points (1560 pts) to form good PDFs. This can, however, be improved through the use of sliding regions for the PDF calculations [1,3].

5 Survey and Analysis of Kauai, HI, Data, (KauaiEx 2003)

Data taken in the Pacific Missile Range Facility range during July 2003 were in support of a separate ONR Ocean Acoustics Program project related to underwater communications known as KauaiEx. While there, we took other data in shallower water (outside the range) with highly variable bottom types. SSS imagery for 0709039 is shown in Fig. 4. Consistent with the visibly distinct regions in Fig. 4 (that we estimate to be due to regions of sand, mud, lava, and coral), Fig. 5 shows clear differences revealed by the tests.

Figure 4: Images for file 0709039 showing considerable and distinct bottom features.

Figure 5: Processed image for 0709039 and several changed detection tests as indicated for both frequencies.
6 Analysis of Ft. Walton Beach, FL, Data (SAX04, 2004)

Data taken off Ft. Walton Beach, Florida, was supported by ONR/SAX04. The SAX04 experiment was a study of acoustic backscatter from a sandy seabed. The project required a broad-area SSS survey of the homogeneity, or lack there of, in the region of the experiment. Some of the results of the survey were reported [3,4]. In final analysis, however, the results may have little bearing on the primary experiments of SAX04 because a severe hurricane traversed the area between our survey and the experiment. Nevertheless, our survey offered useful data for the application of our PDF techniques for change detection. Figure 6 (a combined image of two

![Figure 6](image.jpg)

Figure 6. This composite shows the region NE of the marker block with a distinctly different character.

![Figure 7](image2.jpg)

Figure 7. Image for 0911105 showing a part of the region to the NE of the four markers and an expansion of a region
Figure 7 is an example of another pass through the region. On the right-hand side of the figure is digital data in which separate regions above and below the strong backscattering edge are displayed in greater detail. Figure 8 displays PDFs for the two regions in Fig. 7 for 150 kHz on the left and for 300 kHz on the right. Clearly, there is a strong difference at the lower frequency and essentially no difference at the higher frequency. One might conjecture that at still lower frequencies the difference might persist.

7 Summary

This paper is a brief summary of side-scan-sonar surveys and analyses conducted over the past few years and highlighting a few new techniques developed in the last few months.

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CLASSIFICATION OF ACOUSTIC BACKSCATTER FROM MARINE MACRO-BENTHOS

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This is a review of those results accomplished in the past few studies of Genetic Programming (GP) among other methods on the acoustic classification problems. The purpose of this study is to provide a further insight of the factors that may affect the classification result and its difficulties. The ultimate goal of the study is the provision of a reliable algorithm that can discriminate a variety of acoustic backscatter characteristics of different seafloor habitats. Acoustic backscattered signals from marine macro-benthos (MMB) were roughly classified into several classes like seagrasses of Posidonia sinuosa and Posidonia australis and macro algae along with their substrates, bare reef and pure sand seafloor with the assistance of groundtruthing recordings. The data were acoustic backscatter of the MMB and their substrates collected from Australia’s coastline. One of the methods being used to the collection of data includes the use of a single beam echosounder being synchronized with a pair of stereo image cameras to provide the real time and synchronized groundtruthing recordings for the acoustics. Several techniques were used to classify the acoustic backscattered data. The classification performance by the adoption of a new approach, GP, and other techniques was re-examined. The results gave some indications from the previous studies along with a discussion of the difficulties encountered. The conclusion is that with the adoption of GP the classification performance of acoustic backscatter from MMB and their substrates was enhanced. The contribution of this study can provide as an aid for the understanding of the acoustic backscatter characteristics from different seafloor habitats.

1 Introduction

Classification of acoustic signals is among other signal processing tasks becoming a critical requirement in order to provide useful information for further management. For example, the provision of the bathymetry data of the seafloor is not enough to provide as an accurate depiction of the seafloor habitat types. One of the key issues comes from the marine vegetations. Although there had been several studies [1-28] concentrating on this problem, there is not much effective ways that can be used as a criterion to recognize the difference of the acoustic backscatter from marine vegetations and even from their substrates. A new approach, Genetic Programming (GP), was adopted to assess its effectiveness in the provision of the classification of the marine macro-benthos (MMB).

The adoption of GP on this task was initiated from a study of a diesel engine problem [29]. Although the diesel engine symptoms were easier than the acoustic
backscattered signals from MMB, the mechanism and the algorithm used are worth of study and were adopted.

In order to provide as an indication of the classification performances between GP and other conventional methods, several studies of the acoustic data collected from the Western Australia’s shallow coastal waters had provided [30-33]. Following are a summary of those results accomplished and the difficulties encountered.

2 Materials and methods

2.1 Collection of acoustic data and the synchronized stereo images

The acoustic data were collected from shallow coastal waters around Cockburn Sound and Owen Anchorage in Western Australia on 10th of August 2004. A synchronized stereo image system along with the SIMRAD EQ60 echosounder was employed to provide the groundtruthing recordings. The time difference between the collection of the acoustic data and the images was within a few micro-seconds. It was believed that the stereo images could reflect the actual conditions of the study targets when the acoustic data were taken. The major components of the structure in the whole system are shown in Fig. 1.

Comparing the sampling rate of the echosounder’s two frequencies, 38 and 200 kHz, it was the 200 kHz data that had been utilized for analysis. This is due to the higher sampling rate of the 200 kHz, 25 micro-seconds. The data value provided for the GP system is the volume backscatter coefficient in logarithmic scale. This was decided owing to its ready availability after the data acquired.

2.2 Data preprocessing

Before the GP program run, the acoustic data need to be preprocessed. Within each acoustic backscatter sample, there are at least one or two prominent bottom returns as shown in Fig. 2. It was the first bottom return that has been used for analysis. The selection of the first bottom return only was based on the concept that the interaction of the transmitted sound and the targets could be sufficiently expressed in this portion.

This portion was further represented by a set of statistic values. They are the general statistics: Minimum, Maximum, Mean, 2-nd order Moment, Standard deviation, Skewness, Kurtosis and a redundant Variance. That is, each sample was represented by its statistics from the first bottom return only. These statistics were regarded as the initial features that had been used as the terminal nodes of the classical GP tree structures. There was no study if the whole series of each sample were used nor if the different arrangement of statistic sets were used.

2.3 Selections of representative classes

The selections of representative classes from the acoustic backscattered signals were accomplished by the following method.

Since the synchronized image recordings can provide very accurate and actual conditions of the study targets when the acoustic data were collected, the classification of acoustic samples can be achieved by the examination of the associated stereo images.
After the classification of images by visual inspections, several classes of acoustic data were classified into several groups. Since the natural world never appeared with only one pure species in a cluster, there were variations in extent for a definition of a so called pure class with only one pure biological species appearing in the images. To avoid the uncertainty of this situation, those samples with an obvious mixture of at least two species in a sample were discarded while only those with one predominant species appearing in the images were kept for further analysis. Through this process, several so called pure classes were acquired. They were pure sand seafloor, bare reef, seagrass 1 (*Posidonia sinuosa*), seagrass 2 (*Posidonia australis*) and macro algae. Since the seagrass also varied in density, it was only the densest seagrass that had been used. It was hoped that these groups of data could be regarded as the representatives of their own distinctive properties. With this bearing in mind, the better an algorithm that can correctly classify these distinctive classes the better is its classification performance.

After the above process, a set of 81, 10, 21, 180 and 8 sample numbers representing the pure sand, bare reef, seagrass 1, seagrass 2 and macro algae classes respectively from the original 1232 total samples were acquired.

![Stereoscopic cameras, SIMRAD EQ60 echosounder, Light](image)

**Figure 1.** The data collection structure containing the major synchronized components: the echosounder, stereoscopic cameras, and light.

![Volume Backscatter Coefficient, dB](image)

**Figure 2.** A typical echo with at least 2 bottom returns showing the portion used for analysis.
3 GP system

3.1 The introduction of a fitness function

To utilize GP as a tool to accomplish for the classification mission, a designing of a symbolic regression task was especially required for the GP system to achieve this goal. Since GP is not commonly employed for classification tasks, a fitness function that had played critical role in affecting the classification performance was modified and tested from several conditions. The designing of the whole GP system was initiated from a study of diesel engine problem [29]. However, the complexity of the acoustic backscattered waveforms from the MMB and their substrates were much more complicated than those in the diesel engine study. The general form of the fitness function is expressed in Eq. (1).

\[
f = \left[ \prod_{i \neq j} \frac{D_{ij}^{(between\ mean)}}{\sum D_{i}^{(within\ max)}} \right]^{\alpha}, \tag{1}
\]

The \( D_{ij}^{(between\ mean)} \) denotes the distance between the mean values of two different classes \( i \) and \( j \) and the \( D_{i}^{(within\ max)} \) denotes the maximum variation range in a class \( i \). \( \alpha \) and \( \beta \) are two weighting factors that can be adjusted so that one can experiment which part of the fitness function would like to be emphasized.

3.2 The GP non-terminal and terminal nodes: mathematical operators and initial feature values

From the previous studies [31,33], it was found that the non-terminal nodes may play more critical roles in the achievement of the final classification results than the terminal nodes. The non-terminal nodes were actually the general mathematical operators or any combination of any operators like those used in [29] while the terminal nodes were the initial features of those statistical values of each sample. The whole structure of this GP program tree is a candidate feature that is any combination of the mathematic operators and the initial statistic feature values.

3.3 Genetic operations: cross over, mutation, and reproduction

Each candidate feature is combined from a set of mathematical operators and a set of initial features according to the settings of the GP system. It is then assessed by the provided conditions of the fitness function according to Darwin’s natural selection principle in order to find the best candidate feature that provides the best performance according to the GP parameters provided. The selection and assessment are repeated for every individual candidate feature and from one generation to the next generation until the condition and settings are met. For a more comprehended study of the basics of GP, it is recommended to start from some of the typical GP textbooks and literatures [34,35].
4 Results

The results from some of the previous studies [30,31] were formulated below:

4.1 Non-GP result: Effective Pulse Width (EPW)

A parameter called Effective Pulse Width (EPW) providing comparable classification ability is illustrated in Fig. 3. Its definition can be found from the previous studies [30,31]. As can be seen from this figure, there are still some portion of overlaps between two distinctive big classes, sand and non-sand. The classification ability of this parameter is only limited to the provision of the distinction of pure sand seafloor (flat seafloor surface) from non-pure sand seafloors (rough seafloor surfaces). This parameter is not able to provide any further classification ability for acoustic backscatter from MMB and other substrates like bare reef.

![Figure 3. Distributions of EPW of several habitats at 2 sites.](image)

![Figure 4. Distributions of 5 pure habitats relocated after being mapped by GP.](image)
4.2 GP result

Different GP program runs produced a variety of solutions with classification performance differing in extent. A typical solution found by the implementation of GP as described above transformed the 5 representative classes into a normalized space as shown in Fig. 4. As can be seen from Fig. 4, it is quite obvious that sand had been separated from other classes except two samples of reef still mixed within the sand class. The two seagrass species were unable to separate from each other. There are also little overlaps between algae and reef. Due to the oversize figure of the GP program tree, it is omitted here.

5 Discussion

By looking at the appearance of Fig. 3 and Fig. 4, it is obvious that GP provide better classification ability than the EPW parameter. Although GP is not especially suitable for classification requirements, through a proper design of the fitness function this task was accomplished with improved performance than the non-GP one. However, the solution similar to the one provided here is not always achievable from every GP program run. Each program run is randomly and independently implemented according to the settings of the GP system. It is hardly able to find a feasible way that can be used to assess which part of the components in the GP program tree plays the most critical effects for the designed task. Partly this is due to the nature of the GP algorithm. In order to understand this and to provide any further suggestions, it will need further studies of its mechanisms.

The other difficulty from the result of GP is the interpretation of its physical meaning from the solution provided. Since different GP program runs may give different solutions but similar performance capabilities, the decision to pick out any part of a whole GP program tree which plays the most critical role is almost unachievable, let alone the possibilities of providing the physical meanings of each found solution from GP.

6 Conclusion

A review from the observation of several of the studies of GP algorithm employed on the acoustic classification problem is provided. A comparison between the non-GP and GP results showed that GP algorithm provided more possible opportunities and better classification performance than a conventional method. This concludes that the adoption of GP algorithm may enhance the classification performance of the acoustic backscatter from the marine macro-benthos and their substrates.

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Cooperative Research Centre for Coastal Zone, Estuary & Waterway Management and Curtin University of Technology’s Higher Degree Research funded the study. The GP system was based on GPLAB, a free MATLAB toolbox developed by Sara Silva from Fundação para a Ciência e a Tecnologia, Portugal. Thanks go to Epibenthic Scattering Project members, especially the Coastal Water Habitat Mapping project leader Dr. Rob McCauley and project manager Emeritus Prof. John Penrose.
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Seabed mapping has revealed the importance of submarine landslides in continental margins around the world. These areas are characterized by a large variety of terrains and the compound acoustic characteristics of the seabed often make geological interpretations a difficult task. Sonar backscatter is modulated at several spatial scales by the local slopes (surface processes), by the variable interface roughness and by the high variations in volume scattering processes. To address these problems, we are using marine geophysical data acquired in the SW Iberian Margin. The dataset includes high-resolution (3 m) TOBI sidescan sonar imagery complemented with Simrad EM-12S multibeam bathymetry. We focus on the recent Marques de Pombal mass-wasting complex. Our models and observations show that backscattering is heavily influenced by the geometry of insonification; for instance, seafloors rough at scales comparable to the acoustic wavelength (ca. 5 cm for TOBI) are more likely to exhibit facets scattering back to the sonar. The local distribution of backscatters creates textures, quantified with the TexAn software and associated to geological processes or terrains (e.g. landslides, background sediments). Textural entropy yields information related to the terrain roughness. Similarly, textural homogeneity provides details of the local organization of textures, which can be compared with terrain properties (relative importance of surface vs. volume processes). The results quantify the variability of geological processes along the slopes and for different parts of the submarine landslide. Combining different techniques from acoustic modeling, image processing, and geological interpretation makes a powerful tool to study mass-wasting areas in continental margins. A better appreciation of the complex acoustic interactions with the seabed, associated to awareness of the surveying constraints, provides better opportunities for the geophysical interpretation of sonar images in these challenging environments, whether in deep or in shallow water.

1 Introduction

The last decades of seabed mapping around the world have revealed that submarine landslides are widespread features [1]. They occur in the sedimentary successions of continental margins and within the basaltic edifices of volcanic islands. Their large number and the extensive amount of material involved make submarine mass wasting one of the most important geological processes shaping the continental margin.
Many of these slides are located within hydrocarbon exploration areas [2] and the bigger ones are also often associated with tsunamis. Interpreted with seismic data, when available, sonar maps can provide useful insights into the mechanisms associated with each landslide, and its probability of re-occurrence in geologically short terms. However, continental margins often present steep slopes and complex terrains (Fig. 1), modulating the acoustic returns at several spatial scales [3]. In addition, different terrains will present distinct surface roughness and volume scattering properties, depending on the imaging geometry, contributing to making traditional, visual interpretation a difficult task.

Figure 1. Sidescan sonar surveying of continental margins is affected by highly varying imaging geometries and seabed types. These will affect the interpretation of backscatter values (for individual pixels and for groups of pixels, as used for example to compute local textures).

This article focuses on quantifying and linking to geological processes the acoustic backscatter from a large submarine landslide, thought to be associated with the 1755 Lisbon tsunami and located in a region of high seismic potential [4]. Using the model of [5], we quantified the expected returns at the local scale, for complex seabed types imaged at different altitudes on the highly varying slopes observed in the survey area. This demonstrated the necessity of accurately accounting the local angles of insonification, as the acoustic returns could be easily attributed to the wrong seabed types otherwise. This also quantified the relative importance of surface vs. volume processes for each region of the seafloor along the landslide. The acoustic textures of small groups of pixels were then quantified with the Texan software [6], and their interpretation was assisted with the knowledge of the more likely scattering processes. When available, localised ground truth was also integrated. By systematically and quantitatively mapping the variability of geological processes down the slope and across the landslide, these two approaches (backscatter model; texture analyses) constrain the geological interpretation and assist in the understanding of this region and its possible evolution.
2 The Marques de Pombal mass-wasting complex

Our study focuses on a large and fresh mass-wasting complex, recently imaged offshore Portugal in the Marques de Pombal fault area (Fig. 2). It was mapped during the HITS-2001 cruise on board the BIO Hesperides [7]. Most of this survey was devoted to the use of the high-resolution sidescan sonar TOBI. Operating 200-40 m above the seabed, this deep-towed instrument images the seabed at 30 kHz with a 6-km wide swath [8]. It is supplemented with a 6-7 kHz sub-bottom profiler and was used in conjunction with EM-12S multibeam bathymetry and TOPAS sub-bottom profiling along the track. These different instruments were selected to maximise the synergy between imaging techniques and map resolutions, fundamental to allow a detailed characterisation of the superficial and sub-seafloor structures.

The zone surveyed in the Marques de Pombal area, SW of Portugal, covers 31 x 108 km, from 36°29’N to 37°05’N and from 10°24’W to 9°33’W, in water depths from 1,500 to 3,500 m. Located at the limit of the SW Iberian margin, this area is mostly sedimentary. A fresh mass-wasting complex with steep slopes covers 20 km x 13 km, at depths between 2,500 and 3,500 m. The geological knowledge of this area builds up on the results from previous surveys (e.g. [4]). The mass-wasting complex was subdivided for processing into images of 3 x 3 km, with a resolution of 3 m for TOBI. The local topography was gridded from EM-12S measurements at 100-m resolution. The slope is continuously steep, with several large reliefs perpendicular to the sonar track.

Figure 2. General location of the Marques de Pombal area. The sonar imagery acquired during HITS-2001 revealed this fresh mass-wasting complex, covering 20 km x 13 km approximately. The slopes are very important (1:20 over 18 km), significantly affecting possible interpretations.

The TOBI survey lines were processed with PRISM [9] to provide 3-m and 6-m resolution mosaics (Fig. 2), fully and accurately co-registered with the multibeam bathymetry. High backscatter returns are coded as high grey levels, following remote
sensing conventions. The imagery shows varied and often mottled textures, more visible in Fig. 3. In this typical image, the sonar track (dashed line) delineates the two directions of insonification. The immediate effect is that angles of imaging downslope from the nadir will be higher than expected, and those upslope from the nadir will be considerably reduced. But what will be the influence on the interpretation of the different backscatter patterns?

3 Slopes and insonification angles

The large differences in depths between the upper and lower parts of the landslide are large (e.g. 600 m over 3 km in Fig. 3). This means there are important deviations in the imaging geometries. Traditional, visual interpretation by skilled geologists often assumes the angle of insonification is varying linearly away from the sonar track (nadir). The sonar position and attitude (i.e. the portion of seafloor actually imaged) are known from the length of towing cable out and from sensors on the TOBI platform itself (pitch and depth, mainly). The navigation and attitude files were filtered to remove outliers and spikes when the raw sonar data was processed with PRISM [9]. Calculating the actual angles of insonification on this complex seabed revealed significant discrepancies [3]. The angles can be misestimated by as much as 9°, in particular in the areas of higher relief upslope from the sonar track and in the depressions downslope. These differences induce important backscatter variations, exacerbated by localised reliefs, differences in micro-scale roughness and sediment properties along the slope. They can be quantified with the backscatter model of [5], validated at 30 kHz [10]. Geophysical parameters used in the simulations (e.g. mean grain size) were derived from available ground truth and we added plausible variations around their mean values to account for the intrinsic variability of any type of seabed. The backscatter model provides expected acoustic returns (in dB) as a function of the grazing angle, for each seabed type. Knowing the local imaging angle and the backscatter level, it would therefore be possible to deduce the terrain type. Unfortunately, the TOBI sonar is not calibrated, and it is not possible to associate definite seabed types to each pixel (coded in arbitrary grey levels).

It is possible however to deduce some information, as the simulated returns are divided into contributions from, respectively, surface processes (e.g. micro-scale roughness) and volume processes (e.g. sediment heterogeneity) [5]. Knowing that the acoustic return, for a series of similar generic seabed types (e.g. cobble/sandy gravel/very coarse sand), is dominated by surface processes, it is then possible to interpret local changes in the individual backscatters as, for example, due to variations in micro-scale roughness (at scales comparable to the acoustic wavelength of TOBI, ca. 5 cm). Conversely, knowing that acoustic returns are dominated by volume processes, one can then interpret local backscatter variations as changes in the sediment types or densities. These hints can assist other means of interpretation, such as the quantification of acoustic textures (Section 4) and the general geological context. The question is how sensitive this separation is to the accuracy of the angle of insonification. To this effect, we have compared simulations of the acoustic backscatters for several types of coarse sediments, using the actual angles and the assumed angles. The proportion of backscatter due to contributions from the seabed surface can be misestimated by as much as 15%, thus leading to wrong interpretations of the possible causes for backscatter variations. In the particular case of the image presented in Fig. 3, with steep
slopes and coarse sediment types, surface processes are expected to contribute to more than 75% of the overall backscatter. Two areas only show lesser contributions: at nadir, where there is no useful TOBI data anyway, and at very far range, interpreted with caution in most cases. In this case, we can thus safely assume that all backscatter variations can be attributed to changes in the surface properties of the sediments imaged. For other parts of the mass-wasting complex (where the slopes are different), and for other images in general, the answer is not as straightforward. Some areas are more dominated by volume processes, and others by surface processes. A difference of 15% can adversely affect the interpretation of the backscatter returns.

Figure 3. Bathymetry (left) and TOBI imagery (right, with no vertical exaggeration). Note the steep slopes, typical of the area, and the different insonification directions each side of the sonar track. The altitude and attitude of the TOBI platform will also vary along-track.

In the present case, where one is focusing on the general geological interpretation of the sonar imagery, individual pixels are assessed on their local variations. Acoustic simulations performed on local groups of pixels, and using the exact insonification geometry, show which areas in the image need to be interpreted differently, and how. The local variations in the backscatter returns are quantified through their textures.

4 Textural Analyses and their Interpretation

Textures can be intuitively described as smooth or rough, small-scale or large-scale, random or organised. Theoretical [11] and experimental studies [6] showed that textures are best quantified with stochastic methods, such as Grey-Level Co-occurrence Matrices (GLCMs). Suitably adapted, GLCMs have proved their worth for sidescan sonar imagery (e.g. [3,6]). They have been used successfully in another area of the HITS-2001 survey, south of Almería (Spain) [12]). GLCMs address the average spatial relationships between pixels of a small region, by quantifying the relative frequency of occurrence of two grey levels at a specified distance. Their properties are described by textural indices. Two indices are sufficient to describe the geological information [6]. Entropy measures the lack of spatial organisation inside the computation window. Homogeneity is directly proportional to the amount of local similarities inside this window. Smooth sediments will be associated to low entropies and high homogeneities, rough targets to
high entropies and low homogeneities. Tectonised areas will present medium entropies and homogeneities proportional to the amount of faulting. These two indices are incorporated into a seafloor characterisation software called \textit{TexAn} [6].

Fig. 4 presents 3 subsets of the TOBI imagery of the whole mass-wasting complex. The acoustic textures were computed with \textit{TexAn}, using a computation window of 20 pixels, commensurate with the physical scale of the morpho-geological structures on the ground. Because of the grey-level dynamics in these images, the calculations could be run using 32 grey levels only (instead of 256). Fig.4 (top) shows the variations in sedimentary processes down the slope, with complex patterns and focusing of the landslide in some areas, constrained by the topography. For each pixel of each image, entropy and homogeneity were calculated, producing typical scatter plots like the one in Fig. 4 (bottom left). The (entropy; homogeneity) couples were clustered using the K-
means algorithm (Fig. 4, bottom right). Through supervised classification, these clusters were associated to terrain types. Depending on the complexity of the images, 7 to 8 types were consistently recognised. By order of increasing entropies, they correspond to: dark, homogeneous sediments in the depressions (low entropies, low homogeneities); slightly brighter sediments, interpreted as slightly rougher (on the basis of the analysis in Section 3) (note the “tongues” coming down the slope into the depressions); coarse sediments with more mottled textures; rough sediments, marking the boundary with the next class, consisting of individual boulders and striated zones. The latter two classes have nearly the same entropies but different homogeneities. They correspond to the sediment gradation typical of underwater mass-wasting areas (e.g. [13]). Using the actual angles of incidence and knowing the overall contribution of surface processes to the local backscatter, we can confidently associate these geological interpretations to the different classes.

5 Conclusion

This study shows the synergy between two different approaches to process and interpret sonar data. First, a validated and recognised backscatter model was used to simulate the acoustic returns from a portion of a mass-wasting complex on the SW Iberian Margin. These simulations were informed by localised ground truth and used different types of coarse sediments. Our simulations showed the importance of accounting for the exact angles of insonification, and how the relative importance of surface vs. volume processes can then be quantified accurately throughout the sonar image. The knowledge thus gained can then be used to refine the interpretation of the acoustic textures, calculated with TexAn. Textural variations can then be confidently linked to variations in surface roughness or in volume properties. In some areas, the sediment gradation typical of mass-wasting complexes is linked to sediment “tongues”, possibly associated to additional, localised slope failures.

The mechanics of debris-flows and landslides is now well known (e.g. [13,14]). Fig. 5 shows typical material entrainment and the size segregation of the debris. The real case is of course more complex, because of the heterogeneity of the flowing material, the presence of underlying topography (e.g. outcrops, previous channels) and the volume and speed of the material. By knowing the relative local importance of surface and volume processes, and having assigned preliminary interpretations to the textural

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Figure 5. Schematic view of material entrainment in a mass-wasting event (adapted from [14]).
classes, it should be possible to analyse the different parts of a mass-wasting complex. One can also envisage the possibility of recognizing different types of events within the larger complexes. Combining different techniques from acoustic modeling, image processing, and geological interpretation makes a powerful tool to study mass-wasting areas in continental margins. A better appreciation of the complex acoustic interactions with the seabed, associated to awareness of the surveying constraints, can provide better opportunities for the geophysical interpretation of sonar images in these challenging environments, whether in deep or in shallow water.

Acknowledgements

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References

MAPPING OF CORAL REEFS DISTRIBUTION BY MEANS OF ACOUSTIC AND OPTICAL APPARATUS

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An integrated procedure which incorporated a high-resolution side-scan sonar, an underwater video camera and a global positioning system (GPS) was used to conduct seafloor mapping around a small island, Liu-Chiu Yu, off Southwestern coast of Taiwan. The purpose of this investigation was intended to delineate the characteristics of the seafloor with emphasis to define the area which was covered by live coral reefs. The geocoded, high-resolution acoustic imagery collected by the side-scan sonar illustrated the morphology of the seafloor with an averaged resolution of 5 x 5cm to 3 x 3cm per pixel.

Five different types of seafloor categories were recognized, which include muddy seafloor, sandy seafloor, sandy seafloor with small rocks, seafloor with giant rocks and rocky seafloor. By the cross correlation of images collected by side-scan sonar and underwater video camera, it was concluded that rocky seafloor with the outer appearance of a bush (ex. staghorn coral, bush coral, or table coral etc.) is much prominent and more precisely to be identified. However, for those with the outer appearance of a sphere, there are very limited identification phenomena can be recognized. It was estimated that about 22% of the surveyed area (2.6 km$^2$) was covered by coral reefs. The detailed information of coral reef distribution was then incorporated into a GIS system for display and further investigations.

The proposed procedure which can mapping seafloor effectively, offered good opportunities and an improved methodology for the estimation of live coral reef distribution.

1 Introduction

The world’s coral reefs are home to 25% of all marine species, yet it is estimated that 75% of these reefs will be destroyed or significantly damaged in the next 20 years. Determination of coral reefs’ distribution and prevention of coral reefs’ degradation is an important issue to the conservation of offshore ecosystems. Mapping of coral reefs provides important information about a number of reef characteristics, such as overall structure and morphology, abundance and distribution of living coral, and distribution and types of sediment. Methods employed for the purpose of mapping coral reef distribution includes: visual observation by divers (transect line method, Menta-tow method, etc.), Lidar (light detection and ranging), aerial photography, hyperspectral imagery, dual-frequency sonar technology (echo sounder), multi-beam echo sounder bathymetry, satellite image analysis, and side-scan sonar imagery. No single approach is effective for evaluating the overall health of a reef. It is only through combining techniques that scientists can establish the most complete view of a reef [3, 5, 6, 7, 9, 10].

Among the methods listed above, side-scan sonar produces images of the seafloor with resolution which can easily reach sub-decimeter scale. Therefore, a coral reef mapping procedure based on the application of this instrument can offer a good possibility for the understanding of reef characteristics. In this research, an integrated procedure which incorporated a high-resolution side-scan sonar, an underwater video camera and a global positioning system (GPS) was used to
conducted seafloor mapping around a small island, Liu-Chiu Yu, off Southwestern coast of Taiwan (fig-1). The purpose of this investigation was intended to delineate the characteristics of the seafloor with emphasis to define the area which was covered by live coral reefs.

2 Methods, Principles and Procedures

Acoustic images were acquired with a dual frequency side-scan sonar system (Klein HYDROSCAN® sonar system). Survey positioning was provided by an onboard differential GPS (DGPS 53, GARMIN) as well as an acoustic short-baseline underwater navigation system (LXT, ORE). Underwater video imagery, collected by an underwater towed video camera (TOV, J. W. Fishers), was used for ground-truthing in the classification and interpretation of the acoustic imagery. In addition, Real-time survey guidance was provided by C-MAP digital nautical charts. The survey was performed aboard a small local fishing boat.

Side-scan sonar produces images of the sea floor, made of points whose values are proportional to the amount of energy backscattered, and expressed as grey levels. The backscattering is affected, in decreasing importance, by the geometry of the sensor-target system (relative angle of ensonification), the morphological characteristics of the surface (e.g., micro-scale roughness) and by its intrinsic nature (composition, density, relative importance of volume and surface reverberation). Therefore, the acoustic appearance of living coral reefs will be dark scatters accompanied by shadows. The accompanying shadow will depend on the height of the reefs above the sea floor [1, 2, 4, 8].

The primary advantage to the use of an underwater towed camera is that the divers can have a remote presence for observation. Observations can proceed for far longer times than divers can suffer without risk to human life. In addition, by incorporating with a GPS, the location of a specific image can be identified precisely.

The field work was conducted on five separate days. Among them, side-scan sonar system was operated at 500 kHz with range setting at 50m or 30m. The geocoded, high-resolution acoustic imagery illustrated the morphology of the seafloor with an averaged resolution of 5 x 5cm to 3 x 3cm per pixel. Survey tracks were managed to parallel the coast line with water depth between 10m and 40m (fig-2).

3 Compositions of the Seafloor

Based on the acoustic characteristics (i.e., tonal and textural properties) of side-scan sonar imagery, the compositions of the seafloor around Liu-Chiu Yu offshore area can be classified into five major different types, i.e., muddy or fine sandy bottom, sandy bottom, bottom with small rocks, bottom with giant rocks, and rocky bottom (table-1, fig-3). A detailed description of the acoustic characteristics of each bottom follows:

(a) Muddy or fine sandy bottom: uniform or homogenous light tone without major textures.
(b) Sandy bottom: darker tone than muddy bottom with major ripple textures.
(c) Bottom with small rocks: small dark structures associated with white regions immediately adjacent (acoustic shadows).
(d) Bottom with giant rocks: large dark structures associated with white regions immediately adjacent.
(e) Rocky bottom: dark tone with rougher textures, some areas with significant mottled or speckled structures.

The spatial distribution of these bottom types follows a generalized pattern. Muddy or fine sandy bottom constituted an offshore boundary around the island at deeper area. Sandy bottom was distributed around the east and the west shallow offshore area. Bottom with small rocks located at the north and the east central offshore area and was created by landslide of rocks from the terrestrial environment. Bottom with giant rocks constituted only a very small portion of the
offshore area and was located at the southwest offshore area only. Rocky bottom distributed basically from the shore area to a deeper offshore area around the whole island.

4 Live Coral Reef Distribution of Liu-Chiu Yu

Coral reefs as well as sponges and algae, etc. illustrate mottled or speckled acoustic textures in side-scan sonar imagery. In addition, hard coral reefs, which create calcium carbonate as their bone-fabrics will illustrate specific bush-like textures. In order to discriminate the areas which were covered by coral reefs and coral reef like objects, the specific areas with speckled and bush-like textures in side-scan sonar imagery were delineated initially. The side-scan sonar imagery of these specific areas was then ground-truthed with optical images collected by an underwater video camera.

4.1 Side-scan sonar imagery discrimination

Factors which can contribute to the specific acoustic characteristics of coral reefs and coral reef like objects include: environment characteristics, living conditions, dimensions, organization (outer appearance) and spatial extent. Coral reefs rooted on hard (rocky) bottom only and created communities rather than single individual. A single community can easily occupy an area as small as about 50cm x 50 cm. Based on their diversified species, the outer appearance of coral reefs was ranged from bush-like, flack-like to mound-like, etc. In addition, hard coral reefs constituted calcium carbonate as their matrix, which is a strong reflector to the acoustic pulses. The procedure to discriminate coral reefs in side-scan sonar imagery follows:

(a) Exclude sandy and muddy bottom since coral reefs can not root on these sedimentary bottom. Only rocks (small and large) and rocky bottom were selected for further examination.

(b) Exam the outer appearance of each rock (small and large) first. For rocks with smooth and homogenous outer appearance, the existence of coral reefs on these rocks will be limited or unlikely.

(c) Exam the rocky bottom with varying resolution of the imagery to identify specific characteristics such as mottled or speckled acoustic textures as well as bush-like objects with acoustic shadows (Fig-4). At this stage, an image covers approximately 10 x 10m on the ground was selected to fulfill the requirement of proper resolution.

4.2 Ground-truthing of acoustic imagery with optical images

Based on acoustic imagery, geographic locations which include areas covered by significant amount of coral reefs and areas with limited coral reefs detected were ground-truthed with optical images (Fig-5, Fig-6). Highly positive cross correlation existed between acoustic imagery and optical images. It was concluded that bush-like objects with acoustic shadows in the acoustic imagery represented coral reefs of comparative types. In addition, areas with mottled or speckled acoustic textures represented surficial coral reefs or coral reef like objects.

4.3 Coral reefs distributions

Information of the shallower areas, which was not covered by side-scan sonar imagery, was supplemented by previous investigation. The seafloor of the offshore area around Liu-Chiu Yu was then categorized into two types, i.e., rocky bottom and sedimentary bottom (Fig-7). Among the rocky bottom, areas covered by coral reefs and coral reef like objects were defined based on side-scan sonar imagery (fig-8). It is evident that the most prominent area where coral reefs existed was located at the southern offshore area. In addition, there are significant amount of coral reefs distributed at the eastern offshore area and the south-western offshore area.
5 Conclusions

Five different types of seafloor categories were recognized, which include muddy seafloor, sandy seafloor, sandy seafloor with small rocks, seafloor with giant rocks and rocky seafloor. By the cross correlation of images collected by side-scan sonar and underwater video camera, it was concluded that rocky seafloor with the outer appearance of a bush (ex. staghorn coral, bush coral, or table coral etc.) is much prominent and more precisely to be identified. However, for those with the outer appearance of a sphere, there are very limited identification phenomena can be recognized.

Among the rocky bottom, areas covered by coral reefs and coral reef like objects were defined based on side-scan sonar imagery. It is evident that the most prominent area where coral reefs existed was located at the southern offshore area. In addition, there are significant amount of coral reefs distributed at the eastern offshore area and the south-western offshore area.

It was estimated that about 22% of the surveyed area (2.6 km²) was covered by coral reefs. The detailed information of coral reef distribution was then incorporated into a GIS system for display and further investigations.

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References

### Table 1. Bottom types and sonar imagery.

<table>
<thead>
<tr>
<th>Type of Bottom</th>
<th>Area (m²)</th>
<th>Percentage</th>
<th>Sonar Imagery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muddy or Fine Sand Bottom</td>
<td>925,229</td>
<td>37.8</td>
<td></td>
</tr>
<tr>
<td>Sandy Bottom</td>
<td>153,200</td>
<td>6.3</td>
<td></td>
</tr>
<tr>
<td>Bottom with small Rocks</td>
<td>218,219</td>
<td>8.9</td>
<td></td>
</tr>
<tr>
<td>Bottom with Giant Rocks</td>
<td>13,630</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>Rocky Bottom</td>
<td>1,133,670</td>
<td>46.4</td>
<td></td>
</tr>
</tbody>
</table>

![Figure 1. Geographic location of Liu-Chiu Yu.](image1)

![Figure 2. Side-scan sonar survey Tracks.](image2)
Figure 3. Compositions of seafloor around Liu-Chiu Yu offshore area.

Figure 4. Sonar imagery with prominent speckled and bush-like textures.
(image dimensions: 12 x 6m)
Figure 5. Four photographs taken at south-eastern offshore area of Liu-Chiu Yu. (dimensions of each photograph is about 2.5 x 2m)

Figure 6. Four photographs taken at south-western offshore area of Liu-Chiu Yu.
Figure 7. Major compositions of seafloor off Liu-Chiu Yu.

Figure 8. Coral reef distribution around Liu-Chiu Yu offshore area, based on side-scan sonar imagery.
SEARCHING AND LOCATING OF UNDERWATER PIPELINES

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Five underwater pipelines with various diameters around southwestern coast and offshore area off Taiwan were investigated by an integrated surveying system which includes a side-scan sonar, a high resolution sub-bottom profiler, and a magnetometer. A list of general information of these pipelines, sequenced in geographic locations from the north to the south, follows: 1. Chi-shui creek outflow pipeline (outer diameter: 1.70m), 2. Tso-ying outflow pipeline (1.52m), 3. Chung-chou outflow pipeline (1.80m), 4. Chinese Petroleum Company crude oil transmission pipeline (1.0m), 5. Liu-chiu-yu water transport pipeline (0.2m).

Based on the results of this investigation, side-scan sonar can offer information regarding the existence of a proud pipeline, the height of the proud pipeline, the length of a fresspan, the sedimentalogy of the sea bed around the route of the pipeline, as well as surficial sediment structures and artifacts. Sub-bottom profiler can provide information regarding the existence of an embedded pipeline, the buried depth of an embedded pipeline, as well as the height of a proud pipeline. It is demonstrated that the sub-bottom profiler used in this investigation, i.e., Klein 532S-101, was able to detect embedded pipelines with diameters larger than 1.0m and bury depth over at least 3m. For pipelines with diameter less than 0.2m, this equipment can not provide any detective information at all. For pipelines with diameter between 0.2m and 1m, extra investigation need to be conducted until a comprehensive conclusion can be deduced. Magnetometer can offer qualitative information regarding the existence of a metallic pipeline. At shallow water depth area, it can be used to identify the existence of a embedded pipeline with diameter as small as of 0.2m.

This research demonstrated that the integrated surveying system can offer sufficient information to supplement an engineering evaluation of underwater pipelines.

1 Introduction
The number of submarine pipelines around Taiwan offshore area was increased dramatically during the last decade. In addition, several major projects to construct offshore pipelines were announced and initiated especially by the Chinese Petroleum Company (CPC). The purposes and dimensions of the established pipelines vary from waste water dispose pipelines with diameter of about 2m, petroleum and natural gas transmission pipelines with diameter of about 1m, to small water transport pipelines with diameter of about 0.2m. After the completion of a submarine pipeline, the as-laid position and buried depth need to be surveyed and reported immediately to fulfill the requirements of construction contract. In addition, periodic external inspections are required thereafter to ascertain its conditions, and to prevent risk or damage due to fishing activity, turbulent currents or tidal abrasion, etc. Due to the fact that extremely
limited local contractors had ever established this survey and inspection ability, some of the aforementioned tasks were either conducted inadequately or skipped on purposely.

Detection and classification of embedded objects is still a difficult issue, although it is of the greatest interest in various fields such as mine-hunting operations, pipe survey or archeological research. Commercial off-the-shelf apparatus feasible for the inspection of submarine proud or embedded, metallic pipelines include side-scan sonar, sub-bottom profiler, magnetometer, as well as video camera (e.g., remotely operated vehicle or diver). Among these apparatus, side-scan sonar and video camera can be used to detect and inspect proud pipelines. Magnetometer can be used to detect the existence of a pipeline. However, it lacks the subtle information such as whether a pipeline is proud or embedded. Sub-bottom profiler is the only apparatus which can offer both the existence of an embedded pipeline as well as the type and thickness of sediment above it.

This study was aimed at discussing the feasibility of an integrated surveying system which includes a side-scan sonar, a high resolution sub-bottom profiler, and a magnetometer in searching and monitoring of underwater proud and embedded pipelines. Specific items associated with this goal include: route of pipeline, embedded depth of pipeline, composition and structure of surficial sediment, and artifacts on and around pipeline. The ultimate objective was to investigate the performance and limitations of this integrated system in searching and locating of embedded pipelines. Field survey and investigations were conducted on five different offshore pipelines, which include three outflow pipelines, one crude oil transmission pipeline, and one water transport pipeline.

2 Methods and Principles

Acoustic images of the seafloor and the underlying sedimentary strata were acquired with a combined dual frequency side-scan sonar and 3.5 kHz sub-bottom profiler system (Trifish™, Klein HYDROSCAN® sonar system). Total field magnetic intensities were acquired using a cesium magnetometer (G-881, Geometrics) at 10 Hz sample rate. Water depths were recorded using a Simrad EK-500 echo sounder system and survey positioning was provided by an onboard differential GPS (DGPS 53, GARMIN) as well as an acoustic short-baseline underwater navigation system (LXT, ORE). Underwater photographs and video imagery, collected by divers, were used for ground-truthing in the classification and interpretation of the acoustic imagery. In addition, Real-time survey guidance was provided by C-MAP digital nautical charts. The survey was performed aboard the research vessel “Ocean Research#3”.

Side-scan sonar produces images of the sea floor, made of points whose values are proportional to the amount of energy backscattered, and expressed as grey levels. The backscattering is affected, in decreasing importance, by the geometry of the sensor-target system (relative angle of ensonification), the morphological characteristics of the surface (e.g., micro-scale roughness) and by its intrinsic nature (composition, density, relative importance of volume and surface reverberation). Therefore, the acoustic appearance of proud pipelines will be dark linear scatters accompanied by shadows. The accompanying shadow will depend on the height of the pipeline above the sea floor [1, 2, 7, 8, 11].

High resolution sub-bottom profiler is used to provide a high resolution vertical profile of shallow sediments on the sea floor based on the reflectivity of sediments. For a point source reflector, such as a boulder or a pipeline, the echo from it depends on a
discontinuity in its acoustic impedance as compared with surrounding sediments and its dimensions. These point source objects usually produce hyperbola-shaped signals that are sharpest when the point object is in a direct line with the traverse. For an embedded pipeline, this apparatus can offer information regarding the existence of the pipeline as well as the thickness of the coverage above it [9, 10].

Most pipelines have very high permanent magnetization and show separate anomalies for each length of pipe, i.e., anomalies at each joint due to their independent thermal and mechanical histories. Valves and other attachments to pipelines show separate anomalies as well. Also, the magnetic signature of a pipeline varies inversely as the square of the distance instead of the cube of the distance as in the case of a dipole and the magnetic anomaly amplitude thus remains large. In addition, due to its great length often assures one of actually crossing it, therefore, a pipeline is generally easy to detect magnetically [3, 4, 5, 10].

Typical examples of survey results produced by these equipments are shown in Fig-1 and Fig-2.

3 Survey Results and Discussions
Based on a preliminary evaluation of archival data around southwestern coast and offshore area off Taiwan [6], a total of five offshore pipelines were selected in this study. A list of general information of these pipelines, sequenced in geographic locations from the north to the south, follows (Fig-3): 1. Chi-shui creek outflow pipeline, 2. Tso-ying outflow pipeline, 3. Chung-chou outflow pipeline, 4. CPC crude oil transmission pipeline, 5. Liu-chiu-yu water transport pipelines. Each of the pipelines was surveyed at two to three stages, and each stage basically contains more than one cruise. Generally speaking, an initial stage was conducted to locate the approximate position of a pipeline. During this stage, the vessel sailed an ‘S’ pattern on the pipeline, intersecting with the pipeline at an angle of about 90 degrees. The ensonified range (on either side of the side-scan sonar) and recorded penetration depth (sub-bottom profiler) was set at 25m. The purpose of this stage was to relocate a pipeline properly. A second stage was conducted, thereafter, to collect information of surficial sedimentology and artificial objects around pipelines. The survey lines were collected in parallel with the route of the pipeline and the ensonified range was set at 50m. A third stage, if needed, was conducted specific for the collection of special configurations of a pipeline, such as the diffussors as well as gravel patches that covered pipelines. Due to security constraint, the offshore survey work was conducted only at areas with water depth greater than 10m.

The geocoded side-scan sonar image was processed, which include: geometric corrections (i.e., slant range to ground range), radiometric corrections (i.e., time-varying gain corrections) and mosaicking. Side-scan sonar and sub-bottom profiler imagery as well as plot of total magnetic intensity were edited in a consistent time frame for further cross correlation:.

3.1 Chi-shui creek outflow pipeline (outer diameter : 1.70 m)
The results of the bathymetry survey illustrated that water depth of the surveyed area at this site was ranged from 10m to 17m. The sedimentology of the sea bed around the route of the pipeline is predominately medium to fine sand with mega sand ripples at restricted
areas. In addition, the sea floor is crisscrossed by tremendous quasi-linear trawlmarks. The total length of the pipeline detected in the surveyed area was about 2,800m and extended straightly to the direction at 240° (i.e., 30° from the west to the south). Based on its embedment, the status of this pipeline can be divided into three segments, i.e., east proud segment (280m in length), central embedded segment (1,330m), and west proud segment (1,200m). The survey routes intersect the pipeline at nine different locations. The depth of burial or the height extended above sea floor of the pipeline at each profile was estimated. Based on five sub-bottom profiles, the depth of burial of the pipeline was ranged from 0.5m to 3m. The other 4 profiles illustrated that the height of the pipeline was ranged from 0.2m to 1.2m.

The west proud segment is the most complicated part of this pipeline. It contains five proud sections (Sec#1, 2, 3, 4 and 5) and four embedded sections (Gap#1, 2, 3 and 4). The average height of the proud part was about 1m above sea floor. However, a total of at least ten freespans were identified and located. The longest span found was located in Section#4 with a length of about 300m and maximum height of about 3m. In addition, prominent mega sand ripples existed around the areas where freespans were found. This means that the existence of freespans in this segment was caused specifically by the hydrodynamic effects in this area. Fishing nests clogged on the proud part of the pipeline were common especially at the freespan areas (Fig-4). Side-scan sonar imagery illustrated prominent phenomena of clogged nests which were verified and ground-truthed by divers.

3.2 Tsao-ying outflow pipeline (outer diameter: 1.52m)

Five cruises of field survey were conducted at this site, which covered an area of about 4.5 km² with water depth ranged from 10m to 19m. The sedimentology of the sea bed around the route of the pipeline is predominately medium to fine sand on a flat sea floor without any significant feature on it. The survey route intersected the pipeline at 22 different locations. No acoustic signature of pipeline was ever detected on the side-scan sonar imagery. However, prominent hyperbola-shaped signals were observed on the sub-bottom profiles. In addition, significant magnetic anomalies were located on the total magnetic intensity vs. time plots. Based on the cross correlation of information collected by side-scan sonar, sub-bottom profiler, and magnetometer, the route of the pipeline was concluded. The length of the pipeline within the surveyed area is about 3,700m and extended offshore at the direction of 250° (i.e., 20° from the west to the south). The detected pipeline was embedded completely and the embedded depth was ranged from about 0.8m to 2.5m. The end point of this pipeline, which was located at a water depth of about 17m, was extruded above the sea floor for at least 3 m (Fig-5).

A disposed gravel zone with dimensions of 330m in length, 10m wide and about 2m in height is located along the ending portion of this pipeline. In addition, there are 43 protective, cement blocks (with dimensions of about 4m x 3m) located sporadically around the gravel zone. Scouring depression around these cement blocks is prominent and one of them was found to be buried completely.
3.3  Chung-chou outflow pipeline (outer diameter: 1.80m)

Four cruises of field survey were conducted at this site, which covered an area of about 3.0 km² with water depth ranged from 10m to 25m. The sedimentology of the sea bed around the route of the pipeline is predominately medium to fine sand on a flat sea floor with patches of coarse sand and ripple marks distributed on it. The survey route intersected the pipeline at 14 different locations. No acoustic signature of pipeline was ever detected on the side-scan sonar imagery. However, prominent hyperbola-shaped signals were observed on the sub-bottom profiles. In addition, significant magnetic anomalies were located on the total magnetic intensity vs. time plots. Based on the cross correlation of information collected by side-scan sonar, sub-bottom profiler, and magnetometer, the route of the pipeline was concluded. The length of the pipeline within the surveyed area is about 2,240m and extended offshore at the direction of 232° (i.e., 38° from the west to the south). The detected pipeline was embedded completely and the embedded depth was ranged from about 2.2m to 3.2m. The end point of this pipeline, which was located at a water depth of about 21m, was embedded under gravel patch and therefore was not identified. A set of diffusers on this gravel patch were noticed on the side-scan sonar imagery.

Two disposed gravel patches were detected. The first patch covered a smaller area with dimensions of 130m in length, 10m wide and about 2m in height is located along the route of this pipeline at water depth of 19m to 20m. The second patch, with dimensions of 220m in length, 20m wide and about 2m in height, is located along the ending portion of this pipeline. In addition, there are 72 protective, cement blocks (with dimensions of about 4m x 4m) located either sporadically or closely contacted around the gravel patches (Fig-6).

3.4  Chinese Petroleum Company crude oil transmission pipeline (outer diameter: 1m)

A portion of the CPC crude oil transmission pipeline, with water depth between 22m and 27m, was selected for this investigation. Field survey at this site covered an area of about 3.5 km². Topographically, the surveyed area is inclined slightly to the south-west direction with a prominent, continuously and diagonally distributed depression (with dimensions of 1,200m in length, about 100m wide, and about 2m deep) on it. Prominent pipeline signatures were detected by side-scan sonar, sub-bottom profiler and magnetometer which illustrated that the pipeline was located on the depression and was in a completely proud state. The pipeline, with total detected length of about 1,200m, was extended straightly to the direction of 230° (i.e., 40° from the west to the south). The average height of the proud pipeline was about 1m and no freespan was detected.

The sedimentology of the sea bed around the route of the pipeline is predominately medium sand with linear trawlmarks distributed on the west portion of the surveyed area. Some of the trawlmarks even intersected with the pipeline. In addition, several artifacts with dimensions larger than 1m² were detected on and around the pipeline (Fig-7). Based on the facts that the pipeline was on the topographic depression with a distance of about 1m below the averaged sea floor and the existence of large artifacts on and around the pipeline, it was concluded that the depression was established by artificial effects for the purpose of pipeline maintenance.
3.5  *Liu-chiu-yu water transport pipeline* (outer diameter: 0.2m)

Two cruises of field survey were conducted at this site and magnetometer was not used during the first cruise. In both cruises, acoustic signatures of the pipeline were not detected by either side-scan sonar or sub-bottom profiler. However, prominent magnetic signatures were collected by magnetometer during the second cruise. The survey results illustrated that this pipeline was totally embedded and the embedded depth could not be precisely determined by the sub-bottom profiler due to its small diameter (i.e., 0.2m). The estimated pipeline route is directed at 230° (i.e., 40° from the west to the south).

4  Conclusions

For the purpose of defining an adequate procedure for the detecting and locating of underwater proud and embedded pipelines, five underwater pipelines with various diameters were investigated. This research demonstrated that an integrated surveying system containing side-scan sonar, sub-bottom profiler, and magnetometer can offer sufficient information to supplement an engineering evaluation of pipelines. Among them, side-scan sonar can offer information regarding the existence of a proud pipeline, the height of the proud pipeline, the length of a freespan, the sedimentalogy of the sea bed around the route of the pipeline, as well as surficial sediment structures and artifacts. Sub-bottom profiler collects data along the vessel track. It can provide information regarding the existence of an embedded pipeline, the buried depth of an embedded pipeline, as well as the height of a proud pipeline. It is demonstrated that the sub-bottom profiler used in this investigation, i.e., Klein 532S-101, was able to detect embedded pipelines with diameters larger than 1.0m and bury depth over at least 3m. For pipelines with diameter less than 0.2m, this equipment can not provide any effective information in detecting them at all. For pipelines with diameter between 0.2m and 1m, extra investigation need to be conducted until a comprehensive conclusion can be deduced. Magnetometer can offer qualitative information regarding the existence of a metallic pipeline. At shallow water depth area, it can be used to identify the existence of a embedded pipeline with diameter as small as of 0.2m.

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Figure 1. Typical survey results for a proud pipeline (side-scan sonar and magnetometer).

Figure 2. Typical survey results for an embedded pipeline (side-scan sonar and sub-bottom profiler)
Figure 3. Geological locations of pipelines under investigation.

Figure 4. Side-scan sonar image of freespans, clogged fishing nets and diagonal mega ripples on and around Chi-shui creek outflow pipeline. (image size: 30m x 60m)

Figure 5. Offshore ending portion of Tso-ying outflow pipeline.

Figure 6. Major configurations of Chung-chou outflow pipeline.

Figure 7. Major configurations of CPC crude oil pipeline.
Section 5

Signals in the environment
The random nature of noise and scattered fields tends to suggest their limited utility. Nevertheless, it is possible to extract information about the kinds of structures associated with coherent processes from these type of fields. Thus, coherent wavefronts, for example, can be extracted by cross-correlating noise fields between a point receiver and a vertical array that are equivalent to those propagating from a source at the point receiver to the array. We examine the background physics of extracting these coherent structures and present experimental results confirming these theoretical arguments. Further, we present experimental results of some non-intuitive uses for random noise fields such as using noise for time synchronization between unconnected acoustic receivers and for performing array element localization.

1 Introduction

Though we think of the acoustic field from random sources or scatterers to be incoherent, there is acoustic coherence between two sensors that receive signals from the same individual source or scatterer. Thus, if we have a receiver some distance from a receiving array, both embedded in a random noise field, coherent wavefronts on the array will emerge from a cross-correlation process that accumulates contributions over time from noise sources whose propagation path pass from the point receiver to the array elements [1-3]. If the random field is isotropic, all possible paths between the receiver and the array will accumulate. Theoretically, it is actually the time derivative of the noise correlation function (NCF) that gives the time domain Green’s function (TDGF) between the sensors [3,4]. This phenomenon has now been observed in ultrasonic noise fields, ocean acoustic noise fields and seismic noise fields, Further, an analogous result has been observed in seismic coda; that is the scattered field following the “ballistic arrival” is a random field such that cross-correlations between sensors of this late arriving diffuse field also yields the TDGF [5].

Here we review some recent ocean acoustic results showing the extraction of coherent wavefronts and then we utilize this phenomenon in shallow water to show that we can
synchronize arrays as well as perform array element localization (AEL). For higher frequency and increased scattering, the more diffuse and homogeneous the noise field so that the procedures discussed in this paper are more attainable.

2 Estimating the time-domain Green’s function (TDGF) from the noise correlation function (NCF)

The extraction of the time-domain Green’s function between two receivers from the noise correlation function is derived in [1-4]. Rather than repeat the derivation, we present a simple plausibility argument for free space and using the existing literature, generalize the interpretation to a waveguide.

For a spatially uniform, broadband noise-distribution in a uniform medium with sound speed $c$, the NCF, denoted $C$, between two receivers separated by distance $L$ is zero for $|t| > L/c$ (no wave can travel slower than $c$), non-continuous at $t = \pm L/c$ and continuous for $|t| < L/c$ (waves originating from broadside will appear to travel faster than $c$). Thus the derivative of the NCF is

$$\frac{dC}{dt} \approx -\frac{\delta(t-L/c)}{L} + \frac{\delta(t+L/c)}{L}$$

(1)

It is recognized that the RHS is proportional to the free space TDGF and the time reversed TDGF.

Based on analytic derivations for specific propagation models and discussions in [1,3,6] we construct the following relationship for the time-derivative of the ambient noise cross-correlation $C_{ij}(1,2,t)$ between two stations 1 (located at $r_1$ recording component $i$) and 2 (located at $r_2$ recording component $j$) to the TDGF $G_{ij}(r_1; r_2, t)$

$$\frac{dC_{ij}}{dt} \approx -G_{ij}(r_1; r_2, t) + G_{ij}(r_1; r_2, -t)$$

(2)

The tensor TDGF $G_{ij}(r_1; r_2, t)$ is used as a reminder that some of the derivations were for seismic propagation and the theory applies to all possible polarizations [7]. The cross-correlation $C_{ij}$ is computed from the observed fields $v_i(r_1, t)$ and $v_j(r_2, t)$ by integration over the whole observation period $T$

$$C_{ij}(1,2,t) = \int_0^T v_i(r_1, \tau)v_j(r_2, \tau + t)d\tau.$$
In Eq. (1), the terms on the RHS are respectively: (1) the TDGF which comes from noise events that propagate from station 1 to 2 and yields a positive correlation time-delay $t$ and (2) the time-reversed TDGF which comes from noise events that propagate from station 2 to 1 and yields a negative correlation time-delay $-t$. Thus, for a uniform noise source distribution surrounding the two stations the derivative of the NCF will be a symmetric function with respect to the arrival time because ambient noise sources are

Figure 1. (a) Two arrays are depicted at a separation distance $R$. A schematic of the directivity pattern of the time-domain correlation process between two receivers on each array is projected on the ocean surface. Only a discrete set of lobes have been displayed that correspond to noise sources whose emission angle is equal to $-60^\circ$, $-30^\circ$, $0^\circ$, $30^\circ$, $60^\circ$ and $90^\circ$. Each angular lobe depends on the central frequency and bandwidth and corresponds to a delay time in the correlation function. For the case of equally distributed ambient noise sources, the broad endfire directions will contribute coherently over time to the arrival times associated with the TDGF while the contribution of the narrow off-axis sidelobes will average down. For the case of shipping noise, coherent wavefronts emerge only when there is sufficient intersection of the shipping paths with the endfire beams. However, if there is a particular loud shipping event, it will dominate so that either impractically long correlation times are needed, or discrete events should be filtered out. (b) and (c) The correlation process is done using time-domain ambient noise simultaneously recorded on two receivers in array 1 and 2. (d) Spatial temporal representation of the wavefronts obtained from the correlation process between a receiver in array 1 at depth 500 m and all receivers in array 2 separated by a distance $R=2200$ m. The arrival structure of the correlation function is composed of the direct path, surface reflected, bottom reflected, etc. as expected in the TDGF. The correlation function is plotted in a dB scale and normalized by its maximum. (e) The same correlation processing is performed on data that have not been recorded at the same time on the two arrays. In (d) and (e), the x and y-axis correspond to the time axis of the cross-correlation function and receiver depth, respectively. The correlation functions are plotted in a dB scale and normalized by the maximum of (d).
distributed on both sides of the station pair. However, in the case of a predominant directional noise source (e.g. from a shipping lane or special distribution), the NCF can be one sided. Figure 1 is a schematic of an ocean acoustic example [2] together with experimentally measured results. It has also been shown that the TDGF builds up from the NCF for an observation time proportional to $\sqrt{t}$. Shown in the figure are two potential paths. With a homogeneous random distribution of surface sources, all possible paths will emerge so that the arrival time structure will be the same as the TDGF. However, because surface sources are dipole-like, there will be an amplitude shading emphasizing the more vertical paths. If the sources were homogeneously distributed over the volume, the true TDGF would emerge [1,3]. Presumably the time of arrival structure can be used for tomography; however, in the next section we present a more practical application.

3 Array element localization (AEL) and self-synchronization (AES) using ambient noise

Coherent beamforming requires the accurate location of array elements. Further if the elements are on separate systems, for example, drifting buoys, time synchronization is also required. We have used the noise correlation process to do both AEL and AES [8]. We use an example of noise data in a frequency band 150-700 Hz from two horizontal arrays (denoted NS and EW) lying on the bottom at a depth of 21 m. In this case, the ambient noise was provided by croaker fish (Sciaenidae).

Synchronization is accomplished by noting (see last section) that the NCF should be symmetric about time=0 so that the offset in the “center of mass” of the NCF when using the individual clocks associated with each sensor is the required shift need for synchronization. Figure 2 is an example of the NCF between two elements of the same array (same clocks) whereas Fig. 3 is an NCF between two elements of different arrays (on different clocks) displaying the offset.
Figure 2. Symmetric time derivative of the NCF between elements 30 and 45 of the NW array.

Figure 3. Time derivative of NCF between elements 63 of NW and EW array indicating an offset that can be used to synchronize the two arrays.

With knowledge of the speed of sound at the bottom of the water column, the elements of the array can be located with the time of arrival information obtained between all element pairs using the NCF. An optimization routine is used for combining all the data to obtain the array configuration. Figure 4 shows the results obtained on two different days together with a comparison to a controlled source.
Figure 4. Array element localization from noise with symmetry ambiguity.

Localization result. Figure 5 shows a beamforming result with and without the array noise based AEL. Each row corresponds to one of the ambiguous shapes.

Figure 5. Beamforming with the two ambiguous array shapes. a) and c) are at 95 Hz and c) and d) 370 Hz. Clearly the array shape corresponding to a/b is the correct shape.

Figure 6. The NCF time derivatives for station pair separations of up to 500 km.
4 Noise Tomography

Our first attempt to do tomography has been with Southern California seismic data [9,10] in which temporal medium fluctuation is not important. We used data from a set of seismic stations pairs (see +’s Figure 7) approximately endifre oriented toward the direction of the dominating ocean microseisms. Figure 6 is the time derivative of the NCF (measured over 30 days) of the seismic vertical components ordered in terms of pair separation. We also computed the NCF for the other polarizations indicating we were measuring Rayleigh waves. This data was then inverted by a simple tomographic procedure for the surface shear speed in this region; a map of the results is shown in Fig. 7 in agreement with known results obtained over many years of seismic research. (see also [11,12]).

![Figure 7. Velocity map corresponding to the maximum a posteriori solution for the tomographic inversion scheme. The main regions with slow surface-wave velocity (below 1.5 km/s) are related to large sedimentary basins, as indicated by the arrows (A: San Joaquin Valley, B: Ventura, C: Los Angeles, D: Salton Trough).](image)

5 Discussion

The extraction of the time domain Green’s function from noise data has been shown to be a viable procedure in underwater acoustics. We have also shown that the process is sufficiently accurate to have utility such as for synchronizing arrays or...
determining array element localization. Further, our first venture into tomography with this method, albeit, for seismic fields also demonstrated a potential for environmental inversion.

As mentioned, some of the earlier work applying this correlation technique was for studying the diffuse coda of signals produced by multi-scatter. The time domain Green’s function was also obtained with this procedure using the coda of earthquake signals. For underwater acoustics, the analog is reverberation. We are beginning to study the reverberation problem in this context.

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References
AN AMBIENT NOISE FATHOMETER FOR PASSIVE MEASUREMENT OF BOTTOM DEPTH AND SUB-BOTTOM LAYERING

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Using the ocean ambient noise field, a passive method is presented to measure water depth and seabed sub-bottom layering. A passive technique is useful when active sonar is not practical or feasible. Situations include, for example, operating in environmentally protected areas. In this paper, the technique is described and illustrated using numerical simulations. Encouraging results are also shown from experiments at two sites with different equipment and operating frequency bands.

1 Introduction

The ambient noise field in the ocean is due to a variety of man made and natural sources, depending on the frequency band. We consider noise in the band from 200 Hz to about 5 kHz which is primarily due to wind and waves. In this paper, we outline a passive technique, using the ambient noise field, to extract the water depth as well as the sub-bottom layering in the seabed. A passive technique is useful when active sonar is not practical or feasible. Situations include, for example, operating in environmentally protected areas or when using underwater autonomous vehicles (UUV's) with power limitations. In addition to water depth, information about sub-bottom layers is also tremendously valuable. For example, predetermining the basic layer structure can be used to greatly simplify geo-acoustic inversion methods.

In recent years, several new techniques have been proposed to exploit the ocean ambient noise field for sonar and seismic applications. Harrison and Simons used vertical beamforming to compare the difference between the incoherent noise field coming from the direction of the surface to that coming from the seabed. The comparisons between upward and downward beam intensities give a measure of the seabed reflection loss magnitude (i.e. without the phase) [1]. Roux and Kuperman demonstrated how coherent wavefronts can be extracted from the ocean noise field using two vertical arrays separated by a horizontal distance [2]. Their work was inspired on the conjecture put forward by Rickett and Claerbout [3]: “By cross-correlating noise traces recorded at two
locations on the surface, we can construct the wavefield that would be recorded at one of the locations if there was a source at the other.” The wavefronts reconstructed by Roux and Kuperman showed that, in fact, cross-correlations between two receivers resembled that from a source to receiver with the source appearing more like a dipole than a true point source.

The work described here exploits the same phenomenon. However, we use closely spaced hydrophones vertically separated and we take advantage of both cross-correlations between sensors and beamforming. This combination makes it possible to extract both the water depth and the sub-bottom layering from the ambient noise field. It should be noted that getting the layer information would be very straightforward if the full complex reflection loss were known (i.e. magnitude and phase). However, using incoherent methods, the phase of the reflection coefficient is lost. Methods have been developed to recover the phase [4] but they rely on the assumption of a ‘minimum phase time series’ which cannot be guaranteed. Lack of phase information can give rise to undesirable false layers which cannot be distinguished from real layers. In this paper, we discuss a new technique which resolves this problem and provides the additional information needed to obtain water depth. We also use a method of images construction to elucidate the nature of arrivals appearing in the ambient noise field.

2 Analysis of surface noise and noise correlations

A theoretical approach describing the ocean ambient noise field was derived by Kuperman and Ingenito using wave theory that included seabed interactions [5]. In their approach, the sound generated from wind action on the surface was modeled as an infinite sheet of point sources located just below the surface at \( z' \). The derived cross-spectral density \( C(\omega) \) (at frequency \( \omega \)) between receivers at \((z_i, r_i)\) and \((z_j, r_j)\) is written in terms of the (range-independent) Green’s functions,

\[
C(\omega, R, z_i, z_j) = Q \int_0^\infty [g(k_r, z_i, z')g^*(k_r, z_j, z')] J_0(k_r R) k_r dk_r
\]

(1)

where, \( R = r_i - r_j \), \( J_0 \) is the Bessel function, \( k_r \) is the horizontal wavenumber, and \(*\) indicates the complex conjugation operation. The quantity \( Q \) is related to the strength, \( q \), and directionality of the noise sources and is given by,

\[
Q = \frac{8\pi^2 q^2}{k^2(z')}
\]

(2)

where the wavenumber, \( k \) is related to the frequency and water sound speed via \( k = \omega / c \). The integral in (1) has the same form as that used for obtaining the pressure field from the Green’s function and can therefore be easily evaluated using wavenumber integration techniques [6,7].
Figure 1: Left panel shows the geometry for the fluid halfspace problem. The pressure release surface gives rise to image sources at \( z' \). On the right, the cross spectral density (magnitude-squared on a decibel scale) given by (6) is shown. The source appears to be at the location of the receiver at \( z_1 \); however, it shows a dipole-like radiation pattern. Note that although there is a pressure release surface at \( z = 0 \text{ m} \) there is no surface reflection.

3 Numerical simulation study of extracting bottom depth and sub-bottom layering from ambient noise

3.1 Calculating the Green's function using the method of images in a homogeneous halfspace

To gain insight into the nature of the cross-spectral density in (1) we begin by constructing Green's functions using the method of images. The environment is assumed to be a fluid halfspace with the noise source located at \( z' \). The pressure release surface gives rise to images at \( -z' \). The geometry is shown in the left panel of Fig. 1. The total field at the receiver at \( z_1 \), in wavenumber space, can be written as a free space Green's function at \( z' \) and the image having opposite sign at \( -z' \),

\[
g(k_z, z_1, z') = e^{ik_z(z_1-z')} - e^{ik_z(z_1+z')}.
\]  

where \( k_z = \sqrt{k_r^2 - k_z^2} \) is the vertical wavenumber. If we assume the receivers are not located very near the surface (within a fraction of a wavelength), then we can drop the magnitude sign in the exponential. Denoting \( g_1 = g(k_r, z_1, z') \) and \( g_2 = g(k_r, z_2, z') \), the term in square brackets in (1) is,

\[
g_1 g_2^* = e^{ik_z(z_1-z')} e^{ik_z(z_1+z')} - e^{ik_z(z_1-z')} e^{ik_z(z_1+z')} e^{ik_z(z_1-z')} e^{ik_z(z_1+z')}.
\]

(4)

After some manipulation (using just the real part of \( k_z \)) this can be written,
This is the result for the most common case of a sheet of dipole sources at the surface (equivalent to a sheet of monopoles just below the surface). It is also essentially the result in Appendix A of [5] that was shown to be the same as that derived earlier by Cron and Sherman [8]. The cross-spectral density is written,

\[ C(\omega, R, z_1, z_2) = \mathcal{Q} \int_0^\infty e^{i k z (z_1 - z_2)} \sin^2(k z') J_n(k, R) k dk . \]  

The integral in (6), can be evaluated using wavenumber integration techniques by replacing the usual point source with the term given by (5). This term looks similar to a single, free-space Green's function. However, the source is not originating at the surface but instead originates at \( z_1 \) and is received at \( z_2 \) (or vice versa). Furthermore, compared to the free space problem, there is an extra \( \sin^2(k z') \) term that gives dipole-like shading. We therefore, expect the cross-spectral density to look similar to a shaded, free-space point source. A plot of the cross spectral density given by (6) is shown on the right panel in Fig. 1. In the figure, \( z_1 \) is fixed at 20 m depth and correlated with receivers, \( z_2 \), from 0—100 m (out to 500 m range for frequency of 500 Hz). We can see in the figure that the source appears at \( z_1 \) but note there is no reflection from the surface even though we have included the surface image (the apparent surface reflection requires including higher order image sources).

3.2 Calculating the Green's function using the method of images with surface and bottom images

In this section we approach a more realistic scenario which sheds light on how the ambient noise field can be used as a fathometer and sub-bottom profiler. In this case, we consider single surface and bottom images (pressure release boundary) which, in terms of propagation, correspond to the first surface and bottom bounces. The field at \( z_1 \) consists of contributions from the surface source, and the two images,

\[ g_1 = \frac{e^{i k z (z_1 - z_2)}}{4 \pi k z} - \frac{e^{i k z (z_1 + z')}}{4 \pi k z} - \frac{e^{i k z (z_H - z_1) + (z_H - z')}}{4 \pi k z} \]  

Similarly for \( g_2 \),

\[ g_2 = \frac{e^{i k z (z_2 - z')}}{4 \pi k z} - \frac{e^{i k z (z_2 + z')}}{4 \pi k z} - \frac{e^{i k z (z_H - z_2) + (z_H - z')}}{4 \pi k z} \]  

The product, \( g_1 g_2 \), is,
The first term in large square brackets corresponds to the shaded, free-space Green’s function that appeared in (5). The second and third terms correspond to an image source originating at \( z_1 \) but the combination of the two terms gives rise to the dipole-like image source. The second and third terms also have a conjugate image. To a receiver at \( z_2 \) it simply appears like a shaded source at \( z_1 \) and its image. The source, however, is not a point source but has some directionality. When processing for bottom depth and sub-bottom layering this directionality will have very little impact.

We next consider the cross spectral density in the time domain where the fathometer and sub-bottom profiler are most useful. Further, the complications due to the conjugate sources in (9) are easier to interpret in the time domain. Using Fourier synthesis, we can transform the frequency domain solution to the time domain, \( t \), according to,

\[
C(t, z_1, z_2) = \frac{1}{2\pi} \int_{-\infty}^{\infty} C(\omega; z_1, z_2) e^{-i\omega t} d\omega.
\]

By fixing receiver at a range, depth of \((0, z_2)\) and cross-correlating with receivers that sample the range and depth space, the result should, according to (9), look like a shaded source originating at \((0, z_2)\) with a few differences. One difference between this and a true point source is a weaker initial surface reflection. A second difference is due to the conjugate sources which can be thought of as backwards traveling wavefronts that converges on the source location. In Fig. 2 a series of time snapshots are shown for this case keeping only the first surface and bottom images. (Since the boundaries are perfectly reflecting there would actually be an infinite number of images.) The figure shows the time evolution of a pulse which results using a sum of frequencies in the 1—500 Hz band. The frequency spacing is 1 Hz which gives a time series lasting 1-second. Note the outgoing wave that disappears and then returns traveling in the opposite direction, and eventually collapses back at the source location. This wavefront traveling in the opposite direction is a consequence of the conjugate source terms in (9).
4 Processing vertically separated hydrophones for bottom depth and sub-bottom layering

The previous sections outlined how correlations between the measured ambient noise field on two hydrophones can synthesize a time-series. The time series appears as though one of the receivers is a shaded source. This is essentially how fathometers and sub-bottom profiling sonar systems operate. One of the differences is the source has a shading factor which has little consequence on a fathometer or sub-bottom profiler since only the arrival time is of interest. Another difference between a true source and receiver combination is the conjugate source terms. These should have little impact on the
PASSIVE FATHOMETER

Figure 3: Left panel shows the processing geometry that consists of a vertical array of hydrophones and a seabed with layers over a half-space. Water depth is $z_H$ and shallowest hydrophone is at a depth of $z_1$. On the right, the arrivals are shown. The direct path progresses down the array and this is followed by the bottom reflection arriving on channel 32 at 75.76 m at 0.0362 s. The sub-bottom reflections are also visible. Time series magnitudes are shown on a decibel scale.

We next illustrate the ambient noise fathometer/sub-bottom profiler by considering another simulation that includes a much more realistic seabed and all the surface and bottom reflections. The simulation, using the noise module of OASES [9, 10] allows us to study the processing in a controlled, known environment. The geometry is shown in the left panel of Fig. 3. In this case we use an array of 32 vertically separated hydrophones ($R = 0$) located between depths of 70.18 m to 75.76 m (0.18 m spacing) in the 100 m deep water column. The water column is iso-speed at 1500 m/s. The sediment is made up of a top 3-m layer with sound speed of 1550 m/s, density of 1.5 g/cm$^3$, and attenuation of 0.06 dB/λ. Below is a 5-m layer with sound speed of 1600 m/s, density of 1.65 g/cm$^3$, and attenuation of 0.2 dB/λ. The half-space below has sound speed of 1700 m/s, density of 1.65 g/cm$^3$, and attenuation of 0.2 dB/λ.

The first processing step is to correlate each hydrophone in the array, $z_n$, with each of the others, $z_m$ to form the cross spectral density at frequencies from 50 to 4000 Hz. The result is illustrated in the right panel of Fig. 3 for the shallowest hydrophone (channel 1) correlated with the others. In this case, the time reference is from channel 1 at 70.18 m depth and the direct path arrival can be seen progressing down the array. The later set of arrivals corresponds to the bottom and sub-bottom reflections. With channel 1 as the reference, the first bottom reflection arrives on channel 32 (at depth 75.57 m) at time...
From the figure, the bottom arrivals can be seen progressing up the array and the sub-bottom arrivals are also faintly visible.

Similar matrices of time series are formed for each of the subsequent channels as the reference forming a total of 32 matrices each with 32 time series. Each will have a different effective source position that depends on the channel depth used as the reference. Array processing can be used to combine all these and pull out a stronger signal that highlights the bottom and sub-bottom reflections rather than the direct arrivals. This is accomplished through delay and sum beamforming (since $R = 0$, the argument is removed) leading to the following correlation function:

$$
\widehat{C}_n(t) = \frac{1}{M} \sum_{m=0}^{M-1} C(t + m\Delta t, z_n, z_m),
$$

where,

$$
\Delta t = \frac{\Delta z}{c_w},
$$

and $\Delta z$ is the hydrophone separation (0.18m) and $c_w$ is the water column sound speed (1500 m/s). Regardless of which channel is used for the reference, the bottom and sub-bottom returns will show a monotonic delay progressing up the array although the absolute times still depend on the reference channel $n$. This first stage of beamforming produces an arrival structure for each reference hydrophone.

For the final step, delay and sum beamforming is used a second time to align the bottom arrivals into a single time series, $r(t)$,

$$
r(t) = \frac{1}{N} \sum_{m=0}^{N-1} \widehat{C}_n(t + n\Delta t).
$$

5 Experimental results

Experiments were conducted in 2001 and 2003, but neither of these was designed to test the passive fathometer/sub-bottom profiler. Nevertheless, the combined data sets provide encouraging evidence of the potential for this method. In 2001, the ASCOT-01 experiment took place off the Northeast coast of the U.S. in a site with 101 m water depth. This was primarily a geo-acoustic inversion experiment so sound sources were nearly continuously transmitting with the exception of about 0.5 s of data at the end of each file. Since the vertical array was fixed, these 0.5 s snapshots could be averaged over many snapshots producing, effectively, about a 30 s average. The fixed and well measured geometry of ASCOT-01 provides a useful check of the bottom return timing.

We used 33 elements in a 0.5-m spaced array with the top hydrophone measured to be 52.25 m from the seabed. The frequency band considered is 200—1500 Hz. In Fig. 4, the left panel shows the output after the first stage of beamforming. The bottom bounce is weak yet visible. From the single-phone, correlations the direct path could be seen but the bottom returns were too weak to be visible without beamforming. In the right, top panel of Fig. 4, the second stage of beamforming is applied and the bottom bounce is clearly visible. The peak near 0.07 s, puts the estimate of the distance to the bottom at...
52.5 m, well within the experimental error on the measured hydrophone distance of 52.25 m. The array reference at 52.25 m is very near the mid-water depth, and if a surface bounce were strong enough it could potentially interfere. To break the symmetry, the array beamforming was shifted to the deepest hydrophone and this is shown in the lower right panel of Fig. 4. As predicted, in neither case, is there evidence of a strong surface bounce (in addition to expecting the surface bounce to be weak, the beamforming tends to de-emphasize this return). There are sub-bottom returns here but ground-truth data wasn’t available for comparison.

A second experiment used a drifting array and took place in 2003 near the island of Elba, Italy. The array consists of 32 elements spaced at 0.18 m and the noise was processed in the 500—4000 Hz band. The first stage of beamforming is shown in the left panel of Fig. 5. The bottom paths are clearly visible and there is even a faint indication of the sub-bottom returns. The second stage of beamforming in the right panel more clearly shows the sub-bottom returns corresponding to 1-m and 4.3 m layers (assuming 1600 m/s sound speed).

### 6 Discussion and Conclusions

In this paper we have outlined a technique to passively measure water depth and seabed sub-bottom layering using ocean ambient noise. The method uses the cross-correlation between receivers in a vertical array together with beamforming for signal gain. This method may offer a promising way to passively map bathymetry and seabed layering using the background noise generated at the ocean surface from wind and waves.
Figure 5: Left panel shows the ElbaEx ambient noise processing after the first stage of beamforming. Near time 0.04 s the bottom bounce is seen and—very faintly—a sub-bottom return. The right panel shows the result after the second stage of beamforming with the bottom bounce at around 0.04 s and two layers readily visible corresponding to around 1-m and 4.3 m layers.

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References

MODELING THE COHERENCE OF PROPAGATION, SCATTERING AND REVERBERATION IN VERY SHALLOW WATER IN THE PRESENCE OF SURFACE WAVES

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A simplified theoretical approach to modeling the coherence of long-range propagation, scattering and reverberation in the presence of environmental uncertainty is used to estimate the expected value of active acoustic system performance in very shallow water in the presence of sea-surface motion. An adiabatic approximation for the phase and slowness deviation due to sea surface height excursion is used as the basis for the estimation of the expected value of backscattered target returns in the low to mid frequency band (1-10 kHz). Closed form solutions are compared to Monte-Carlo results for uncertainty induced by wind driven waves and swells (Work supported by ONR).

1 Introduction

Performance prediction for mine-hunting sonars operating at ranges much beyond a few water depths in very shallow water (VSW) is hampered by the lack of coherence introduced by environmental fluctuations, especially sea surface motion. In this paper we evaluate the expected value of the field incident on mine-like objects, the field backscattered from these objects, and the background coherent bottom reverberation in the presence of slight sea surface motion. Our approach is to treat the effect of the sea surface height excursions on normal mode propagation in VSW perturbatively, accounting for travel time and accumulated phase effects only. Although this approach is only appropriate for the regime of the lowest sea states, it is capable of illuminating the expected effects of environmental uncertainty on VSW sonar operations as the weather first transitions from calm to small waves. In this regime, we expect the regular interference structure superimposed by the environment on the response of objects and the bottom to begin to become unpredictable. One positive aspect of this effect is that coherent blind spots enforced by perfectly coherent propagation become illuminated.

2 Theory

2.1 Predictability of propagation in very shallow water in the presence of surface waves

Using the adiabatic approximation for the pressure in a range dependent waveguide [1], the ensemble average of the time domain narrowband co-intensity between the pressure
field at center frequency $\omega_1$ at the point $[r, z_1]$ and the pressure field at center frequency $\omega_2$ at the point $[r, z_2]$ is approximately [2-4]

$$\langle p(t, \omega_1, r, z_1) p(t, \omega_2, r, z_2) \rangle = 2 \text{Re} \left\{ \frac{2\pi}{\rho^2(z)} \sum_{n=1}^{N_z} \sum_{m=1}^{N_z} e^{i(k_\eta(\omega_1) - k_\eta(\omega_2))} \phi_n(\omega_1, z_1) \phi_m(\omega_2, z_2) \phi_n(\omega_1, z_1) \phi_m(\omega_2, z_2) \right\}$$

$$= \frac{1}{4\pi^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} e^{-i\omega_1\tau - i\omega_2\tau - \frac{1}{2}\omega_1^2 - \frac{1}{2}\omega_2^2} \sum_{e=1}^{E} \left( \Delta k_{n,m} + i\Delta S_{n,m} \right)^2 \right\}$$

where $S_{n,m}$ are the slownesses of the modes $n$ or $m$, defined as the derivatives with respect to circular frequency $\omega$ of the wavenumbers $k_{n,m}$, and $D_{n,m}$ are the modal dispersions $\partial S_{n,m} / \partial \omega$. The perturbations $\Delta k_{n,m}$ and $\Delta S_{n,m}$ to the model wavenumbers and slowness, due to Gaussian distributed surface height excursions of power $\sigma_n^2$ and correlation length scale $l_e$ indexed over an uncorrelated wave index $e$, are well approximated [5] as

$$\Delta k_n = k_n \left( k'_n \int_{-D}^{0} k^{-1}(z) dz \right)^{-1},$$

and

$$\Delta S_m = \frac{2\omega}{c^2(0)} - 2k_s' \left( k'_n \int_{-D}^{0} k^{-1}(z) dz \right)^{-1}$$

$$- k_n(0) \left( k'_n \int_{-D}^{0} k^{-1}(z) dz \right)^{-1}$$

$$+ k_n(0) \left( 2\omega \int_{-D}^{0} \frac{2\omega}{c^2(0)} - 2k_s' \right) k^{-1}(z) dz \right)^{-1}.$$  \hspace{1cm} (3)

The quality of these approximations is shown (Fig. 1), where the exact wavenumber and slowness deviations for 10kHz modes in an 11 m deep isovelocity waveguide with a 10 cm surface height excursion are compared to Eqs. (2) and (3). The results show that Eqs. (2) and (3) offer a sufficiently accurate representation of the perturbations expected to the accumulated phase and travel time of modes in VSW in the presence of waves.
Figure 1. Performance of perturbation approximations for $\Delta k_{en}$ and $\Delta S_{en}$ for modes at 10 kHz.

Note that the ensemble average in Eq. (1) may be evaluated either through Monte-Carlo techniques or formally by evaluating the frequency integrals over $\omega_1$ and $\omega_2$ [3].

2.2 Predictability of object backscatter in VSW

The time-domain co-intensity of the backscatter from a target imbedded in a waveguide under the single scattering [6] and narrowband approximation is [4]

$$\langle p_T(t, \omega_1, r, z_t) p_T(t, \omega_2, r, z_t) \rangle =$$

$$2 \text{Re} \left\{ \frac{4\pi^2}{\rho^2(z_t) \rho^2(z_s) r_{T}^2} \sum_{n,m=1}^{N_1} \sum_{n',m'}^{N_2} e^{i(k_{en}(\omega_1)-k_{en}(\omega_2))r}$$

$$\cdot \phi_n(\omega_1, z_s) \phi_{n'}(\omega_2, z_s) \left\{ \sum_{i=1}^{16} T_{enm,i}(\omega_1, \omega_2) \right\} \phi_{n'}(\omega_2, z_s) \phi_n(\omega_1, z_s) \right\}$$

$$- \frac{1}{4\pi^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} e^{-i\omega_1\frac{\omega_1^2\alpha_1^2}{2\Delta\omega_1^2}} e^{-i\omega_2\frac{\omega_2^2\alpha_2^2}{2\Delta\omega_2^2}}$$

$$\prod_{m=1}^{E} \left\{ \Delta S_{en}(\omega_1) \Delta S_{en}(\omega_2) \right\} e^{i\alpha \frac{\omega_1^2\alpha_1^2}{2\Delta\omega_1^2}}$$

where $k_{en} = k_n + k_m$, $S_{en} = S_n + S_m$, etc. The object scattering matrix $T_{enm'}$ is a combination of the four distinct object backscattering functions $ss\left( \pm \alpha \cos\left(\frac{k_n}{k_m}\right), \pm \alpha \cos\left(\frac{k_m}{k_n}\right), 0 \right)$ (as derived for a sphere for instance by Ingenito [6]), and the corresponding plane-wave decompositions of the mode shape functions at the scatterer depth $\phi_{n,m}^{k_n}$.

Thus for example
2.3 Predictability of reverberation in VSW

Bottom or surface roughness reverberation has a form similar to Eq. (4), with the modifications that an integral over all scatterer ranges is required for each pressure component of the co-intensity, and the assumption that the scatterers couple only down-going energy into up-going energy at the bottom, or up-going energy into down-going energy at the surface. This assumption reduces to one the potential number of scattering paths, yielding

\[
\langle p_b(t, \Omega_1, z_1) p_b(t, \Omega_2, z_2) \rangle = 2 \text{Re} \left\{ \frac{4\pi^2}{\rho^2(z_1) \rho^2(z_2)} \sum_{n,m=1}^{N} \sum_{l=0}^{\infty} \int_0^\infty \int_0^\infty \frac{d\rho_1}{\rho_1} \frac{d\rho_2}{\rho_2} \frac{e^{i(k_n(\omega_1) - k_n(\omega_2)) / 2\rho_1}}{\sqrt{r_2 k_n(\omega_1) k_n(\omega_2) k_m(\omega_1) k_m(\omega_2)}} \phi_n(\Omega_1, z_1) \phi_n(\Omega_2, z_2) \phi_m(\Omega_1, z_1) \phi_m(\Omega_2, z_2) \right\}.
\]

For Lambert’s law the bottom scattering functions are evaluated as

\[
ss_{\text{bottom}}(\omega) = 10^{27/20} \sin \left( \alpha \cos(k_n(\omega) / k_n(\omega)) \right) \sin \left( \alpha \cos(k_m(\omega) / k_m(\omega)) \right),
\]

and the scatterer correlation length scale \( l \) must be taken as much smaller than a wavelength. Both Eq. (4) and Eq. (6) may be evaluated either via Monte-Carlo techniques or through explicit evaluation of the frequency (and in the case of Eq. (6) the range) integrals.

3 Results

3.1 Very shallow water scenario

We simulate performance in an 11 m deep waveguide overlying a dispersive sandy isovelocity halfspace. The sound speed and attenuation of the halfspace are shown (Fig. 2, left panel). The density of the halfspace is 2 gm/cm³. The sound speed in the water...
column is 1537 m/s. The source and receiver are at a depth of 7.45 m for the backscatter and reverberation calculations, while the receiver is at the sediment water interface for the propagation calculations.

The target is a 30 cm steel sphere whose scattered response has been measured in the NRL tank. We are able to simulate the broadband response of the sphere using the narrow band approximation by combining numerous narrowband results. A comparison of the measured frequency domain target strength of the sphere and the Fourier transform of a sum of narrowband time domain approximations for free space propagation is shown (Fig. 2, right panel). The narrowband results have a bandwidth and spacing in the frequency domain of 2.5% of their respective center frequencies. The fidelity is considered to be acceptable for conducting an average of the sonar response over an ensemble of surface waves.

![Figure 2. Dispersion of sandy bottom in VSW environment (left) and free space target strength of steel sphere in the 1-10 kHz band (right).](image)

### 3.2 Incident field uncertainty at 5kHz

We estimate the expected value of the field for two different sea surface conditions. The first are fully developed homogeneous isotropic surface waves corresponding to the Pierson Moskowitz (PM) frequency spectrum for 10 kts of wind assuming the deep ocean surface wave dispersion relation [9]. We model this spectrum with two uncorrelated von Karman spectra of the form

$$ P_\eta(k) = \frac{\sigma_\eta^2 \Gamma(2)}{2 \pi \Gamma(3/2)} \left(1 + k^2 l^2\right)^{-2} $$

with standard deviations $\sigma_\eta$ of [30 15] cm and correlation length scales $l$ of [2 1] m. A comparison between a surface realization obtained with the one-dimensional PM spectrum and our two uncorrelated spectral components shows good agreement (Fig. 4).

The second free surface condition corresponds to small amplitude, long wavelength swells, as might be expected impinging in VSW from the direction of the open ocean due to distant storms. This second condition is approximated with two wave components with standard deviations of [10 2.5] cm and correlation length scales of [100 50] m.
The resulting average total field on the bottom at 0.8, 0.9 and 1.0 km is shown for 10 kt winds (left panel Fig. 5) and swells (right panel Fig. 5). In each case the Green curves show the total field in the absence of uncertainty, and the red curves shows the expected value to the total field in the presence of assumed surface wave motion. The blue curve represents a Monte-Carlo estimate of the average over 16 realizations of the free surface.

The results for the total field show that low values expected at certain ranges due to destructive coherent multipath become illuminated on average in the presence of surface wave induced uncertainty. For 10 kts of wind, only the lowest coherent nulls in the total field are filled on average, while for the swells the expected total amplitude is increased by as much as 5-10 dB for much of the signal duration, with only the highest positive values of the unperturbed field are reduced on average by the presence of fluctuations.
3.3 Backscattered field uncertainty

The variability introduced by the surface waves has the effect of increasing, on average, the return from bottomed objects in coherent nulls. Backscatter simulations for the two scenarios are shown (Fig. 6). The average response of the sphere in 10 kt seas is seen to be as much as 5 dB greater, and the response in the swell as much as 10 dB greater, than the unperturbed response.

Figure 6. Unperturbed and expected value of field scattered from steel sphere bottomed in VSW in the presence of 10 kt wind generated waves (left) and swells (right).

The average backscattered response of the sphere deviates more from the unperturbed response than the incident fields for two reasons: the path of propagation is twice as long, and the scattered response is a product of all the incident and scattered paths, and therefore is more sensitive to the phase stability between the individual paths.

Figure 8. Bottom reverberation for swells at 5kHz (left) and corresponding average broadband reverberation striation structure over the 1-7.5 kHz band (right).
3.4 Reverberation uncertainty

Coherent reverberation predictions are shown for swells at 5Khz (Fig. 7, left panel) and over the 1-7.5 kHz band (Fig. 7, right panel). The effect of sea surface motion on reverberation is to reduce the certainty and therefore the depth of the deep nulls in the coherent reverberation prediction. The effect over very broad bandwidths is to reduce the definition of the striation pattern in the frequency-time pattern of the predicted reverberation. The simulations show that reverberation from a multipath environment has a predictable striation pattern. As environmental variability is introduced, either through a changing environment, or through an azimuthal average over an azimuthally dependent environment observed through broad beamwidths and back beams, the strength of the observed striation pattern is reduced.

4 Conclusions

The coherent, highly overlapped multipath characteristic to propagation, target scattering and reverberation beyond a few water depths in VSW renders performance prediction for mine hunting sonars sensitive to the exact characteristics of the environment. Surface motion imposed by wind drive waves and swells can introduce significant uncertainty into coherent multipath predicted for these types of environments. We have introduced a simple method to begin to account for the uncertainty superimposed by environmental factors on mine hunting sonar performance. The method predicts higher average responses from objects nominally at ranges of strong destructive interference, as well as a diminishing of the predictability of the striation patterns in the time-frequency of background reverberation. The method is currently being extended to obtain coherent broad-band predictions of the average propagation, scattering, and reverberation expected for mine hunting sonars in very shallow water.

References

Section 6

Targets
INTEGRATED, AUTONOMOUS SONAR CONCEPT FOR CONCURRENT DETECTION, CLASSIFICATION AND LOCALIZATION IN LITTORAL MCM

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Ocean exploration and naval operations are currently experiencing a dramatic paradigm shift from platform-centric sensing and operation towards net-centric off-board sensing networks capable of fully autonomous operations in denied littoral areas. This paradigm shift is largely driven by the revolutionary development in autonomous vehicle technology, and wireless network communication, command and control experienced over the last decade. However, the lack of GPS severely limits underwater navigation, and communication underwater is several orders of magnitude slower than wireless RF communication, and inherently characterized by strong intermittency and latency. Consequently such sensing networks must be capable of operating with no or at least very limited operator control. Most existing sonars are dependent on a human operator for interpretation and intervention, and are unlikely to be optimal for adaptation to AUVs, which are still a far cry from having human intelligence. This paper discusses the limitations of the existing sonar concepts in this regard, and demonstrates how a relatively simple, generalized SAS sonar may be integrated with the autonomous vehicle control to concurrently detect, classify and locate targets, while simultaneously and adaptively navigate the platform using autonomous, feature-based navigation concepts.

1 Introduction

With the successful development, demonstration and operational transition of the new autonomous underwater vehicles (AUV) technology, and significant progress in underwater communication networking, a paradigm shift is being experienced in ocean exploration and naval operations, away from traditional, platform-centric ocean sensing systems, towards new net-centric, autonomous, off-board sensing systems. However, the transition of similar, mature terrestrial networking technology is non-trivial due to the complex, uncertain underwater acoustic communication and sensing environment. Thus, the communication capabilities are several orders of magnitude lower than in wi-fi systems, with high inherent latency, and intermittency. This in turn imposes strong constraints on the network control architectures, and eliminates the possibility of having an operator interpreting sensing data during operations in denied areas. Also navigation is a serious issue, in particular in cases where neither GPS nor acoustic navigation infrastructure exists. When it comes to sensing, most of the use of AUVs for MCM in the past has been based on adaptation of the traditional, platform-centric sensing concepts, such as side-scan sonars (SSS) and synthetic aperture sonars (SAS), inherently being developed for accurately navigated platforms, and designed for operator interpretation.
With no operator access it is likely that these sonar concepts are sub-optimal for fully autonomous operation in remote, denied areas.

This paper summarizes research under the GOATS [1], and SWAMSI projects, aimed at developing new mono-, bi- and multi-static sonar concepts, which are tailored for fully autonomous, concurrent detection, classification and localization of targets in denied littoral areas without reliable communication and navigation infrastructure. The concept emerging is a network of AUVs applying integrated feature-based acoustic sensing and navigation, combining track-before-detect algorithms for detection and localization with Simultaneous Localization and Mapping (SLAM) for collaborative navigation, and spectral characterization for classification, while individually and collectively exploring benefits of adaptive and collaborative sensing, processing and control.

2 Feature-based Navigation and Adaptivity
The reality of not having external, global navigation aids available for operating the autonomous sensing networks has lead to a major push towards the development of un-aided navigation concepts which are independent of pre-existing maps. Even though inertial navigation systems are available, even the high-end, very expensive systems have a finite drift which make them inadequate for stand-alone navigation of long-term submerged systems. The development of feature-based navigation concepts, referred to as SLAM, is receiving significant attention. The idea is to continuously update and track relative position information for identifiable environmental features, e.g. the slant ranges, and then use a Kalman filter to estimate and track a state vector representing the position of all features and platforms, consistent with the measurement uncertainties. SLAM is inherently applicable to stationary as well as moving features, thus allowing for collaborative autonomous network navigation. Pushed by the need for accurate, reliable navigation for robotic surveillance in hostile, unmapped environments such as caves and buildings, where GPS is not available, SLAM has received strong attention from the robotic research community, with several impressive demonstrations, and operational applications [2]. However, as is the case for communication, the strong spatial and temporal variability in the underwater environment is a severe complication. SLAM has been successfully demonstrated using uncertain and intermittent range-only measurements obtained with an LBL system, but with limited success using sonar ranging data and conventional detection algorithms [3]. Below we demonstrate how advanced acoustic signal processing can alleviate this limitation.

Another advantage of the feature-based environment representation and perception is the possibility of adaptively controlling the platform to optimally explore the properties of interesting features once they are detected. Such feature-inspired adaptivity is one of the major potential gains that may be associated with the autonomous networks as compared to the platform-centric approaches.
3 Pseudo-Imaging MCM Sonars

The most common sonars applied to MCM are the classical side-scan sonar (SSS), and the related synthetic aperture sonar (SAS). Both SSS and SAS create images of the seabed as illustrated in Fig. 1. However, neither are true imaging sonars, which would create an image of the seabed ‘as seen from the AUV’. Instead they will be referred to as pseudoo-imaging sonars, because they create an image of the seabed as if observed from above, while being ‘illuminated’ by an acoustic ‘flood-light’ on the AUV. SSS and SAS use physical apertures of similar length, compatible with small and mid-size AUVs. Both achieve range-resolution of the image by high bandwidth, but while the SSS achieves angular resolution using high carrier frequency, typically 200-800 kHz, yielding horizontally narrow beams, the SAS achieves angular resolution using a synthetic aperture created by multiple pings, made possible by the lower carrier frequencies, yielding a wider beam and therefore multiple insonifications of each bottom ‘pixel’. The advantage of SAS is that it yields range-independent angular resolution, and increased bottom penetration, yielding some buried target detection capability.

Both SSS and SAS rely on an accurate platform track, requiring real-time, precise navigation and control. On a local scale this may be achieved using INS or some pre-deployed acoustic navigation system. Although high-resolution images provide a convenient data representation for human operators, both SSS and SAS are at odds with the real-time feature-based navigation and adaptive behavior that are envisioned as cornerstones of the off-board autonomous sensing networks, due to the computationally intensive two-step process required for feature extraction. Even if the imagery is generated in real-time, it must then undergo secondary processing for feature identification, which is generally an extremely computationally intensive procedure. In the case of SAS, the image generation necessarily involves a time lag while the synthetic aperture is built, during which time the vehicle must follow a nearly linear path. This path limitation severely restricts the mobility of the sonar platform. If the imaging and feature extraction steps cannot both be performed in real-time, then the system must follow a strict, pre-determined survey pattern, creating an inherent incompatibility with feature based SLAM for global navigation, as well as an incompatibility with the use of...
real-time adaptivity for improving classification performance. Finally, the pseudo-imaging does not allow the tracking of moving targets such as other network nodes, and is therefore inapplicable to collaborative, feature-based network navigation.

![Image of low-frequency SAS sonar](a) ![Image of acquisition payload](b)

Figure 2. Low-frequency SAS sonar with nose-mounted 2x8 element array and acquisition payload with 4-20 kHz SBP source and 16-channel DSP acquisition system.

4 Autonomous DCLN Sonar

4.1 Low-frequency, Generalized SAS Sonar

As part of the GOATS and SWAMSI programs, MIT has developed a low-frequency, wide-beam research sonar, fully integrated with two MIT-owned Odyssey III AUV’s [4]. In what may be considered a generalized SAS configuration, the sonar uses a COTS sub-bottom profiler source operating in the 4-20 kHz band, tilted to insonify the seabed on either the starboard or port side of the vehicle, as shown in Fig. 1(a). The source has a nominal beamwidth of approximately 30 degrees. As receiver, the sonar uses one of two 16-element arrays built specifically for GOATS by SACLANT Undersea Research Centre [5], and mounted in a swordfish configuration in the nose of the vehicles, as illustrated in Fig. 1(b). One array is configured as a single linear array with element spacing 5 cm (15 kHz), while the other has a vertical aperture with 2 8-element arrays with 10 cm spacing (7.5 kHz), separated by 15 cm. A dedicated acoustic acquisition system has been developed by MIT and integrated in a pressure vessel in the payload section of the vehicles.

Developed for research, the DSP-based acquisition system was designed to be fully flexible in terms of investigating both traditional sonar processing and new integrated, autonomously adaptive behaviors. Thus, all channels are sampled individually, at programmable sampling rate up to 100 kHz. In addition to being stored for post-processing, the data are accessible in real time to the acquisition computer and the DSP for on-board processing and adaptive decision-making. The systems are time synchronized to GPS, maintained during submerged operations using rubidium oscillators, allowing time-synchronized, multi-vehicle collaboration, including bi- and multi-static sonar processing. The acquisition computer runs Linux and is capable of
either detached self-contained operations, or operations that are fully integrated with the AUV control. This is achieved by controlling the acquisition operations within the same MOOS (Mission-Oriented Operations Suite) control architecture applied on the MIT autonomous vehicles. In the integrated mode, the sonar will be a MOOS client similar to all other sensors and actuators on the vehicle, allowing it to directly affect and alter the vehicle operations, which is obviously a crucial requirement for sonar-adaptive mission behaviors.

In the following we will demonstrate how this relatively simple sonar may form a prototype for a feature-based DCLN sonar concept, performing concurrent target Detection, Classification, Localization, while simultaneously Navigating the platforms using SLAM.

![Figure 3. Detections (left) and estimated target tracks using the Track-Before-Detection algorithm (right) on SAS data collected during GOATS/MASAI’2002.](image)

4.2 Concurrent Detection, Tracking and Localization

Both natural and manmade features are often weak, aspect-dependent targets, introducing a significant intermittency in the feature tracking. It is crucial to SLAM that multiple targets can be tracked for extended periods, and that time-separated tracks associated with each specific target can be reliably associated with each other.

To achieve this consistent tracking performance for weak, aspect-dependent buried targets in particular it is necessary to integrate the tracking with the detection such that the detection statistic can be integrated along an estimated target track. Such a Concurrent, Track-before-Detect (TBD) algorithm has been developed [6]. By coherently integrating the time signals over the estimated AUV path, weak targets with intermittent sonar response may be robustly tracked and detected, without the tight navigation constraint of traditional SAS. In fact the TBD benefits from the spatial diversity associated with a non-linear track, e.g. by breaking ambiguities and allowing identification of individual multi-path. The resulting continuous target tracks allow the AUV to robustly navigate using SLAM.
Figure 3 shows the results of the TBD algorithm applied to GOATS’2002 data. Clutter, modem and LBL navigation signals are totally eliminated due to their lack of ping-to-ping coherence. The bathymetry returns and multi-path returns from the targets are identified using beamforming, and used for AUV navigation and target detection, respectively. In a traditional scheme, these multi-paths could be treated incorrectly as targets. The associated SLAM-generated target map and AUV track are shown in Fig. 4. The red circles indicate the locations of the seabed targets, while the blue track shows the estimated vehicle track, comparing well with the LBL navigated track in green.

![SLAM produced map of target locations corresponding to TBD sonar tracks in Fig. 3. LBL navigation of AUV shown in green; vehicle track by TBD/SLAM shown in blue.](image)

4.3 Concurrent Detection and Classification

An autonomous, concurrent detection and classification (CDAC) concept has been developed using a series of simple classification tasks that utilize the mobility and adaptivity of AUV sonar networks. Directly linked to the detection algorithms, these concepts have the potential of significantly reducing the false alarm rate in a mine hunting mission. The classification technique involves the detection of an elastic response in the signal backscattered from the object [7]. Rocks and boulders do not exhibit the strong coherent structural waves, which are characteristic of man-made objects, such as mines of other more regular geometries. The elastic waves are strongly aspect- and object-dependent and are delayed in time with respect to the specular return due to the fact that the waves must travel around the object to build the target resonance. To capture this delayed return, a temporal window is applied to the signal following the specular return, and analyzed for the presence of an identifiable elastic response. The length of the window is related to the characteristic dimension of the target and must be chosen as a compromise between two opposing needs: it should be long enough to contain the main elastic component and short enough to avoid interfering signal from nearby targets. This procedure performs the classification task as a binary hypothesis
test for each target: the weak elastic response must be detected inside the search window, in the presence of correlated reverberation. To this purpose, higher-order spectral analysis techniques have been employed [7], in particular the second (spectrum) and third order cumulant spectra (bi-spectra).

The spectral classification step is illustrated in Fig. 5, showing the estimated spectrum of a 1 m diameter buried spherical shell compared to the estimated reverberation spectrum for both experimental and simulated data. The experimental data were collected during the GOATS 2002 experiment, while the simulated data were generated using the SEALAB target scattering simulator (developed by VASA Associates). In addition to the spherical shell simulated data were generated for a rigid sphere without structural resonances. In both experimental and simulated data the elastic peaks are clearly distinguishable from the reverberation spectrum, although they appear to be more pronounced in the simulated data. The simulation tool models the surface scattering process, but neglects the volume scattering process, which shows up at lower frequencies.

In addition to allowing for real-time range-only SLAM, the DCLN sonar concept is also inherently compatible with real-time adaptive behavior, e.g. autonomously modifying the vehicle path to explore aspect-dependence of targets for classification, as has been demonstrated and reported elsewhere [8].

![Figure 5. Sphere spectrum estimation compared to the reverberation and rock spectra, using the GOATS 2002 experimental data and SEALAB simulated data.](image)

**5 Conclusion**

Ocean exploration and naval operations are currently experiencing a dramatic paradigm shift from platform-centric sensing and operation towards the use net-centric off-board sensing networks capable of fully autonomous operations in denied littoral areas. This paradigm shift is largely driven by the dramatic development in autonomous vehicle technology, and wireless network communication, command and control experienced over the last decade. However, the lack of GPS severely limits underwater navigation,
and communication underwater is several orders of magnitude slower than its in-air counterpart, and is inherently characterized by strong intermittency and latency. Consequently such sensing networks must be capable of operating with no, or at least very limited, operator control. This stands in stark contrast with existing sonars, which are dependent on a human operator for interpretation and intervention, and therefore sub-optimal for adaptation to AUVs. This paper has demonstrated how a relatively simple, generalized SAS sonar may integrated with the autonomous vehicle control to concurrently detect, classify and locate targets, while simultaneously navigating the platform using an autonomous, feature-based, navigation technique.

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References

RAY METHODS AND EXPERIMENTS FOR TARGETS WITH AND WITHOUT BOUNDARY INTERACTIONS

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In shallow water high frequency sound is sometimes used for target detection and classification. Some ray methods and experiments are summarized here for understanding the scattering of sound by targets and the interaction of sound with boundaries. Special attention is given to scattering enhancements associated with caustics.

1 Introduction

It has been demonstrated using experiments that truncated solid objects in water can exhibit significant high frequency backscattering enhancements [1-12]. These enhancements can produce signatures that greatly exceed those expected for a rigid object having the same shape and dimensions as the target under investigation. The dependence of the tilt or orientation of the target with respect to the illumination is such that the recognition and identification of enhancements of this type may be helpful for the classification of targets and their material properties. To facilitate an understanding of these enhancements it is appropriate to introduce quantitative ray methods in which the interaction of sound with a target is modeled using local coupling processes [13-26]. In the present paper some underlying principles pertaining to quantitative ray methods are reviewed and some relatively recent developments pertaining to boundary influences are noted. Many of the enhancements discussed here are not caused by target resonances.

2 Geometrical Aspects of Scattering and Diffraction

The shape of incident and scattered wavefronts associated with specific scattering processes is important for identification of which processes will be the most significant ones for any given measurement. The identification of the important processes is helpful since, in many situations, it is found that the weak processes need not be calculated if observations can be made in such a way that the scattering is dominated by mechanisms associated with enhancements. The importance of wavefront shape is illustrated by inspection of Fig. 1 [13,14,27,28]. The ray tube associated with a patch of wavefront is shown. That wavefront may be associated with some specific scattering process, for example, the radiation of supersonic leaky waves guided by the surface of a solid object, and there may be many other contributions to the total wavefield that may be considered
As the wavefront shown in Fig. 1 propagates, the area of the ray tube evolves. Neglecting attenuation in the water (which often may be re-introduced at a later stage if necessary), the pressure amplitude $|p|$ along the ray indicated by vector $\mathbf{n}$ evolves according to purely geometrical reasoning as follows:

$$|p(z)| = |p(0)| \sqrt{A(0)/A(z)},$$

(1)

where $z$ denotes the distance from $P$ along $\mathbf{n}$, $A(z)$ is the local ray tube area, $A(0)$ is the area of the ray-tube for the patch at $P$, and $|p(0)|$ is the amplitude of the quasi-steady state signal at $P$. Ordinarily, for tone bursts having a sufficiently slow time variation of their envelope, it is often possible to neglect the slow variation of the envelope. In addition to the limitations of geometric reasoning, for the purpose of simplifying this discussion, the properties of the water are taken to be uniform so that rays in water become straight lines. An important feature of Eq. (1) is that the geometrically predicted amplitude diverges at caustics where the local area of the ray tube $A(z)$ vanishes. At such locations $|p(z)|$ diverges and corrections associated with diffraction become essential, even for an arbitrarily high frequency [13,14,27-29].

In Fig. 1, the radius $r_1$ denotes the reciprocal of one of the principal curvatures at $P$ of the wavefront patch. The sign convention is such that $r_1 < 0$ for the converging patch shown. The example shown is such that the reciprocal of the second principal curvature, $r_2$, is also $< 0$. The area ratio in Eq. (1) becomes $A(0)/A(z) = r_1 r_2 / [(r_1 + z)(r_2 + z)]$ so that the caustics are at $z = -r_1$ and $z = -r_2$. If either principal curvature vanishes for the outgoing wavefront, then $|r_1| = \infty$ or $|r_2| = \infty$ so that there is a far-field caustic. Such caustics are commonly known as "directional caustics" [27] since they are associated with a propagation direction. As is the case for ordinary caustics at a finite distance $z$, diffraction corrections become essential for directional caustics. In many situations it is possible for targets to generate an outgoing wavefront for which the magnitudes of both principal radii $|r_1|$ and $|r_2|$ diverge.

3 Conditions for (and Approximation of) Far-Field Scattering Enhancements

From the discussion below Eq. (1) it follows that it is important to be able to calculate the curvature of the outgoing wavefronts associated with specific scattering processes. Furthermore, if the acoustic receiver is at a large distance from the scatterer, it is important to be able to identify scattering processes from which either or both of the principal wavefront curvatures $1/r_1$ and $1/r_2$ vanish. If such a process is associated
with some guided mode of the target that couples sufficiently strongly with the acoustic wavefield, it is often possible to restrict attention to that specific process. This is especially the case when both $1/r_1$ and $1/r_2$ vanish. In practice, the receiver is never located infinitely distant so that it only is necessary that either or both of $1/r_1$ and $1/r_2$ be small. The degree of smallness is determined by the distance to the observer and by diffraction. Diffraction is influenced by the wavelength in water, the target dimensions, and other parameters that influence the outgoing wave such as the spatial attenuation rate [24,25] of leaky elastic waves guided by the target.

In the modeling of the outgoing wavefront and the associated local amplitude, the first step is to use standard wave-vector coupling conditions. The projection of the incident acoustic wave vector on the target surface matches the wave vector of a guided mode or the wave-vector projection of refracted longitudinal or shear waves [13,15,17,23,24]. Examples of guided wave modes include leaky Lamb waves and Rayleigh waves. Transmitted and refracted longitudinal or shear waves are sometimes referred to as “bulk waves” to distinguish them from surface guided waves. The outgoing wavefronts are constructed using a similar wave-vector matching condition with the radiated sound field [23,24]. Coupling conditions for leaky waves may be expressed as a generalization of Fermat’s principle and the width of the coupling regions expressed as a generalization of Fresnel zones [23-26].

Once the relevant outgoing wavefronts are identified, in many situations involving leaky waves it has been possible to obtain useful approximations of the outgoing amplitudes by evaluating a convolution integral [22-24] involving: (a) the complex incident wave amplitude at illuminated points on the surface of the target and (b) a propagator (a specific leaky-wave contribution to a path-dependent Green’s function). This formulation was first tested by comparing outgoing amplitudes obtainable by other methods [23,24] and by considering benchmark cases [25,26,30] pertaining to different types of leaky waves in infinitely long tilted cylinders. In the case of truncated targets, the evaluation of the far-field scattering involves the approximation of a diffraction integral [3-5,25].

For certain situations it is possible for the outgoing wavefront to be associated with one of the standard diffraction catastrophes [13,27-29] provided the wavefront is
sufficiently wide. For real situations, however, the outgoing wavefront is truncated because of the finite target size or some other aperture. In those situations the far-field amplitude is approximated by a convolution of an elementary diffraction catastrophe wavefield with an aperture-diffraction function. See Section 3.15 of [13].

4 Examples of Enhancements for Metallic Truncated Targets

Though several observed enhancements were recently reviewed [31], a brief summary is listed here. It is convenient to distinguish between relatively "soft" materials (such as plastics) to be considered in Section 5, and "hard" materials such as most metals, glasses, and ceramics. Ray theory of enhancements for smooth targets, such as spheres and cylinders illuminated broadside, has been derived with Watson transformation methods and related extensions [15-22] and those examples are not emphasized here. For "hard" targets, the shear wave velocity and the Rayleigh wave velocity for the target material exceeds \( c \), the speed of sound in water. For these targets, leaky wave modes (those modes having a phase velocity \( c_l \) that exceeds \( c \) on the fluid-loaded target) exist over a wide frequency range and the methods discussed in Sections 2 and 3 are often directly applicable. For backscattering from tilted cylinders, it is necessary for the guided wave to reflect from the end of the cylinder. Examples that have been modeled include: (a) guided waves on tilted cylindrical shells (with or without water on the inside) [6-9], (b) Rayleigh-like waves guided by tilted solid steel cylinders [3,4,22,23], (c) Rayleigh-like waves that cross and reflect from the edges of a tilted steel cube [5], and (d) various waves guided by hard (glass) tilted circular plates in water [10,11]. That example includes the special case of waves that circumnavigate the edge of the plate. In these examples quantitative application of ray theory requires estimates of the reflection coefficient of the guided wave by a truncation [3-7].

5 Examples of Enhancements for Plastic Targets

Plastic targets (such as PMMA or polystyrene) are relatively soft so that the shear wave velocity is less than \( c \) of water. For those materials the Rayleigh wave velocity is also less than \( c \). Nevertheless, Rayleigh waves on PMMA spheres in water were found to enhance the scattering in a way described by ray theory [32]. The relevant ray theory was a revision of one developed for subsonic flexural waves in thin metallic shells [20] and the subsonic Rayleigh waves were associated with narrow resonances. (Some authors would refer to this Rayleigh wave as a Sholte-Stoneley wave.) Examples of enhancements of plastic targets with truncations include: (a) the caustic merging transition of a flat-ended tilted plastic circular cylinder [12]; (b) various enhancements observed for tilted plastic cylinders having rounded ends [33]; and (c) various enhancements observed for a plastic truncated frustum of a cone [33]. In the cases involving cylinders it has been helpful to investigate the scattering of light for a partial analogy: a dielectric object (glass or fused silica) having the same shape as the target [33,34]. The refracted light waves are partly analogous to shear waves in the plastic target. In (a), (b), and (c) it is possible to have one of the principal outgoing wavefront curvatures vanish for certain tilt conditions.
6 Boundary Interactions and Boundary Caustics

In the case of a smoothly curved sea floor or sea surface, the sound reflected from a source can produce acoustics according to conditions noted in the discussion of Eq. (1) [13,14,27-29,35-37]. It was recently demonstrated and modeled that the scattering by smooth targets placed at such a caustic can be enhanced [38]. A potentially difficult problem for ray methods is the case of a target that only partially crosses a surface. This may include: (i) objects that are partially buried and partially exposed, or (ii) objects that are partially lowered through the top surface. Singularities associated with the sudden change in the number of reflected rays were avoided by introducing a Kirchhoff approximation and the results were confirmed by lowering a cylinder through the free surface of water [39]. Finally, in the case of a smooth sea bottom with sound at grazing incidence, evanescent acoustic waves can be produced in the sediment. While prior experiments on the scattering of blunt objects by evanescent acoustic waves have involved waves in air [40], recent progress has involved evanescent waves in a liquid simulated bottom [41].

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References


THE USE OF THE EQUIVALENT SOURCE TECHNIQUE IN CALCULATION OF SCATTERING FROM UNDERWATER TARGETS

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The equivalent source technique is a method of computing scattering and radiation from a target by replacing the target by a distribution of discrete sources, whose complex amplitudes are determined by applying the boundary condition on the total field. The advantage of using this method, particularly in underwater acoustics, is that it essentially transforms the scattering and propagation problems into just a propagation problem, where the target can be treated as a distribution of sources rather than an impedance discontinuity. The equivalent source technique is outlined and applied to two and three-dimensional targets in free space and in a waveguide.

1 Introduction

Detection and classification of underwater targets, whether located in the water column, on the bottom or buried in the sediment, requires the solution of the wave equation in a waveguide in the presence of a scatterer. In most cases a single-scattering approach is used, where the scattering and propagation problems are decoupled [2]. In this approach the scattered field is computed using a Green’s function for the waveguide, which is computed in the absence of the target. Since the scattering and propagation problems are solved separately, this approach does not account for multiple scattering between the target and the waveguide boundaries; more importantly, it is incapable of treating partially buried targets. An exact solution of this problem, which will be free of the above shortcomings, requires that boundary condition be simultaneously imposed on all boundaries, including the boundaries of the target. One way to obtain this solution is to use the finite difference or finite element methods, where boundary conditions are incorporated into the governing discretized equations [1]. However, since the size of the resulting matrices in both methods is a function of frequency, the numerical cost of solving a scattering problem in a waveguide many thousands of wavelengths in size can quickly become insurmountable.

In the equivalent source approach (also known as the equivalent source approach) the target is replaced by a collection of sources, whose complex amplitudes are determined by satisfying the boundary conditions at the surface originally occupied by the target [4, 3]. By choosing these sources to be the waveguide Green’s functions, a self-consistent solution is obtained that satisfies the wave equation as well as the boundary conditions on all surfaces, including the surface of the target. Furthermore, by replacing the target with a collection of sources, the scattering and propagation problems...
are converted to a muti-source propagation problem, which can be solved by any standard propagation model.

In the following sections the equivalent source technique is outlined and applied to various problems.

2 The Equivalent Source Technique

Let us first consider the case of an impenetrable target occupying a volume $V$ in free space. The field, satisfying the Dirichlet boundary condition, can be expressed as:

$$\psi(x) = \psi_{\text{inc}}(x) + \psi_{\text{scat}}(x),$$

$$\psi(x) = 0, \ x \in \partial V.$$ 

In the equivalent source approach, the target is replaced by a collection of point sources with complex amplitudes. Mathematically this can expressed as

$$\psi(x) = \psi_{\text{inc}}(x) + S G(x, y).$$

Observe that in the above equation the scattered field has been replaced by a vector, $S$, containing the complex source amplitudes, times a matrix, $G$, which is the free space Green’s function for point sources located at points specified by the vector, $y$. Application of the boundary conditions yields the unknown amplitude vector as follows

$$S = -G^{-1}(x, y) \psi_{\text{inc}}(x), \ x \in \partial V.$$ 

The location of the point sources is arbitrary and largely depends on the type of problem. Placing the sources just inside the target boundary surface seems to be the most intuitive choice and has been adopted by most researchers.

For the case of a penetrable target, in addition to sources that produce the field in the exterior of the target, another set of sources are needed to produce the field in its interior. This situation is depicted in Fig. (1), where a cylindrical target is replaced by two sets of sources, one just outside the original surface of the target to produce the interior field and a second set just inside the original surface of the target to produce the exterior field.

![Figure 1: In the equivalent source approach a penetrable target is replaced by two sets of sources to produce the field in its interior and the exterior medium.](image-url)
Since the field is composed of pressure and displacement, each source can be viewed as two sources collocated to produce one of the above components. The response of the target to the exterior sources can be expressed by the target’s interior Green’s function. If the target is surrounded by a fluid medium, the continuity of pressure and normal displacement just outside its boundary can be expressed as

\[
\begin{align*}
 p_{inc}(x) + G_p^{(1)}(x, y) S &= G_p^{(2)}(x, z) Q, \\
 u_{inc}(x) + G_u^{(1)}(x, y) S &= G_u^{(2)}(x, z) Q.
\end{align*}
\]

In the above equations \( G \) with the subscript \((p, u)\) represents the pressure and normal displacement Green’s functions, respectively. Similarly, the vectors \( S \) and \( Q \) respectively represent complex amplitudes for the interior and exterior sources. The solution of the above equations gives the interior source amplitudes,

\[
S = \left( G_p^{(1)} - KG_u^{(1)} \right) \left( K u_{inc} - p_{inc} \right).
\]

\[
K = \left( G_u^{(2)} - G_p^{(2)} \right)^{-1}.
\]

Since the interior sources produce the field in the surrounding medium, knowledge of their amplitudes and the Green’s function for the exterior medium are enough to solve the problem. The matrix \( K \) can be computed using the target’s Green’s function, which can be obtained from a finite element model for targets of arbitrary composition.

3 Results

In this section we use the theory outlined in the previous section to compute scattering from various targets. As a first example we present the solution of scattering of a plane wave from a solid cylinder in free space. This problem can be solved analytically and provides a means of verifying the performance of the equivalent source approach. The results are shown in Fig. (2). In this calculation the target has a compressional sound speed of 1700 m/s, a shear sound speed of 600 m/s and a density is 1.5 g/cc. The surrounding medium is water. The incident field is a plane wave incident along the positive x-axis. The left panel shows a comparison of the pressure field as a function of angle of observation computed using the exact method and the equivalent source technique, where 50 sources were used. The right panel shows the same comparison when 60 sources are used. Note that 60 sources are enough to produce the exact results.

![Figure 1: The total field resulting from scattering of a plane wave along the positive x-axis from a solid cylinder. The left panel shows a comparison between the exact solution and the equivalent source solution when 50 sources are used. The right panel shows the same when 60 sources are used.](image)
Next, as an example of a three-dimensional target, which also has an exact solution, we present the solution of scattering of a plane wave from a sphere. In this case a plane wave is incident along the negative z-axis, which makes the axis of the cylinder. The results are shown in Fig. (3). This figure also shows the distribution of sources just inside the surface of the sphere represented by red dots. The black dots represent the nodal points where the boundary condition is imposed. The product of wavenumber and the radius of the sphere in this calculation is $ka=8$, which corresponds to a frequency of 1900 Hz in water, for a sphere of one meter radius. This calculation required about 1800 sources.

As a second example of a three-dimensional target, we calculate scattering from a truncated cone in free space using the equivalent source technique. In this calculation the height of the truncated cone and its base are one meter each, while the radius of its truncated top is 2/3 of a meter. This is a mono-static calculation where the incident field is a plane wave and both the source and the receiver move from zero to 90 degrees measured from the axis of the cone. The frequency of the incident wave is 1900 Hz and approximately 1800 point sources are used. Due to the lack of an exact solution, the equivalent source solution is compared with the solution obtained from the Kirchhoff approximation, which is valid at this frequency ($ka=8$, where $a$ is the radius of the base of the cone). The results are shown in Fig. (4), where the left panel shows the absolute value of the total back-scattered field as a function of the polar angle measured from the axis of the cone, and the right panel shows the same result obtained using the Kirchhoff approximation. Note that the two solutions agree very well, except in the region between 20 and 50 degrees. In this region the back-scattered field is primarily due to diffraction from the edges, where the Kirchhoff approximation is not valid. The peak at
approximately 70 degrees is due to back scattering from the curved surface of the cone, which is correctly accounted for by both models.

Figure 3: The back-scattered field from a truncated cone. The left panel shows results obtained from the equivalent source technique and the right panel shows results obtained using the Kirchhoff approximation. The inset shows the geometry of the problem.

As a final example of the use of this technique, we compute scattering from a rigid cylinder in an ideal waveguide, where the field vanishes at its boundaries. A 717 Hz line source is located at a depth of 20 meters in a 50-meter deep waveguide. The target is located at a range of 10 meters and at a depth of 25 meters. The waveguide Green’s function is computed using the spectral integral method and 70 line sources are used to model the equivalent source problem. The results are shown in Fig. (5).

Figure 4: Scattering from a rigid cylinder in an ideal waveguide. The top left panel shows the field in the absence of the target and the top right panel shows the field when the target is placed in the waveguide. The bottom two panels are close-up views of the field in the absence and presence of the target and show how the presence of the target modifies the field.
The left and the right panels in Fig. (5) show the acoustic pressure field in the absence and in the presence of the target. The close up views of the field in the bottom two panels show how the field is modified when the target is present.

Discussion

Problems in waveguide propagation are typically treated by methods such as normal modes, ray theory, parabolic equations, and wavenumber integration. These techniques exploit various approximations, e.g. dominance of the forward scattered field, to yield field calculations over hundreds of wavelengths, and to do so very efficiently. However, these methods are not naturally suited to calculating the multiple scattering effects within a complex target. This in turn is the province of finite-element methods. Conversely, finite elements are not immediately suited to handling propagation in the medium in which the target is embedded.

The challenge then is to provide a simple linkage between these two diverse approaches to wave propagation. The equivalent source method does exactly that, dividing the complete problem of waveguide plus scatterer into two independent problems requiring simply Green’s functions for the waveguide and scatterer independently. Thus, one needs the response of the channel (without the scatterer) due to a point source (the exterior problem), and, separately, the response of the scatterer embedded in some arbitrary medium (the interior problem). The equivalent source method then shows how to glue together the responses of the two problems to construct a single field satisfying the interface conditions on the target.

The equivalent source method can be viewed as “substructuring”. This is a term used in the finite-element literature, which addresses the problem of joining substructures (such as an airplane wing to a fuselage) and doing independent finite-element analyses of each of the smaller structures. The advantage is the same that it is easier to divide and conquer than to tackle the whole problem at once. Another term used is “superelements” in which one studies the modes of vibration of substructure and similarly links those modes of vibration to a main structure.

It is important to note that these modes of the substructure (the interior Green’s function in our terminology) do not need to be precisely linked to the nature of the surrounding medium. Thus we can embed our target in a variety of homogeneous media to construct modes of vibration. These modes obviously change if we use a different surrounding medium. However, the modes are used only as a basis set to construct the whole field so the critical requirement is simply that the solutions of the interior Green’s function can be summed to accurately represent the internal field of the combined (waveguide plus scatterer) problem.

The examples show here use targets with complicated shapes, but homogeneous internal structure. However, the procedures used are identical for an internal Green’s function derived from a finite-element model for an arbitrarily complicated elastic
structure. Indeed, the equivalent source method even allows us to link a waveguide to an impulse response of the target that might be measured in the laboratory, as opposed to calculated numerically. (These extensions for 2 and 3D problems will be discussed in future work.) The only significant assumption is that the scatterer plus waveguide must both be governed by linear wave equations permitting the final solution to be calculated by superposition.

References

FINITE ELEMENT AND HYBRID MODELING TOOLS FOR THE DETECTION AND CLASSIFICATION OF BURIED OBJECTS IN SHALLOW WATER

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The detection and classification of buried objects is significantly aided by employing low frequency sonars, which have the potential of penetrating the sea bottom sediments. Furthermore, low frequency measurements make it possible to observe the elastic targets in a regime which is rich of structural information related to the target and its contents. On the other hand, low frequency scattering data cannot be interpreted easily by acoustic imaging, and hence the detection and classification process must be aided by model based knowledge of the echo time series. The 3-D scattering from targets is studied by the finite element (FE) method, with the aim of reducing the number of FE computations to a minimum, while at the same time preserving the accuracy required to obtain useful far field echo time-series predictions. Buried targets are modeled with the help of a hybrid approach, in which the FE model is used to compute the near field of the target, and a propagation tool is used to propagate the target echo into the far field.

1 Introduction

Computing the echoes scattered from 3-D targets using the FE method requires a large amount of time- and memory-consuming operations. For the low frequencies of interest to modern classification and detection studies (1-10’s of kHz), and for realistic target sizes, the computational cost of the 3-D FE technique limits the extent of the computational domain to the vicinity (within a few wavelengths) of the target. Hence, it is critical to establish minimal meshing criteria, which can lead to computational results capable of predicting the time-series of target scattered sonar pulses with an acceptable degree of accuracy compared to measured data. Furthermore, techniques are needed for predicting the target echoes not only in the free field, but also inside shallow water waveguides, and in the case of burial.

In Section 2, the frequency domain 3-D FE tool FESTA [1,2], which uses infinite elements to approximate the radiation condition [3], is used to treat an apparently simple test problem of scattering from an elastic spherical shell. A peculiar convergence behavior, which appears to arise in the presence of subsonic elastic surface guided waves [4,5], is analyzed. Considerations regarding the elastic wave phase speed, which can be significantly smaller than the soundspeed of the surrounding medium, lead to meshing criteria which yield converged results.
Section 3 presents a source superposition method for obtaining the far field response from FE computations based on work by Jeans and colleagues [6,7] coupled with the propagation code OASES [8,9]. Using the far field computations, it is shown how certain Lamb-type wave resonances appear to have no effect on the far field. Such considerations may prove useful in designing FE meshes which minimize the computational load when only far field predictions are needed. In addition to the sphere, a cylindrical target is analyzed at different frequencies and the results are compared to a thin-shell axisymmetric FE code [10], and to previous results by Dey et al. [11].

In Section 4, the 3-D FE tool coupled to the 3-D waveguide propagation tool OASES [8,9] is used to compute a first order approximation to the scattered far field for the buried cylinder at supercritical and at subcritical incidence. It should be noted, that the results presented here relate to currently on-going work, and hence the findings of Sections 2 and 3 must not be considered as final. Rather, the purpose of this paper is to stimulate a discussion on the topics presented, and to communicate some preliminary findings which, to the authors’ best knowledge, have not been presented before.

2 Physics based meshing guidelines

Meshing is a critical aspect of finite element modeling, since it affects directly the computational cost and the memory requirements of a simulation. This aspect is most relevant in fully 3-D codes, where the problem size grows rapidly with increasing frequency. Hence, it is critical to identify efficient meshing guidelines which make it possible to keep the model sizes within acceptable bounds. Previous authors [12] have successfully used finite element discretizations of 6 quadratic elements per wavelength on the target surface for scattering from a submerged 1% thick-walled steel spherical shell. In [12], agreements with an analytical reference solution are presented which are within 1% over wide frequency bands (\(ka=0.1\) to \(ka=100.0\) with \(k\) being the wavenumber, and \(a\) the outer radius). The term “quadratic” refers to the polynomial degree of the finite element shape functions. Dey et al. [11] propose using fewer elements of higher polynomial degree per wavelength, leaving the overall number of degrees of freedom per wavelength essentially unchanged. Discretizations like the ones used in [11,12] are motivated by the desire to approximate a sinusoid having a wavelength of \(\lambda_0 = c_0 / f\), where \(c_0\) denotes the soundspeed in the water and \(f\) is the frequency. This appears to be insufficient in the presence of subsonic elastic waves.

The scattering from a void spherical plexiglas shell of outer radius 25cm and thickness 2cm, is computed with the 3-D FE code [1], and compared to an analytical reference solution based on the spherical harmonic expansion of the scattered field. The target is representative of typical dimensions and material properties found in objects of interest to the underwater acoustics community. The shell is submerged in water, with a plane wave incident at frequencies ranging from 50 Hz to 2 kHz, with 5Hz increments. This corresponds to \(ka \sim 0.05 - 2.1\). Figure 1.a shows that the meshing guideline of 6 quadratic elements per \(\lambda_0\) on the target surface is not sufficient to achieve convergence for the entire frequency band of interest. The backscattered pressures on the wet surface, obtained with a FE mesh having approximately 11 quadratic elements per \(\lambda_0\) on the wet surface for case m1, and with approximately 23 quadratic elements per \(\lambda_0\) for case mc1, are compared to the reference solution. The wavelength is \(\lambda_0 = 0.75m\) at 2kHz in water.
Convergence is observed up to approximately 0.7 kHz, but as the frequency increases, the curves start to deviate from each other, and spurious resonance peaks appear.

Figure 1. (a) Near field backscattering for the spherical shell at range 25.1 cm from the target center. (b) Phase speed and resonance modal orders of the A0- Lamb wave for the spherical shell.

The apparently peculiar FE convergence behavior can be explained by the presence of surface guided subsonic Lamb-type A0- waves in the spherical shell. Such waves have a frequency dependent phase speed on the target surface [4]. Figure 1b shows the Lamb wave phase speed for the spherical plexiglass shell computed according to [5]. The Lamb wave phase speed is remarkably smaller than the external fluid sound speed, with a minimum approximately at 1.07 kHz. Above this frequency, the Lamb wave phase speed increases, converging eventually to the sound speed of the exterior fluid at the coincidence frequency around 25.5 kHz. Because of the trace velocity matching principle, the Lamb wave couples to short wavelength waves in the external fluid. The discretization of the Lamb-type wave on the target surface in the fluid is approximately 2.8 elements per wavelength for case m1, and approximately 5.6 elements per wavelength for case mc1. Hence, mesh mc1 satisfies approximately the 6 element per wavelength rule applied to the Lamb-type surface guided wave. This example suggests that curved surfaces and shells should be studied a priori with the purpose of identifying Lamb waves before the finite element meshing process is undertaken. Such an approach would be similar to the near field refinement in a direction perpendicular to the target surface, which accounts for exponentially decaying evanescent waves [12]. As opposed to the case of evanescent waves, the Lamb-type waves would require a refinement of the discretization in-plane with the target surface.

3 Far field computations

Because of the cost associated with finite element techniques, such computations are typically confined to the close vicinity of the wet surface. In the results presented here, the infinite elements, which spatially delimit the outer bounds of the computational domain, are located at a distance of $0.35 \lambda_0$ from the target for the spherical scattering cases presented above. The cylindrical target computations presented further below are obtained with the infinite elements located less than $0.1 \lambda_0$ from the target surface. On the other hand, the results of practical interest are typically far field quantities, such as
target strength. To obtain such quantities from finite element computations, one can sample the near field results for pressure and pressure gradient on a set of points surrounding the surface, and propagate the results into the far field by using the Helmholtz-Kirchhoff boundary integral representation, as is done in [11]. The approach pursued in this work consists of a wave superposition method based on the single- and double-layer potential representation of the scattered field. The source superposition method is particularly attractive in this context, because it replaces the evaluation of a boundary integral with the discrete superposition of Green’s functions multiplied by position- and frequency- dependent source strengths. Furthermore, the sampling of the pressure gradient, which is inherently less accurate than the sampling of the pressure in the FE solution, can be avoided. The determination of the source strengths can be shown to be equivalent to the discrete solution of an integral equation of the first kind, and hence it suffers from non-uniqueness problems which arise at special “interior” resonances of the fluid volume occupied by the target. Jeans and co-workers present a technique which overcomes these difficulties, without requiring the addition of redundant degrees-of-freedom [6,7]. The technique can be illustrated briefly by considering two alternative representations of the scattered field. The first representation is obtained using monopole sources (also called single-layer potential representation):

\[ p_{\text{scat}}(x) = \iiint_{S - \varepsilon} \sigma(x_0) G(x, x_0) \, dS_0 = L[\sigma](x) \]

where \( p_{\text{scat}}(x) \) denotes the scattered pressure field evaluated at a point \( x \) away from the integration surface \( S - \varepsilon \). The position dependent source strength is \( \sigma \), and the integration variable is \( x_0 \). To determine \( \sigma \), one can let the point \( x \) lie on a surface \( S \) which is removed outward by a small distance \( \varepsilon \) from the integration surface \( S - \varepsilon \). The term “small” in this context means “small with respect to the wavelength and to the overall geometry of the target”. As mentioned above, the inversion of such an integral equation raises problems of non-uniqueness associated with resonances of the fluid volume interior to \( S \), which essentially corresponds to the volume occupied by the target. This difficulty can be circumvented by considering a second representation of \( p_{\text{scat}} \) based on dipole sources (also called double-layer potential representation):

\[ p_{\text{scat}}(x) = \iiint_{S - \varepsilon} \sigma(x_0) \partial G(x, x_0) / \partial n_0 \, dS_0 = M[\sigma](x), \]

where \( \partial / \partial n_0 \) represents the normal derivative at the point \( x_0 \). The normal is directed into the surrounding fluid. Although the dipole potential representation suffers from non-uniqueness problems of the same nature as those encountered in the monopole representation, Eqs. (1) and (2) can be joined into a mixed representation which allows for a unique inversion of the integral equation. The mixed single- and double-layer potential representation suitable in this context is introduced in [6,7], and can be expressed compactly in operator notation by:

\[ p_{\text{scat}}(x) = (L - i\eta M)[\sigma](x). \]

Here \( i = \sqrt{-1} \), and \( \eta \) is a real constant to be determined. Eq. (3) is discretized by sampling \( p_{\text{scat}}(x) \) from the finite element solution at a discrete number of points on the surface \( S \), which can be chosen to coincide with the wet surface of the elastic target or with a closed surface surrounding the target. The continuous distribution of sources is replaced by a discrete one by projecting the points \( x \) onto \( S - \varepsilon \) along the direction...
−n₀. This procedure yields a linear system of algebraic equations which can be solved for the source strengths σ. Once the source strengths are known, the pressure at any point in the far field is determined by evaluating the discrete version of Eq. (3), with x being the far field point of interest.

The method of Jeans et al. [6,7] was implemented within the scattered field module of OASES [8], using free field point source Green’s functions

\[ G(x, x₀) = \exp\left(\frac{\pm k |x - x₀|}{|k - x₀|} \right) \].

The separation distance \( ε = 0.6 \) was determined empirically, and the constant \( \eta = ε/k \) was determined from considerations of numerical stability inherent to the superposition of the monopoles and dipoles evaluated at close distances. By replacing the free space Green’s functions with waveguide Green’s functions, the finite element code can be used in conjunction with the waveguide propagation code to compute the scattered far-field in underwater waveguides.

Figure 2. Far field TS for plexiglass spherical shell. (a) Backscatter frequency sweep. (b) Multistatic results at 580 Hz resonance. The m₁ and mc₁ results are obtained with FESTA coupled to the potential formulation of Jeans et al. implemented in OASES.

Figure 2 shows the far-field computations obtained with the method presented above for the elastic plexiglass shell of Section 2, compared to the analytical solution. In contrast to the near field computations of Fig.1, it can be seen that both the mesh m₁ and the mesh mc₁ are converged to the analytical solution at the sampled far-field frequencies, except for minor disagreements in amplitude at 580Hz and at 720Hz. The 580Hz scattering pattern is shown in Fig. 2.b. The dissipation through radiation of the Lamb-type wave resonance modes appears to be the motivation for the fact that most of the discrepancies between m₁ and mc₁, seen in Fig. 1, don’t propagate into the far field.

As a second case study, a void steel cylindrical shell with hemispherical endcaps of \( L=1.9216m \) length and \( a=0.1608m \) radius, and having a wall thickness of 1% relative to the mean radius is considered. The target is immersed in water, and a plane wave is incident from broadside. Figure 3a shows the scattered field at a frequency of 4kHz computed with FESTA at a distance of 1cm from the target (\( ka~2.7, kL~32 \)). Clearly, there is no convergence in the near field using two different meshes which have approximately 22 elements per \( λ₀ \) on the wet surface. Mesh M₁ uses only quadratic elements, while mesh M₂ uses elements which are cubic in-plane with the wet surface, and quadratic perpendicularly. Figure 3b shows that the far-field results appear to be in fairly good agreement with the predictions from the axisymmetric thin-shell code by
Fawcett [10]. Also in this case, the effect of the Lamb-type waves appears to be limited to the near field, although the frequency is well below the coincidence frequency of ~124.6kHz. This evidence is insufficient to claim that the utilized mesh is appropriate also for other frequencies in the vicinity of 4kHz, since an a-priori Lamb-wave resonance analysis, and possibly a frequency sweep, would be necessary to ensure the absence of radiating Lamb-type modes.

The target specifications for the cylinder correspond to the ones given in the paper of Dey et al. [11]. A far-field comparison with the results of Ref. [11], at a frequency of approximately 15kHz (which corresponds to $ka = 10$ and $kL \sim 120$) is shown in Fig.4. The blue curve shows the far-field result obtained with the axisymmetric thin-shell code [10], and the red curve shows the results of the 3-D FEM [1] computed with a mesh of 6 elements per $\lambda_0$ on the wet surface, and with polynomial degrees as in M2 above. The objective of these studies is to determine the tradeoff between FE meshes which make computations at high $kL$ values possible, and computational accuracy. The metric is the accuracy of the prediction of far-field echo time-series.

![Figure 3](image1.png)

Figure 3. Near field (a) and far field (b) scattering from the cylinder at 4 kHz. There is no convergence in the near field, but in the far-field the propagated solutions of the 3D FE code (M1 and M2) are converged and approximate well a converged solution from the thin-shell code.

![Figure 4](image2.png)

Figure 4. Cylinder far field TS at f=15 kHz (kL ~ 120). Panel (b) shows a comparison with results presented in the paper by Dey et al. [11]. Results for panel (a) were not published in [11].
4 Buried target computations

The hemispherically end-capped cylinder of Section 3 is buried in a sandy sediment of density $1800 \text{ kg/m}^3$, and soundspeed $1640 \text{ m/s}$. The sediment half space lies below an infinite water half space. The field incident on the buried target is obtained from the analytical plane wave reflection and transmission solution for two-fluids separated by a common planar interface, and it is used to compute the boundary conditions at the target/sediment interface in FESTA [1]. The FE computed scattered pressure is sampled in the near field according to the procedure described in Section 3, and it is propagated outward in the two-layered medium by OASES using the monopole layer representation of Eq.(1) in conjunction with the Green’s functions for the wavenumber integration solution in the two-layered medium [8,9]. The results for two different cases at 4kHz are shown in Figure 5. Results like the ones presented here can be used to investigate target classification and detection clues, which help researchers in the development of novel sonar concepts. The extension to include additional effects in the model, like multiple fluid and sediment layers and an ocean surface is straightforward in OASES. Such computations are the subject of future work by the authors.

The formulation of Jeans et al. [6,7], which is necessary to guarantee unique far field computations also in the hybrid FE/OASES framework, should be implemented via Eq.(3), using the appropriate Green’s functions for the multi-layered problems [8,9]. It should also be mentioned that the present approach describes a single scatter approximation, in the sense that multiple reflections between the target and the sediment/water interface are neglected. Multiple scattering effects can be taken into account...
account, for example, by implementing a mobility matrix approach, as envisioned by Schmidt [9].

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References

IDENTIFICATION OF OBJECT PARAMETERS FROM
TRANSIENT BISTATIC SCATTERING DATA

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An inversion technique is described for identification of submerged or buried objects using a ROV-mounted acoustic source and a separately located vertical receiver array. Parameters of the object are estimated by nonlinear global minimization of the misfit between observed and model-predicted scattered echoes. A fast approximative technique for computing the scattered field, the RK (Ray-Kirchhoff) method, is presented and used as forward model at the parameter search. The accuracy of the RK method is assessed in two representative model cases, using an accurate full-field boundary integral equation (BIE) method as reference. The technique is applied on experimental data from a sea trial within the EU SITAR project in the Stockholm archipelago in Sept 2003. Estimates of seven physical parameters - range, depth, roll, yaw, pitch, density and sound speed - of a semi-buried box-shaped object are determined in a step-wise manner. The estimated parameter values are shown to reduce the model-data misfit significantly compared with those based on prior information only.

1 Introduction

In this work, we study computational methods for modelling of acoustic scattering from submerged or buried objects, and for identification of parameters of such objects by

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{scatter.png}
\caption{Diagram of the experimental setup with an acoustic source and receivers.}
\end{figure}
acoustic inversion. The methods are applied to analysis of data from a sea-trial for identification of buried objects from their acoustic scattering signature. The trial was conducted in the Stockholm archipelago in Sept–Oct 2003 as a part of the EU project SITAR (Seafloor Imaging and Toxicity: Assessment of Risk caused by buried waste).

In the experiment, transient pulses from a ROV-mounted TOPAS 120 parametric sonar were emitted within a narrow beam directed towards the object, and the scattered echoes were recorded with a separately located vertical receiver array as shown in Fig 1. The water depth at the site was ca 75 m, and the source was located ca 11-15 m above the seafloor. In each registration some 80-100 pulses were recorded, with the source fixed in position and orientation. The target was a semi-buried acoustically penetrable box with dimensions ca 130 x 30 x 30 cm, as estimated from a close-range video survey of the target area.

2 Modelling

Two modelling methods are considered, a full-field boundary integral equation (BIE) method and a fast approximative Ray-Kirchhoff (RK) method. Both methods use a frequency-domain formulation of scattering from a 3D object in a layered, range-independent medium. Transient scattering is handled by Fourier synthesis of monofrequency fields. The complex acoustic pressure $p_i(r)$ at a point $r$ outside a scattering body can be written

$$p(r) = p_i(r) + p_s(r)$$

(1)

where $p_i(r)$ and $p_s(r)$ are the acoustic pressure of the incident field, i.e. the field that would be excited without the scatterer present, and the scattered field, respectively. By Green's theorem, at a point $r_0$ outside the surface $S$ of the scatterer

$$p_s(r_0) = \int_S [g(r, r_0) \nabla p(r) - p(r) \nabla g(r, r_0)] \cdot \hat{n}(r) dS(r)$$

(2)

where $\hat{n}(r)$ is the unit outward pointing normal of $S$ at $r$ and $g(r, r_0)$ is the Green's function of the outside layered medium. Letting $r_0 \rightarrow S$ in eqn (2) gives a boundary integral equation (BIE) for the unknown $p(r)$ and its normal derivative on the surface $S$

$$\frac{1}{2}p(r_0) + \int_S \left( \frac{\partial g(r, r_0)}{\partial n} p(r) - g(r, r_0) \frac{\partial p}{\partial n}(r) \right) dS(r) = p_s(r_0)$$

(3)

For a rigid scatterer $\partial p/\partial n = 0$ on $S$ and then $p(r)$ is determined on $S$ by eqn. (3), outside a discrete set of eigenfrequencies of an associated interior problem, see Sec. 2.2. For acoustically penetrable scatterers both $p(r)$ and $\partial p(r)/\partial n$ are unknown, and eqn (3)
must be complemented by an additional equation derived from the interior dynamics of the scatterer. For a homogeneous fluid body the interior dynamics is described by a BIE of the form (3) with with zero right hand side, and Green's function

\[ g(r, r_0) = -\frac{e^{j\beta_p |r - r_0|}}{4\pi |r - r_0|} \]

where \( k_p = \pi/\lambda \) denotes the wavenumber in the interior fluid.

2.1 Model of scatterer

The box-shaped scatterer is described by a smooth map of the unit sphere onto the surface of a super-ellipsoid with half-axes 65, 15 and 15 cm as shown in figure 2. The interior of the ellipsoid is fluid with density 1630 kg/m\(^3\), velocity 2680 m/s, absorption 0.7 dB/wavelength. The parameter values are representative of a TNT explosive.

![Computational model of the box](image)

Figure 2. Computational model of the box: A homogeneous fluid super-ellipsoid with half-axes 65, 15 and 15 cm, exponent 10. Right: View from above. Yaw angle 19 deg.

2.2 The BIE method

In the BIE code XFEM-S used in this study, eqn (3) and the analogous interior equation are discretized by collocation, using a high-order B-spline basis for functions on \( S \). The Green’s function of the outside layered medium is computed by adaptive transform integration and exact finite elements [2]. The singularity of the integrand of the BIE is eliminated by transforming to ‘tilted’ coordinates, and the integrals are computed by high-order numerical quadrature.

Since the BIE (3) for both the exterior and interior problems is of the first kind in the normal derivative \( \partial p/\partial n \) their straightforward use for numerical solution will lead to loss of accuracy or even failure due to poor conditioning. As is well known [3], equivalent, well-conditioned, forms of the BIE are obtained by linearly combining (3) with the BIE derived from the gradient of (2) in a similar way as (3). Numerical integration of the resulting ‘hypersingular’ BIEs is handled by splitting the the second derivative of the Green's function into terms that are singular and nonsingular, respectively, at \( \theta' = 0 \). The contributions from the singular terms are then known analytically, and the regular terms are computed by the high-order quadrature schemes used for (3). For scatterers with rotationally symmetric shape about the z axis, the discretized BIE system is transformed into block diagonal form by discrete Fourier transform over the azimuthal B-spline
index. The resulting diagonal blocks are of moderate size and may be solved efficiently by conventional LU decomposition. For other scatterers, such as the box studied here, an iterative method for linear general systems [4], enhanced by preconditioning with a solver for a nearby rotationally symmetric case is used.

2.2 The Ray-Kirchhoff method

Kirchhoff’s approximation of the scattered field \(p_s(r)\) is obtained by assuming a reflection coefficient \(R(r)\) to be known, such that on the surface \(S\), \(p_s(r)\) is given by

\[
p_s(r) = R(r)p_i(r) - \frac{\partial p_i(r)}{\partial n} = -R(r)\frac{\partial p_i(r)}{\partial n}
\]

(5)

By inserting eqns (1) and (5) in (2)

\[
p_s(r_0) = \int_S \{(1 - R(r))g(r, r_0)\nabla p_i(r) - (1 + R(r))p_i(r)\nabla g(r, r_0)\}\cdot\hat{n}\,dS

\]

\[
= -\int_S R(r)\{g(r, r_0)\nabla p_i(r) + p_i(r)\nabla g(r, r_0)\}\cdot\hat{n}\,dS
\]

(6)

where the last equality follows from Green’s theorem applied on \(p_i(r)\). \(R(r)\) is a function of the incidence angle \(\theta_{inc}(r)\) and possibly of frequency \(f\), and is defined as the reflection coefficient of a transversally homogeneous layered medium with structure equal to that of the scatterer locally at \(r\). The direction of incidence is defined as the direction of the intensity vector of the incident field \(I_s\), and the reflection coefficient \(R(r)\) is zero at points \(r\) on the surface \(S\) where \(I_s\cdot\hat{n}(r) > 0\) (non-insonified points).

Kirchhoff’s approximation (6) is computed by numerical evaluation of a surface integral, with an integrand defined by the incident field \(p_i(r)\), the Green’s function \(g(r, r_0)\) and the reflection coefficient \(R\). Although this is computationally much less demanding than the BIE method, the work required for numerical evaluation of the transform integral for \(p_i(r)\) and \(g(r, r_0)\) in a layered medium may still make it impractical as a forward model for the iterative parameter identification. A method without this drawback is obtained by replacing \(p_i(r)\) and \(g(r, r_0)\) in (6) by their ray-theory approximations [5]. In the special case when \(r_i\) and \(r_z\) are located in adjacent homogeneous halfspaces, the ray approximation is obtained in two steps. First, Fermat’s principle [6, Sec 3.5.4] is used to derive a fourth degree polynomial equation for the position of the corner point of the two-segment eigenspace from \(r_i\) to \(r_z\). The corner point is then found by solving the fourth degree equation with a fast iteration-free algorithm. The ray-theory approximation of \(g(r_{r_2}, r_{r_1})\) is then,
IDENTIFICATION OF OBJECT PARAMETERS

\[ g(r_2, r_1) = -\frac{T(k)}{4\pi (r_1 r_2)^{1/2}} e^{i(k_1 R_1 + k_2 R_2)} \tag{7} \]

where \( k_1, k_2 \) are the wavenumbers in the two halfspaces and \( k \) is the horizontal wavenumber at propagation along the eigenray. \( R_1, R_2 \) are the lengths of the two eigenray segments. \( T(k) \) is the transmission coefficient at the halfspace interface

\[ T(k) = \frac{2\rho_2 \gamma_1}{\rho_2 \gamma_1 + \rho_1 \gamma_2} \tag{8} \]

where \( \rho_j \) and \( \gamma = (k_j^2 - k^2)^{1/2} \) are, respectively, the density and the vertical wavenumber in halfspace \( j \). The factor \( \int (\frac{1}{r_1} r_1 \frac{1}{r_2} r_2)^{1/2} \) accounts for the change of sound pressure amplitude induced by the change of the ray tube cross-sectional area, [6, Sec 3.2.2]. Denoting the incidence angles of the ray segment with \( \theta_1 \) and \( \theta_2 \), then \( r_1 = R_1 + c_2 / c_1 R_2 \) and \( r_2 = R_2 - c_2 \cos \theta_1 / (c_1 \cos \theta_2) + R_1 \cos \theta_2 / \cos \theta_1 \).

The gradient of \( g(r_2, r_1) \) with respect to \( r_2 \) is required in (6) and is computed by differentiating (7) and the ray endpoint \( r_2 \) with respect to the launch angles and the arc-length, and then using the chain rule to convert to derivatives with respect to the components of \( r_2 \). The integral (6) is formulated in tilted spherical coordinates with north pole at the point of the insonified region where incidence is vertical. The boundary of the insonified region is approximated by an interpolating spline, and the Kirchhoff integral is computed by high order quadrature formulas.

![Figure 3: Field scattered from a buried box, predicted by the BIE (solid) and the RK (dotted) methods. Left: All 7 receivers. Right: Closeup of receivers 1 and 7.](image)

Fig. 3 shows predictions of scattering of a 5kHz Ricker pulse from a buried box, obtained with the RK and the BIE methods. The RK method is seen to predict the arrival times and the duration of the pulses, as well as the detailed shape of their leading half, with satisfactory accuracy. The predictions of the trailing half however overestimate the amplitude by between 1% (at receiver 7) and 55% (at receiver 2). This suggests that the
fitness function of the inversion should preferably use only leading portions of the received signals.

3 Experimental data

The waveform $\hat{s}(t)$ emitted by the TOPAS 120 is shown by the dashed curves in the left frame of Fig. 4. $\hat{s}(t)$ was obtained from calibration measurements by averaging over ca 130 pings to reduce effects from random perturbations. The solid curve shows a smoothed and band-limited approximation $s(t)$ of $\hat{s}(t)$, used as the model source pulse in the simulations. $s(t)$ was obtained by weighted least-squares fitting a smooth spline to $\hat{s}(t)$ with penalty terms suppressing high frequencies. The right frame of Fig 4 shows traces recorded by the vertical array of the pulse reflected from the semi-buried box and the seabed, see Fig. 1. The traces are averages of 84 pings with the transmitter fixed in position and orientation. Only traces from the five middle receivers are shown, since no useful signals were recovered by sensors 1 (top) and 7 (bottom). The dashed cross-trace curves show ray-theory predictions of the arrival times of the direct arrivals (through sidelobes of the sonar) and the specular reflection from the scatterer. At all receivers, the experimentally recorded echoes are composed of (i) a direct arrival occurring at ca 31.4 ms, (ii) the specular reflection from the scatterer (iii) a relatively quiescent period with length ca 1 ms, and (iv) a ca 5 ms long unstructured tail with larger amplitude that the specular reflection. The quiescent part (iii) of the echoes indicates a very soft and homogenous top sediment layer. The long tails (iv) are likely to be caused by scattering from subbottom layers of more inhomogeneous materials with higher acoustic contrast. It is interesting to note that the detailed and apparently random structures of the long tails are in fact unchanged in all 84 pings, indicating a good stability of the position control system of the ROV.

The left frame of Fig. 5 is a blow-up of the segment of the traces in Fig. 4 containing the specularly scattered arrivals. The right frame shows simulated echoes, computed with the RK method (solid) together with the specular echo intervals of the observed traces (dashed). In the simulations the medium was assumed to be a homogeneous water space, i.e. no bottom interactions were included in the model. In view of the small acoustic contrast of the top sediment layer, the simulations should still be fairly representative for the specular echo from a semi-buried box.
The arrival times of the model-predicted echoes are seen to agree well with the experimentally observed. However, their amplitudes as function of receiver depth are nearly uniform, with a weakly pronounced maximum at receiver 4, the depth for which the specular reflection occurs at the flat upper surface of the box. In contrast, the experimentally observed echo amplitude is maximal at the deepest receiver, and decreases with depth. Possible reasons for this mismatch are error in the orientation of the model box (causing erroneous predictions of the direction of specular echoes), and an overly smooth shape of the model box (reducing the spatial directivity of the scattered field).

4 Estimation of object parameters

We seek estimates of a vector \( u \) of parameters of the scatterer, such as size, shape, orientation, sound speed and density, from measurements of the scattered field. Denoting the experimental data by \( q = q(x,t) \) and the model-predictions by \( p(u) = p(x,t,u) \), the identification problem is then to find \( u \) such that a fitness function \( \Phi(u) \), measuring the distance between \( p(u) \) and \( q \) is minimized.

Motivated by the characteristics of the experimental data and the accuracy properties of the RK-predicted transient echoes the fitness function \( \Phi(u) \) for the parameter inversion was defined as

\[
\Phi(u) = \sum_{i=1}^{N_{\text{rec}}} |T_i(u) - \tau_i|^2 + |A_i(u) - \alpha_i|^2,
\]  

where \( T_i(u) \) and \( A_i(u) \) is the modelled arrival time and the normalized amplitude at receiver \( i \), and \( \tau_i \) and \( \alpha_i \) are the corresponding experimentally observed quantities. In general \( \Phi(u) \) is a complicated nonlinear function, and the optimal \( \hat{u} \) must be sought by methods for global minimization. Two such methods were used, a differential evolution algorithm (DE) [7] and a hierarchical genetic algorithm (GA) [8], both combined with final search of local minima by the downhill simplex method [3]. The RK method described in Sec 2 was used as forward model for computing the scattered field \( p(u) = p(x,t,u) \).
5 Parameter estimation results

We seek estimates of seven parameters: (i) the angles of rotation (roll, pitch, yaw) of the box, (ii) the range and depth coordinates of its center, and (iii) its interior density and sound velocity. Initially, a few attempts were made to search for all or several of these parameters simultaneously. However, the convergence of the inversion algorithms in such composite runs turned out to be too slow to provide useful results. Therefore, instead

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Initial</th>
<th>Inverted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range (m)</td>
<td>24</td>
<td>23.95</td>
</tr>
<tr>
<td>Depth (m)</td>
<td>74.85</td>
<td>74.85</td>
</tr>
<tr>
<td>Roll (deg)</td>
<td>0</td>
<td>0.9</td>
</tr>
<tr>
<td>Pitch (deg)</td>
<td>0</td>
<td>4.8</td>
</tr>
<tr>
<td>Yaw (deg)</td>
<td>19</td>
<td>11.7</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>1630</td>
<td>1490</td>
</tr>
<tr>
<td>Soundspeed (m/s)</td>
<td>2680</td>
<td>2570</td>
</tr>
</tbody>
</table>

Table 1: Parameters of the scatterer determined by inversion

A cruder, stepwise approach was followed in which only a few parameters were sought in each step, and their values then used in subsequent steps. The parameters fitted in the steps were (i) roll and yaw angle, (ii) interior density and soundspeed, (iii) range and depth and (iv) pitch angle. The results are collected in table 1.

In Fig. 6 the model predicted received echoes obtained with the scatterer parameters shown in Table 1 are shown together with the experimentally observed specular echoes.

Figure 6: Received signals. Dotted: Experimental data. Solid: Modelled, with parameters from acoustic inversion shown in the right column of Table 1. Left: RK, Right: BIE.

By comparing Fig. 6 with the right frame of Fig. 5 the parameter inversion is seen to improve the match between the modelled and the experimental data significantly. Most notably, the echo amplitude as function of receiver depth in the experimental data is quite well reproduced by the models after inversion. This improvement reflects the sensitivity of the vertical distribution of the scattered energy to the rotation of the scatterer, which was not accurately known at the outset.
References
A POTENTIAL ALGORITHM FOR TARGET CLASSIFICATION IN BISTATIC SONAR GEOMETRIES

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The recent evolution in oceanographic sensing and platforms, including the availability of Autonomous Underwater Vehicles (AUVs), is encouraging the investigation of new high-resolution sonar concepts based on multistatic geometries. The rationale behind this concept is that multistatic systems, in particular if the geometry can be adapted with the experiment, can be located in the regions where the scattered signal is carrying the most information. The work described in this paper is a follow-up of the research carried out by the authors as part of the European Union project SITAR (Seafloor Imaging and Toxicity: Assessment of Risks caused by buried waste), in which a Multiple Aspect Scattering measurement technique has been investigated with the aim of imaging buried objects of small dimensions. Within SITAR, a very rich data set has been acquired in the tank facilities of the University of Bath. The data set consisted in scattered signals from a set of targets, ensonified with a high frequency source (238 kHz) as a function of grazing, scattering and bistatic angle. Moreover, the targets were proud on the surface, semi-buried or flush-buried in different kinds of seabed sediments. The SITAR data set has been processed by a suite of algorithms, inspired from spectral distances often used in speech processing, with the aim of determining some characteristics that may allow the automatic classification of the object. Within this process, significant relative differences in the received signal power at bistatic angles different from the azimuthal (180°) angle have been systematically observed. This experimental finding is reported here as a potential basis for an automatic classifier, particularly advantageous because of the simplicity in the data processing requirements.

1 Introduction

Within the last years a consistent number of contributions have been presented in the scientific literature, concerning the problem of classification of objects either buried or proud on the seafloor (see for instance [1 - 3] and references therein). The major driving force behind this research direction is the problem of mine detection [4], although similar approaches can be efficiently employed in other underwater applications, such as marine
One particularly interesting aspect of this research line has emerged with the increasingly popular use of Autonomous Underwater Vehicles (AUVs) as transmitting and/or receiving platforms of a multistatic acoustic scattering system: AUV characteristics make feasible and affordable the deployment of adaptive systems in which the source/receiver(s) configuration can be re-arranged rapidly as a function of the received signal themselves [7 - 8]. The possibility of geometrical adaptation of the system configuration makes even more interesting the investigation of multistatic scattering and related detection/classification methods. Unfortunately, high frequency scattering from the seabed is a rather complex process: there is still a lack of physical models capable of convincingly reproducing the field data collected at sea without strong assumptions on the system geometry and/or the environmental conditions. Within this context, laboratory experiments of acoustic scattering in controlled conditions are of great relevance: data from such experiments can be used to validate/refute model predictions, and can provide hints for favourable at-sea deployable configurations [9].

In this paper, we report some of the results obtained from the analysis of a data set collected in the laboratory tank test facilities of the University of Bath [10], as part of its activities in the European Union project SITAR [6]. A subset of the data collected has been processed in a number of ways to bring into evidence some systematic differences that may be exploited in an automatic target classification procedure [11]. Distance measures among signals adapted from speech analysis have been employed [12 - 13]. The results reported here show how the scattered power received from different targets as a function of the grazing and the bistatic angle exhibits pronounced differences at bistatic angles different from the azimuthal (180°) angle, even if the difference is negligible at 180° bistatic angle. The fact that diversity emerges with variation of the bistatic angle confirms the richness of information obtained through a multistatic configuration (either synthetic or real) and it can be exploited in an automatic classification algorithm.

Section 2 will describe the experimental procedure employed and the portion of the SITAR dataset used. In Section 3 the distance between signal powers as a function of grazing and bistatic angles is reported for two cylindrical targets of similar dimensions but different fillings (fluid- and air-filled). These results are discussed in Section 4.

2 Experimental set-up

The bistatic scattering data have been acquired using the tank facilities of the University of Bath, U.K. Different kinds of sediment, as well as different targets, have been used to perform the experiments [9-11]. During the experiments, the water level of the tank (controlled by an electric pump) has been kept constant, 1.45 m above the sediment surface. Four steel trays, 30 cm deep, fill the bottom of the tank and contain different kinds of sediment (silt, sand, fine and coarse gravel). These sediments were thoroughly degassed and have not been disturbed for several years, to ensure good stability and homogeneity.

The SITAR Project imposed some restrictions on the characteristics of the targets. In fact one of its aims was to developed new methods for the detection and classification of human made objects like barrels of toxic and/or munitions waste. According to the
project specifications, a scaling factor of 10:1 was used in the design of the experiment and cylindrical shaped targets have been chosen. Figure 1 and 2 show, respectively, the longitudinal section of the tank and the top view of the experimental set-up, together with the definition of grazing, scattering and azimuthal angle. All targets have been used proud, half buried and flush buried. Table 1 shows the characteristics of the targets.

![Figure 1. Longitudinal section of the tank used for the experiments; $\theta_s$ is the scattering angle, $\theta_i$ is the grazing angle. Both receiving hydrophone and acoustic projector can be moved to achieve the configuration desired in terms of grazing and scattering angles.](image)

Table 1. Characteristics of some of the targets used in the experiments [4].

<table>
<thead>
<tr>
<th>Target</th>
<th>Characteristics</th>
<th>Dimensions Diam x Length</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>T₁</td>
<td>Sealed aluminum tin</td>
<td>67 mm x 100 mm</td>
<td>Fluid filled</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Air filled</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Sidewall thickness 3 mm</td>
</tr>
<tr>
<td>T₂</td>
<td>Stainless-steel cylinder</td>
<td>58 mm x 104 mm</td>
<td>End cap thickness 2 mm</td>
</tr>
<tr>
<td>T₃</td>
<td>Solid aluminum cylinder</td>
<td>51 mm x 81 mm</td>
<td></td>
</tr>
<tr>
<td>T₄</td>
<td>Solid steel cylinder</td>
<td>70 mm x 80 mm</td>
<td></td>
</tr>
<tr>
<td>T₅</td>
<td>Solid brass ring</td>
<td>105 mm x 75 mm</td>
<td>Wall thickness 7.5 mm</td>
</tr>
</tbody>
</table>
Figure 2. Top view of the experimental set-up. The receiving hydrophone can be positioned along the arc depicted as a continuous line at bistatic angles from 160° to 200°, at 10° steps. The configuration with a 180° bistatic angle is the configuration at azimuthal bistatic angle, or in-plane scattering, since the acoustic ray always travels in the plane defined by projector, target and receiver. TAX refers to the hydrophone position.

According to the function of the different devices, it is possible to separate the experimental set-up into three main sections:

1. Transmission of the acoustic pulse.
2. Reception and pre-processing of the scattered signal.
3. Storage of the signal.

The core of the transmission section is the acoustic projector, an active piezoelectric PZT5A characterized by a very narrow beam width (10°), and calibrated before starting the experiments. A track-supporting system allowed the projector to move along the longitudinal axes of the tank. The tilt angle of the transducer could be set to any value by an apposite mechanism. A single sinusoidal pulse with an amplitude of 20.43 V and a frequency of 238 kHz, has been used as acoustic source. A Bruel & Kjaer omnidirectional hydrophone has been used to receive the scattered signal. After an analogue pre-processing stage (bandpass filtering, amplification, anti-aliasing), the output of the hydrophone was connected to a Lecroy LT-264 digital oscilloscope. The whole experimental set-up (signal transmission, source/receiver position, etc.) was controlled and monitored by a LabView™ programme resident on a PC connected to the experimental instrumentation by a GPIB bus. The received waveforms were averaged over 100 sweeps at a time, in order to improve the signal to noise ratio, and then stored digitally.
3 Results

This section describes some results with data collected with the previous experimental set-up. As mentioned in the introduction, a set of different methodologies has been applied to the data in order to experimentally determine if some distance measure among signals could be employed in order to discriminate from one target to the other. The class of possible distance measures explored has been adapted from those most commonly used in speech processing applications. They consist in a set of frequency domain norms applied to the Fourier transform $S(f)$ of the signal $s(t)$, as the $L_q$ norm:

$$d_q(s) = \left[ \int |S(f)|^q \, df \right]^{1/q} \quad (1)$$

or the Log Spectral Deviation among two signals $x(t)$ and $s(t)$:

$$d_q(x,s) = \left[ \int \log |X(f)| - \log |S(f)| \right]^{1/q} \quad (2)$$

A comprehensive report of the many results obtained can be found in [11]. In the following some examples are shown using the Log $L_2$ norm of the signals plotted as a function of the scattering angle, with fixed grazing and bistatic angle. The Log $L_2$ norm of a signal $x(t)$ is easily computed, since it is simply the Log of the signal power, which in turn equals the value of the autocorrelation function at the origin:

$$\log P_x = \log |R_{xx}(0)| = \log \left[ \int |X(t)|^2 \, dt \right] = \log \left[ \int |X(f)|^2 \, df \right] \quad (3)$$

Note that, differently from the Log spectral deviation, in the Log $L_2$ norm of equation (3), the Log operation is applied after the averaging in frequency, and not at each frequency.

In order to compare the norm as obtained from different targets, expression (3) has been normalized by the power of the scattering signals as obtained from the seabed when no targets are present; moreover, the numerical values in the following are expressed in dB. That is, each value in the following for any signal $x(t)$ is computed as:

$$\Delta P = 10 \log P_x - 10 \log P_S \quad (8)$$

Log $P_S$ being the Log $L_2$ norm of the signal $s(t)$ obtained when no objects are present. Consider that each signal $x(t)$, $s(t)$ is obtained as the time-domain average of 100 sweeps.

In the following the results obtained with the targets $T_1$ (fluid filled aluminum tin can) and $T_2$ (stainless steel air-filled cylinder) are compared in a configuration with a grazing angle always equal to 45°, varying scattering angles (2.5° interval), and at two different bistatic angles: 180° (in-plane scattering in the azimuthal direction) and 200° (off-plane scattering). The first example is reported in Figure 3; the seabed here was silt, and the two targets were oriented with their longitudinal axis parallel to the X axis (see Figure 2 for axis orientation convention) and proud over the seabed. It can be observed that, in the case of in-plane scattering ($\Phi_s = 180^\circ$) the difference between the Log $L_2$ norm of both signals is negligible (< 3dB) for any value of the scattering angle. On the contrary, when off-plane scattering is considered ($\Phi_s = 200^\circ$), for scattering angles between 40° and 65°, there is a systematic difference of the order of 5 dB. In Figure 4 the results from the same configuration are reported with the difference that now the cylinder’s longitudinal axis is oriented along the Y axis. Again, differences among the response of the two targets become clearly visible only when off-plane scattering is considered ($\Phi_s = 200^\circ$).
Figure 3. Power (dB) vs. scattering angle for targets $T_1$ (continuous line) and $T_2$ (dotted line). The power is normalized with respect to the seabed response without targets. Both targets are proud on silt sediment, their longitudinal axis oriented in the $X$ direction (see Figure 2), grazing angle $\theta_i = 45^\circ$, bistatic angle $\Phi_s = 180^\circ$ (left) and $\Phi_s = 200^\circ$ (right).

Figure 4. As in Figure 3, but with both targets having their longitudinal axis oriented in the $Y$ direction (see Figure 2), grazing angle $\theta_i = 45^\circ$, bistatic angle $\Phi_s = 180^\circ$ (left) and $\Phi_s = 200^\circ$ (right).

Figure 5. Power (dB) vs. scattering angle for targets $T_1$ (continuous line) and $T_2$ (dotted line). The power is normalized with respect to the seabed response without targets. Both targets are half buried on silt sediment, their longitudinal axis oriented in the $X$ direction (see Figure 2), grazing angle $\theta_i = 45^\circ$, bistatic angle $\Phi_s = 180^\circ$ (left) and $\Phi_s = 200^\circ$ (right).
TARGET CLASSIFICATION IN SONAR BISTATIC GEOMETRIES

Figure 6. Power (dB) vs. scattering angle for targets T₁ (continuous line) and T₂ (dotted line). The power is normalized with respect to the seabed response without targets. Both targets are proud on gravel sediment, their longitudinal axis oriented in the X direction (see Figure 2), grazing angle \( \theta_i = 45° \), bistatic angle \( \Phi_S = 180° \) (left) and \( \Phi_S = 200° \) (right).

The same pattern has been observed when the two targets have been partially buried (gently pushed into the silt) - see Figure 5. With respect to the previous case, the difference between signal powers now becomes relevant for scattering angles above 50°. While the above results have been observed quite systematically on targets resting over silt, when the same configurations have been repeated with the same targets over the gravel bottom, the results have been negative (see for instance Figure 6): the difference in response from the two targets both for the in-plane and the off-plane scattering case are less than 3 dB, and not likely to be observed in a realistic, at sea, situation.

4 Discussion and conclusions

These results are typical examples of those reported more fully in [11]. They are an experimental indication (or confirmation, since the same observation has already been made several times in the literature, with theoretical, computational and experimental arguments) (e.g. [9]) that the 3-D acoustic field scattering does indeed provide additional information that can be successfully exploited in target classification. In addition to previous studies, the results reported show that sometimes even the bistatic configuration may not be sufficient, and that multistatic configurations should be preferred. In particular, the differences in normalized power of the scattered signals are most evident when plotted as a function of the scattering angle, and when departing from the in-plane scattering configuration. The role played by the sea bottom is also non-negligible: the results reported are significant for target detection only in the case of silt sediment (remember, however, that the experiment is scaled: with wavelengths of an order of magnitude larger, the silt grain size scales to that of a sandy bottom). When the gravel bottom has been employed, scattering processes seem so dominated by the bottom that there is no appreciable difference in the response from different targets, at least with the dimensions employed in the experiment.
Acknowledgements

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References

UTILISATION OF THE APPLICATION OF HIGH FREQUENCY ACOUSTICS TO SEDIMENT PROCESSES FOR MINE BURIAL PREDICTION

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Over the past decade, high frequency acoustics, 0.5 MHz -5 MHz, has made significant contributions to the measurement of nearbed sediment processes. The capability of acoustics to provide co-located high temporal and spatial resolution profiles of the bed forms, the hydrodynamics, and the suspended sediments, is providing new insights into the interactions and feedback mechanisms of sediment transport. Acoustic instrumented mines, AIM’s, were developed that could utilize this concept of acoustics, formulated for sediment studies, and apply it to scour burial. The AIM’s were designed to measure not only the behavior of the mine, ie the roll, pitch, heading, and percentage burial, but also the near-field hydrodynamics, sediment movement and bedform changes, that cause the burial. The AIMs utilise 112 flush mounted acoustic transducers to measure percentage mine burial, expressed here as the surface area covered by sediment. By utilising the backscattered signal from a number of these transducers, sediment processes around the mine could be examined. This paper presents an analysis of backscattered signals collected during a deployment of the AIM’s, within the Martha’s Vineyard Coastal Observatory, between September 2003 and April 2004. Using the processed backscatter data in combination with pitch, roll, heading and pressure data, attempts are made to relate the hydrodynamic forcing conditions and sediment response, to the process of mine burial.
1 Introduction

Acoustics has been used for about two decades for the study of sediment transport processes [1]. Recent developments and integration of systems onto common platforms, has lead to acoustics providing detailed measurements of the hydrodynamics, suspended sediments and the bed morphology, within a common measuring volume. Such observations are providing fundamental information on the linkage and feedback between the flow, the sediment movement and the bedforms. In the present work advantage has been taken of this application of acoustics and it has been utilized in the study of mine burial processes, as part of the ONR Mine Burial Programme, MBP.

Acoustic Instrumented Mines, AIMS, were designed, developed and constructed as part of the MBP [2]. The AIMS were designed to measure the hydrodynamic processes, sediment movement, and bedforms close to the mine, in addition to the mine behavior of heading, roll, pitch, and percent burial, during burial. A total of 4 AIMS were built and have been used in mine burial experiments in the Gulf of Mexico and at the Martha’s Vineyard Coastal Observatory. The AIMS are cylindrical in shape with a diameter of 0.5 m and a length of 2 m and have 112 acoustic transducers mounted on the surface the mines, which operate at 0.5 MHz, 1.5 MHz and 3.0 MHz. A number of the 1.5 MHz and 3.0 MHz transducers were used in a mode for measuring suspended sediment concentration around the mine and this is the focus of the present study. The AIM’s utilise electronic compasses and 3-axis magnetometers and accelerometers to measure pitch, roll, and heading and have 6 pressure sensors to measure near bottom pressure fluctuations. These pressure data are used to determine a time history of significant wave height and period and, in conjunction with fixed mounted pressure sensors, determine mine burial relative to a fixed depth or the sediment water interface, if there are no major changes in the bedforms. A schematic of an AIM showing the acoustic beams is shown in figure 1, and figure 2 shows an AIM on the sea bed.

Figure 1. Schematic of an AIM showing the acoustic backscatter beams.
The present work reports on the analysis of acoustic backscatter, ABS, data collected on the AIMs for suspended sediment measurements during a recent deployment at the Martha’s Vineyard Coastal Observatory, MVCO. Two of the AIMs were deployed in 12 m of water on a fine sandy bed at approximately 25 m from the MVCO node during the period from September 2003 to April 2004. The layout is shown in figure 3. The Martha’s Vineyard mine burial experiment was a large field campaign with a number of mine types deployed and numerous environmental measurements conducted [3]. A provisional inspection of the raw data showed some potential relationship between the significant wave height, $H$, and the 3.0 MHz AIMs backscatter data, it was therefore considered interesting to analyse this data set in some detail first. Hydrodynamic parameters derived from the significant wave height and period were used to obtain the bed friction velocity, which with a criterion for suspended sediment entrainment, is used to interpret the temporal variations in suspended sediment concentration. The hydrodynamic and suspended sediment time series are used in a provisional way to interpret the motions of the AIMs.
2 Background

2.1 Suspension scattering

For a suspension, insonified in the farfield of a piston source transceiver, the suspended sediment concentration, $M$, can be written as [1]

$$M = \left( \frac{V_{\text{rms}}}{k_s k_t} \right)^2 e^{\alpha r}$$  \hspace{1cm} (1)

$$\alpha = a_w + \frac{r}{o} M r$$

$V_{\text{rms}}$ is the root-mean-square backscatter signal, $r$ is the range from the transducer, $k_s$ represents the backscattering properties of the sediment in suspension, $k_t$ is a system constant, $a_w$ is the sound attenuation due to water absorption and $\xi$ is the sediment attenuation coefficient.

Since only one frequency, 3.0 MHz is analysed, knowledge of the size of the particles in suspension is required to evaluate equation (1). For the present work the value was not known, therefore an estimate for the suspended grain size was made from the size distribution of the bed sediments. A sensitivity test was carried out to examine the effect changing the particle size had on the acoustic inversion and this is described in section 3. As seen in equation (1), $M$ also occurs on the RHS of the equation in the expression for the sediment attenuation. Therefore to evaluate equation (1) $\xi$ was initially set to zero and the equation evaluated to obtain an initial estimate for $M$. This value for $M$ was then used to evaluate the sediment attenuation and an improved value for $M$ obtained. The process was repeated until a convergent solution was obtained.

2.2 Sediment entrainment

It was considered of use and interest to establish the threshold for suspending sediments at the mine location, and to compare the expected requirements for entrainment, with the observations of the suspended sediments collected with the ABS. A simple and often used criterion for suspending sediments is that the bed friction velocity, $u_*$, is greater than the settling velocity of the sediments in suspension, $w_s$ [4]. In the present work a criterion of $1.2w_s$ was set. Using this requirement we have,

$$u_* \geq 1.2w_s$$ \hspace{1cm} (2)

$w_s$ can be expressed as

$$w_s = \frac{V}{d_{s0}} \left[ (10.36^2 + 1.049d_{s0}^3)^{0.5} - 10.36 \right]$$ \hspace{1cm} (3)
\[ D_s = \left[ \frac{g(s-1)^{1/3}}{v^2} \right]^{1/3} d_{50} \]

Where \( g \) is the acceleration due to gravity, 9.81 m\( s^{-1} \), \( s \) is the relative density of quartz sand to water, 2.65, \( d_{50} \) is the mean bed grain diameter in metres and \( v \) is the kinematic viscosity of water and was taken to be \( 1.3 \times 10^{-6} \text{ m}^2\text{s}^{-1} \). To calculate the bed friction velocity the following was used,

\[ u_* = \sqrt{f_w/2} U_w \]

\[ U_w = \frac{nH_s}{T_z \sinh(kh)} \]

\[ f_w = 0.237 \left[ \frac{k_s}{A_w} \right]^{-0.52} \]

\( f_w \) is the wave friction factor, \( U_w \) is the wave orbital velocity amplitude at the bed, \( T_z \) is the zero-crossing period of the waves, \( h \) is the water depth, \( k \) is the wave number of the waves, \( A_w \) is the orbital amplitude of the wave motion at the bed and \( k_s = 2.5 d_{50} \) is the Nikuradse equivalent grain roughness. Using \( k_s = 2.5 d_{50} \) for the calculation of the wave friction factor assumes the bed is nominally plane and there is limited ripple formation; this approximation may need further analysis.

3 Data Analysis

As mentioned above, to invert the 3.0 MHz data to obtain the suspended sediment concentration, \( M \), an estimate for the suspended particulate size was determined from samples of sediments collected from the seabed. Figure 4 shows cumulative size distributions of the bed sediments.

![Cumulative size distribution](image)

Figure 4 Cumulative size distribution, \( d_{50} = 150 \mu\text{m} \).

To assess the impact of particle size, figure 5 shows acoustic measurements of suspended sediment concentration using \( d_{50} = 100 \mu\text{m} \) - \( 200 \mu\text{m} \) in the inversion. This range covers the greater part of the size distribution. Figure 5 shows very comparable magnitudes and temporal variation for the different particle sizes. The inversion was
relatively insensitive to the particle size used and therefore the acoustic concentrations were considered to be reasonably robust.

To examine the data sets that came from the AIMS, time series of $M$, $u_*$, $H_s$, $T_z$ and roll were generated. An example from one of the 112 transducers, transducer 21, is shown in figure 6. One of the first points to note is the clear correlation between the ABS concentration time series and the friction velocity. Increases in $u_*$ above the threshold velocity, 0.016 m s$^{-1}$ show significant increases in suspended concentration. This relationship between $u_*$ and $M$ provides confidence in the veracity of the data set.

Examination of the time series for $u_*$, $H_s$, and $M$ does provide a degree of explanation for the movement of the mine, represented here by the degree of roll. From figure 6 it can readily be seen that at the beginning of the record, days 270-295, there were high values of $H_s$ and $u_*$ with associated increase in suspended sediment. The increase in concentration of suspended sediment is coincident with scour around the mine. After sufficient scour, the mine began to pitch and eventually roll into its own scour depression, realigning the main axis of the mine with the dominate wave direction. At this point the mine was buried to a depth of 0.45 m relative to the sediment surface but with only 40% of the sensors covered as a large scour pit surrounded the mine. (See Figure 7) Between days 300-315, the values for $u_*$, $H_s$ and suspended sediment concentration were relatively low and there was little or no scour and the mine did not move. Activity does pick up in $u_*$ and $H_s$ after day 315, however, the sediment suspended sediment concentrations remained relatively low suggesting that scour around the mine was less than during previous storms. It appears this activity was insufficient to create significant scour depressions around the mine and the mine remained static. The change in roll near day date 340 was caused by a repositioning of the mine. A large storm with significant wave heights close to 4 m occurred near day date 346, only 6 days after repositioning the mine. The significant increase in suspended sediment concentration at that time coincided with a significant roll of the mine of nearly 25 degrees. By the end of the storm nearly 80% of the mine’s acoustic sensors were covered. The next two storms filled in the scour pit with a sand/mud mixture and the mine was nearly fully buried for the remainder of the experiment. Transducer 21 was the only backscatter sensor that was
not completely covered during the rest of the experiment and provided backscattering from the water column. Though, even transducer 21 was apparently buried during parts of the experiment and the low values of suspended sediment concentrations beyond day 370 may reflect partial burial of the transducer by low density mud. The other transducers, which were buried, provided no analyzable data after day 370.

![Image of plots](image)

Figure 6. Plots of: a) the suspended sediment concentration within 0.25 m of AIM4 ABS transducer 21, b) the concentration at 0.05 m from the mine, c) the friction velocity (---) and suspension threshold velocity (--), d) significant wave height (---) and zero crossing period (---), and e) the roll of the mine. The time base is in days starting on Julian day 270, 27th September 2003 and concluding on day 470, Julian day 105, 14th April 2004. The mine was repositioned on day 340.

As shown in figure 3, as well as the acoustics on the AIMs, a 2-axis acoustic rotary pencil beam system was deployed close to the mine. This provided a measurement of the location of the mine and the seabed around it. An example of the data collected is given in figure 7. This shows the mine being partially buried prior to a storm that came through on the 22 October 2003, day 295. It is anticipated that the generation of such images, coupled with the AIMs hydrodynamics and sediment dynamics reported in this study, will provide data sets which will make a significant contribution to understanding the mine burial process.
4 Conclusion

The AIMs were developed to measure not only mine behavior during scour burial, but also the hydrodynamic processes, waves, currents, and suspended sediments, responsible for that burial. This paper has focused on the measurement of the suspended sediments in the near-field of the mine and this was successfully extracted from the data collected. The suspended sediment variability has been compared with the hydrodynamic conditions and there was seen to be a direct correlation with the bed friction velocity. The movement of the mine has been linked to the hydrodynamic processes associated with scour burial. The coupling of the AIMs data with images from the rotary sector scan and pencil beam sonars should further aid the interpretation of the AIMs data and provide valuable information for modelling the mine burial process.

References

HIGH RESOLUTION SONAR IMAGING, TARGET DETECTION AND CLASSIFICATION

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The automatic detection and classification of targets on the seabed from acoustic imagery is a demanding problem, requiring firstly the production of high-quality images and secondly the development of robust algorithms to perform the detection and classification processes. Key problems to be addressed have been the spatial sampling problem inherent in the synthetic aperture approach, and characterising and compensating motion errors of the platform carrying the sonar system, and high quality imagery with resolutions of a few centimetres at ranges of several hundred metres, from UUV platforms, is now readily achievable. The second part of the problem is being addressed by a range of techniques. Characterisation of seabed texture using statistical models allows the image to be segmented, and correct detection thresholds to be set to detect targets against these backgrounds. Interferometric (bathymetric) processing is able to determine target height, and to some extent target shape. Multi-aspect imagery may additionally be exploited, both to provide different views of the target and to give shadow shape information from different aspects.

1 Introduction

The automatic detection and classification of targets on the seabed from acoustic imagery is a demanding problem, requiring firstly the production of high-quality images and secondly the development of robust algorithms to perform the detection and classification processes. Significant advances have been made in the past decade in the development of synthetic aperture sonar imaging from UUV platforms, and in the development of detection and classification algorithms. Both of these sets of advances have been aided by parallel advances in the equivalent techniques in radar imaging, detection and classification.

The purpose of this paper is to review these techniques and the current state of the art, and to consider other areas where ideas from the radar domain may be useful.

2 Synthetic Aperture Sonar imaging

2.1 Incentives and constraints

For minehunting and other survey applications, autonomous underwater vehicles are increasingly the platform of choice for sonar imaging systems. However, the economics and practicality of AUV technology limits the total length of the sonar array to about a
metre or so. Using such an array, conventional beamforming sonars need to operate at very high frequencies (e.g., 400 kHz) in order to obtain the required along-track resolution of a few millimetres for target detection and classification. At these high frequencies, the range of the system is limited to 200-300m by rapid attenuation of sound in the ocean. The essential advantage of synthetic aperture systems is that they can achieve a given along-track resolution using the same length of sonar array but operating at a much lower frequency than a conventional beamforming sonar. The frequency reduction is a factor of three or four. This corresponds to a change of many tens of dB/km in the attenuation properties of seawater and effectively removes the constraint on range due to attenuation. However, other factors come into play to limit the performance of synthetic aperture sonar systems.

An early concern was that the medium would not be sufficiently stable to allow imaging by means of a coherent sum of sonar echoes. In fact, measurements showed that medium stability would not actually be a problem in well-mixed shallow water environments of interest [1,2]. A more serious constraint on synthetic aperture sonar is that the receiver needs to travel through the water slowly enough to avoid undersampling the pressure field. If the sound field is not sampled at sufficiently small intervals, grating lobes arise due to spatial aliasing of the pressure field and produce spurious artefacts on the image [3]. Specifically, grating lobes will arise if the hydrophone array moves more than 50% of its length between pulses [4]. If a distant target is to be imaged, a significant time may elapse before the echo is received, and consequently the array must travel rather slowly. In the case of a sonar array of length 1 m traveling at 1 m/s, the maximum unambiguous range is 375 m.

2.2 Motion compensation

Another issue with synthetic aperture sonar is defocus of the image due to across-track motion of the sonar array. In coherent processing of the returns from several pulses, it is essential to know exactly where the sonar array was at each instant of time. Across-track motion errors of only a couple of millimeters will create significant phase errors and defocus the image. Inertial navigation systems have turned out to be inadequate for this task. A widely-used and successful method of dealing with across-track motion errors is to cross-correlate the returns from one pulse with the next – the Displaced Phase Centre Array method [5]. The leading hydrophones at one pulse are cross-correlated with the trailing hydrophones at the next pulse. If the hydrophones are chosen so that their phase centres are coincident, the correlation is between two measurements that are taken at precisely the same point in the ocean but at different times. Any difference in the apparent range of the scene must therefore be due to across-track motion of the array.

DPCA has proved successful for controlled experiments using a system on a rail, in which the sonar array moved very slowly giving an adequate number of overlapping phase centres [6]. On the other hand, in AUV trials at realistic speeds we have found it necessary to add an extra layer of motion compensation, adopting autofocus methods such as Phase Gradient Autofocus [7] from the synthetic aperture radar community. In PGA the small errors which remain after DPCA processing are inferred from the image itself. If conventional one-dimensional PGA is used, special measures are necessary to handle the large range migration which occurs in synthetic aperture sonar systems [8]. Recently a two-dimensional PGA algorithm has also been proposed for sonar [9].
2.3 Images from shallow-water AUV trials

Figure 1 shows a synthetic aperture sonar image obtained from an array of length 1.1 m that was attached to a large (7 m long, 533 mm diameter) underwater vehicle undergoing trials in very shallow water (12 m depth) [8]. The image was obtained by combining the sonar returns over a track length of 15 m. The motion compensation used both DPCA and PGA. The Figure shows a synthetic aperture sonar image of a cylinder of about 2 m length strapped to a section of duckboard (photograph inset). The range of the target object was 42 m. The image shows a useful level of detail of the object including the straps, together with a clear shadow.

Figure 1. SAS image of cylinder at 42 m in shallow water, obtained from a 1.1m array carried by an underwater vehicle travelling at 1 m/s. Sonar returns were combined over a track length of 15 m.

Figure 2. SAS image of cylinder at 262 m in shallow water, obtained from a 1.1m array carried by an underwater vehicle travelling at 1 m/s. Sonar returns were combined over a track length of 20 m.
Imaging of distant objects was made difficult by the very shallow water. In a depth of just 12 m there are significant multipath contributions due to reflection from the sea surface. As the surface is moving, the multipath contributions sum incoherently and tend to create a haze. Figure 2 shows an image of a cylinder on the seabed at a range of 262 m. The vehicle speed was 1 m/s and the pulse repetition rate was 0.5 s, giving a maximum unambiguous range of 368 m. The DPCA method was used to infer sway motion of the vehicle, but not yaw, as there was only a minimal overlap of phase centres from one ping to the next. Here the track length was 20 m.

2.4 Signal processing for spotlight and squint mode

The AUV-based sonar images presented above were created using a 1.1 m array of 192 closely-spaced hydrophones to sample the sound field created by each acoustic pulse. Thus in the course of generating a synthetic aperture of suitable length, the field is sampled at several thousand points along track; and each of these points is a time series of several thousand range points. Reconstruction of the two-dimensional field of scatterers is therefore a significant computational problem in itself, quite apart form considerations of motion compensation. Image reconstruction using basic ‘sum and add’ techniques takes several hours on a PC.

In generating the images shown above, we have grouped the hydrophones together 10–20 at a time in subapertures, along the lines suggested in [5]. Conventional beam forming applied to the (overlapping) subapertures creates a set of broadside beams along track at suitable intervals dictated by spatial sampling considerations. This preprocessing gives a data set similar to that collected by a radar antenna, and Fourier techniques adopted from the radar literature were used to generate the images in two or three minutes. Steering the subaperture beams leads to spotlight and squint mode synthetic aperture sonar.

More recently, fast factorised backprojection [10] has brought a further advance to synthetic aperture sonar processing. In FFBP there is no requirement to maintain all the collected data in memory at once, but the image is built up progressively in a process that has some similarity to the Fast Fourier Transform. Special purpose hardware has been developed at UCL for real-time processing at high speed.

3 Detection and classification

3.1 Texture modelling

The statistical behaviour of high resolution sonar imagery of the seabed can be quite successfully modelled using the compound K-distribution, originally developed to model optical scattering and now widely used to model radar clutter. This represents the texture as the product of a chi-distributed underlying texture and a Rayleigh-distributed speckle. Indeed extensive data analysis work on the correlation between resolution, grazing angle, seabed type and probability distributions distinctively demonstrated that as sonar resolution increases the probability laws rapidly change from a Rayleigh hypothesis to a K-law [11]. The results are extrapolated from the experimental data to produce a surface as a function of grain size of the sediment, grazing angle. Below this surface only the K-
law hypothesis will be accepted. As an example, in Figure 3, this surface is plotted in red and compared to typical insonified areas for a low resolution sonar on the left and wide-band high resolution sonar on the right. Clearly, as the resolution increases, the textural and statistical nature of the data changes and classification techniques should incorporate this information accordingly.

Figure 3. Surfaces of insonified areas (in blue) compared to statistical surface limit (in red) for a low resolution sonar on the left and a high resolution sonar on the right.

Abraham and Lyons [12] have also demonstrated the direct link between the K-law parameters and the number of scatterers within the insonified area, also dependent on seabed type. This provides a basis for the prediction of reverberation induced probability distribution functions from measured geo-acoustic data as well as a consideration of more complicated seafloor scattering scenarios. Other developments of the basic model have also been used with success [13].

Bell et al. [14] have shown that the texture may also be a function of direction. They demonstrate this with examples of ripples in a sandy seabed observed from different directions; from some directions the ripples are very distinct, from other directions less so. This is because the sonar image acquisition process acts as a directional filter of seabed texture and any classification scheme should take this into account.

### 3.2 Detection and classification

This allows the image to be segmented into regions of different texture, and to detect objects against a given texture background. An analysis of the statistics of the different zones in a SAS image can in the first instance provide a simple mean to detect highlights. As an example, Figure 4 shows a fully focused SAS image of a sphere and a cone. Histograms of the three different regions, shadow, seabed and target are compared to the Rayleigh distribution in red and to the K-law distribution in green.

However, a robust detection process can (and should) make use of as much information as possible, such as shadow, target shape and height. The examples in Figure 1 and Figure 4 show quite well the additional information provided by the shadow. Bell et al. [15] have devised and demonstrated techniques based on ‘statistical snakes’ to delineate the shadow boundary, and from the highlight associated with the object and from the shadow to classify the target. Although this approach is developed assuming a Rayleigh distribution, extrapolation to high resolution imagery is trivial.
Classification is then achieved using the Dempster-Shafer theory. This theory is a generalisation of the Bayesian theory of subjective probability. Its most attractive property is its ability to consider unions of classes and an ideal framework for fusing classification results from multiple images.

Figure 4. Focused SAS image of a sphere and cone on the left. On the right, histograms of the three different regions (from top to bottom shadow, seabed and target) compared to the probability distribution functions of the Rayleigh pdf in red and the K pdf in green.

3.3 Interferometry

The technique of interferometry (bathymetry) has been developed to provide target height and shape information. Essentially this consists of comparing two images (sidescan or SAS) of the target scene, obtained from transducers separated vertically by a fixed distance (baseline). Subtracting the phases of corresponding resolution cells of the images gives a phase difference image (interferogram), where the phase difference values are a function of the range, baseline and its orientation, wavelength, and the height of the target in that resolution cell above a reference level. Hence from the phase difference values, the target height can be determined if the other parameters are known or can be estimated, giving a topographic map of the target scene, to the same resolution as the original images [16].

3.4 Multi-aspect imaging

The combination of views of a target from a number of different aspects would be expected intuitively to provide an improvement in classification performance. Work in the radar domain at University College London has investigated this, using experimental radar imagery of vehicle targets. Three different ways of combining the aspects were
used: Naïve Bayesian Classifier, K-nearest neighbours (KNN), and Feed-forward Artificial Neural Networks (FANN). Details of these algorithms are provided in reference [17]. Figure 5 shows the improvement in classifier performance as a function of number of perspectives. It can be seen that there is a significant benefit in going from 1 to 2 perspectives, and a small additional benefit from 2 to 3, but rather less from further additional perspectives.

Shadow information may also be used in multi-perspective classification. A variant of this is a bistatic configuration, in which a target will display two shadows; one associated with the transmitter and one associated with the receiver. This effect is readily observed in bistatic synthetic aperture radar images [18].

![Figure 5. Multi-perspective classifier accuracies.](image.png)

Finally, we can note some further work from both the radar and sonar domains, in which information from interferometry, texture classification, shadows, and linear features, can be combined using Bayesian or Dempster-Shafer techniques [19, 20].

4 Conclusions

We have shown how the twin problems of production of high-quality high-resolution sonar imagery, and of automatic target detection and classification, may be approached. High quality imagery with resolutions of a few centimetres at ranges of several hundred metres, from UUV platforms, is now readily achievable.

There are several techniques from the radar domain that may be useful in this work. Characterisation of seabed texture using statistical models allows the image to be segmented, and correct detection thresholds to be set to detect targets against these backgrounds. Interferometric (bathymetric) processing is able to determine target height, and to some extent target shape. Multi-aspect imagery may additionally be exploited, both to provide different views of the target and to give shadow shape information from different aspects.
References

LOCALIZATION OF SEABED DOMAINS ENSONIFIED BY OBJECT-REFLECTED SOUND AT VERY HIGH FREQUENCIES

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The ability to detect and identify an object located on the seafloor by application of images acquired from monostatic sonar depends on the shape and orientation of the object with respect to the sonar. For example, on-axis incidence on a cylinder results in a strong reflected wave, but with a few degrees of rotation, the only contribution to the direct backscattered signal may be diffracted waves. Sound interaction with the seabed, however, may contribute significantly to the backscattered signal. In this paper, domains on the seabed ensonified by reflected sound from a smooth arbitrarily shaped object are localized. These domains can be applied for computing the second order scattered field relevant for a sonar model. Analysis has been carried out in two and three dimensions. In two dimensions, object reflected rays are visualized for a sphere/cylinder and a truncated cone (Manta-mine) together with their estimated ensonified seabed domains. In three dimensions the estimated ensonified seabed domains are visualized for a sphere and a cylinder.

1 Introduction

This work is related to the generation of synthetic sector sonar images, that is, images acquired with high frequency (>100 kHz) sonar systems. The interest is focused on images of naval mines, but also man made objects in general, located on a sandy seabed. The model developed so far computes, coherently, the scattered field from the object and the seabed separately and finally the contributions are summed to give the total field. The Kirchhoff approximation or the physical optics solution [1-4] is the basis of the model. The model has been presented in Ref. [5], where synthetic images were compared qualitatively with authentic images of a finite cylinder on a sandy seabed. At angles close to normal incidence, i.e., normal incidence with respect to the cylinders axis, the resemblance was found to be reasonable, but away from the normal incidence the only contribution to the backscattered field may be diffracted waves and higher order reflections, features that are not implemented in the model at this stage. In the off-normal
incidence cases the synthetic images only include seabed backscattered pressure and a shadow cast by the object, whereas pressure contributions caused by the sound interaction between the seabed and object are absent. If a model based on the boundary element method was employed instead higher order reflections would be an inherent part of results obtained. In the scenario under consideration the dominant wavelength is equal to approximately three millimeters and the object has, say, a length of 1 m and it is located on a rough seabed covering several square meters. Hence, a boundary element model would require an excessive computational capability. Instead, the Kirchhoff approximation will continue to be the fundamental building block in the model and it will also be used to model the seabed object sound interaction.

Sound field interaction between the seabed and a proud object has been analyzed by Fawcett [6-7] who applies an image source method because the dominant wavelength is large compared to the roughness heights, i.e., the seabed interface can be described as perfectly flat. Bell [8] has developed an incoherent sonar model for high frequency sound propagation in a refracting medium. The model is based on optical ray tracing with higher order reflections being an inherent part of the method. The incoherent model by Capéron [9] only applies straight line rays, but likewise, higher order reflections are also an inherent part of the sound propagation model. The coherent model by G.S. Sammelmann [10] only uses ray tracing to estimate the sound field interaction between the seabed (consisting of randomly distributed point scatters) and an object, whereas object backscattering is based on the physical optics solution.

In the model presented here, a ray - or wavefront component is intended to be assigned to each visible facet on the object, and, by application of the physical optics solution, the coherent field reflected down toward the seabed from the object will be computed. The next step will be to calculate the field scattered back to the sonar. However, in order to reduce the computational load it is necessary to include only seabed areas ensonified by a suitable amount of energy. This paper describes how essential areas on the seabed ensonified by object reflected sound are found.

In section 2 the second order field caused by the object-seabed interaction is considered. It is argued how the sonar-object-seabed-sonar paths can be found relatively easy, and additionally, when these paths are estimated they can – approximately - describe the full second order field. In section 3 the method to localize essential areas on the seabed ensonified by object reflected sound is described. In section 4 results are presented for two- and three-dimensional simulations. Finally in section 5 a discussion and conclusions are presented.

2 Second order scattering caused by object-seabed wave interaction

The basic assumption for the work presented here is that the surface of the object is smooth, i.e., the radius of curvature on any point on the surface is much greater than the dominant wavelength. In other words, nearly anywhere on the surface the field is scattered coherently, i.e. reflected, and the Kirchhoff approximation works very well.

Consider the field emitted from a sonar incident onto an object. On the surface of the object the field scattered from a surface element with dimensions larger than, say, three wavelengths will be concentrated in the specular direction, see Fig. 1A. Hence, each
Figure 1: High frequency sound interaction between an object and the seabed for mono static sonar. Figure (A) shows the sonar-object-seabed-sonar path and Figure (B) shows the ray when the direction has been reversed, i.e., when the sonar-seabed-object-sonar path is considered.

The surface element acts as a local mirror, which, when directed down toward the seabed, only ensonifies a limited area. From the limited region on the seabed ensonified by the small reflector on the object, the sound is scattered diffusely (but it may also contain relatively weak coherent components, depending on the roughness characteristics of the seabed). There are no ambiguities associated with the direction of the wave field scattered from the seabed since interest only is on the part of the wave field received by the sonar. The seabed topography, or roughness, governs the resulting wave interference generated here. Hence, the sonar-object–seabed-sonar path, see Fig. 1A, appears with the assumption of a smooth object, to be unambiguous. The opposite sonar–seabed-object-sonar path, see Fig. 1B, is far more difficult to estimate, because here it is necessary to search for the point on the sphere where the seabed scattered sound will be reflected up to the sonar. In any other direction the field is reflected away. However, the full second order field, i.e., the field that experiences a single bounce on the object and a single bounce on the seabed is assumed to be approximately provided by multiplying the results obtained from the sonar-object–seabed-sonar path by 2, and hence, the interference between different wave paths is neglected.

In order to reduce the computational workload for second order scattering a preliminary wave field calculation for the estimation of the most important ensonified seabed areas is carried out. The method is described in the next section.

3 Method for localizing of the essential ensonified seabed regions

In the sonar model, the surface of three-dimensional objects and the seabed roughness interface, a height field, are represented by plane triangular facets. The scattered field is computed coherently in the pressure domain by application of the Kirchhoff approximation, which relates the incoming field to the total field on a surface. The Kirchhoff approximation reduces the Kirchhoff-Helmholtz integral equation to an integral. Consider an arbitrary facet in the numerical representation of the geometry, say, the m’th facet. Let $p_0$ be the peak pressure 1 meter from the source, $r_0$ the vector from the
facet to the sonar with the length \( |\mathbf{r}_0| = r_0 \), \( \mathbf{r}_1 \) the vector from the facet to the observation point with the length \( |\mathbf{r}_1| = r_1 \), and \( \mathbf{n}_s \) the normal vector of the facet surface, \( S \). If \( k \) denotes the wavenumber and \( x_s \) the integration variable over \( S \), then the bistatic expression for the scattered pressure from any plane facet in the numerical representation of the geometry is

\[
p^{(m)}_{ac}(x) = \frac{p_0 (\mathbf{r}_0 \cdot \mathbf{n}_s) e^{ik(\mathbf{r}_0 + \mathbf{r}_1)}}{2\pi r_0 r_1} \int_{S_m} e^{-ik(\mathbf{r}_0 + \mathbf{r}_1) \cdot x} \, dS_m ,
\]

where a vector with a superscripted hat (^) corresponds to a unit length vector. For each facet on the object surface, the specular direction corresponds to the stationary point of (1) where the complex exponential phase term vanishes, and the pressure is

\[
p^{(m)}_{ac}(x_{sp}) = \frac{p_0 e^{ik(\mathbf{r}_0 + \mathbf{r}_1)}}{2\pi r_0 r_1} \mathbf{r}_1 \cdot \mathbf{n}_s S_m ,
\]

where, \( x_{sp} \), corresponds to any point on the line that originates from the facet and points in the specular direction down toward the seabed. A cone around the specular ray is constructed. The cone width shall resemble, say, the 3 dB width of the radiation pattern in the specular direction from the object facet. The cone intersects the average seabed level, a perfect plane, as an ellipse. The area of the ellipse depends on the location and orientation on the facet, and the perimeter will be found numerically. The analysis is aimed at the localization of seabed areas essential for second order field computation, that is, areas on the seabed where the incoming object-reflected field is concentrated. In the analysis the field is regarded as incoherent and the total sum of all time averaged intensity contributions from all facets on the mean seabed plane is calculated. A coherent summation would result in a misleading interference pattern for energy on the flat seabed, because, the real interference pattern caused by the seabed most likely would differ significantly. An incoherent summation, on the other hand, will give a smoothly distributed intensity map independent of the seabed roughness interface. Hence, the time averaged intensity [11] received at the average seabed plane and radiated by, say, the \( m \)'th object facet is given by

\[
I^{(m)}_{av} = \frac{|p_0|^2}{4\pi r_0^2} \frac{\cos(\theta_1)}{r_1^2} \frac{S^{(m)}_{obj}}{S_{ellipse}} \approx \frac{\xi \cos(\theta_1) S^{(m)}_{obj}}{S_{ellipse}} ,
\]

where \( \xi \) is a proportionality constant. The area of the ellipse, \( S_{ellipse} \), is approximately proportional to the square of the range, \( r_1 \), i.e., the range from the facet to the intersection point on the smooth seabed plane. Only when the ellipse is very large compared to the object, that is, when the centerline of the cone intersects the seabed far from the object, the approximation is invalid. A cone with an axis that intersects the seabed a distance larger than, say, five times the characteristic length of the object, is discarded. Hence, the
average intensity of the incoming field is assumed constant over the elliptical shaped area. Additionally, the variation of $r_0$ when considering different object facets is neglected, and consequently, $\xi$ is constant for all ellipses and is set equal to 1.

A mesh grid in the seabed plane is generated, and for each object facet the points within the seabed ellipse are found. For all of these points the magnitude of the intensity given by Eq. (3) is added to previous values assigned from other facets. Finally, an intensity matrix for the incoming field onto the seabed around the object is obtained. The essential ensonified area is found by using a threshold value which is a certain fraction of the maximum intensity value in the intensity matrix. Hence, all values larger than the threshold value are considered within the region of ensonification.

4 Numerical models

Simulations have been carried out in two and three dimensions. The threshold value has been set to 10% in all cases. The radiation cone in the specular direction has an angle of 12º.

In the two dimensional case the scattered field from the cross the section of a cylinder and a Manta-mine is analyzed. In both cases the sonar is 3 m above the seabed and the ground range distance to the object is 9 m. The cylinder has a radius of 0.35 m and its cross section is numerically represented by 1D facets, i.e., line segments of 3 mm length. In Fig. 2 (top) rays outgoing from some of the facets are shown. The major part of the ensonified energy is concentrated in front of the cylinder. Behind the cylinder seabed areas are also ensonified, but the incoming intensity there is weak as the effective reflection area on the object is small. In Fig. 2 (bottom) the object reflected area has been estimated and the ensonified area covers approximately 1 m. The Manta mine, see Fig. (3), is located at the same position as the cylinder, it has a bottom radius equal to 0.35m, its slope is 50º, and its height is 0.42m. As can be seen the stealthy Manta mine does not reflect any sound onto the seabed and the top-surface reflected sound is directed away from the sonar. The incoming field will be perpendicular to the object surface and a reflected wave is generated only in very exceptional cases. However, roughness on the surface of the object might produce a backscattered wave, but this topic is not treated here.

Three-dimensional simulations have been carried out for a sphere and a finite cylinder. In both cases the sonar is located 3 m above the seabed with a ground range distance to the object equal to 6 m. The plane triangular facets had a maximum side length of 14 mm. Figure 4 shows the estimated ensonified area by a sphere with radius 0.2 m. The sphere ensonifies an area approximately equal to 0.4 m². The cylinder has a length of 1 m, radius of 0.2 m, and the cylinder axis is rotated 30º with respect to the y-axis of the seabed plane, see Fig. 5. The cylinder ensonifies an area on seabed along the cylinder axis which is approximately equal to 0.5 m². Additionally, an area of 0.2 m² is ensonified by the endcaps.
Ground range [m]  
Depth [m]  
Reflected rays from a sphere (R=0.35m)  
SONAR  
incident rays  
reflected rays  

Figure 2: Reflections from a sphere/cylinder (2D). (Top) shows incident rays and some of the reflected rays from the object and (Bottom) the area of seabed ensonified by object reflected sound assuming a threshold value of 10%

Seabed ensonified using a 10% threshold  

Ground range [m]  

Reflected rays from a Manta–mine type (R_{\text{bottom}} = 0.35m, H = 0.42m, \alpha = 50\degree)  
SONAR  
incident rays  
reflected rays  

Figure 3: A Manta mine on a flat seabed. (Top) shows incident rays and reflected rays from the object and (Bottom) the stealthy properties of the mine are revealed as no seabed is ensonified by object reflected rays.
Figure 4: Estimated seabed domains ensonified by a sphere of radius 0.2 m and positioned 6 ground range meters from the sonar. The sonar is located at $x = 0$, $y = 0$, and it is elevated 3 m above the seabed. The applied threshold value is 10%.

Figure 5: Estimated seabed domains ensonified by a cylinder of radius 0.2 m and length 1 m. The cylinder is 6 ground range meters from the sonar and its axis is rotated 30° with respect to the y-axis. The sonar is located at $x = 0$, $y = 0$, and it is elevated 3 m above the seabed. The applied threshold value is 10%.
5 Discussion and conclusion

A numerical method that estimates domains on the seabed ensonified by object reflected sound has been developed. The method assumes that the objects are smooth and that nearly anywhere on the surface of the object the field is scattered coherently. The assumption of smooth surfaces may only hold in certain cases, since at other times, an object can be covered with plants and different species, and consequently, it will scatter more or less diffusely. In the very rough cases the idea presented in this paper becomes irrelevant, and the object might as well be considered as a part of the seabed, where only the shadow can reveal any presence of a man made object. Scattering of orders higher than two, e.g., third order sonar-seabed-object-seabed-sonar or sonar-object-seabed-object-sonar paths, may also have a significant influence on the total field. The influence of higher order scattering primarily depends on the loss of sound energy per bottom bounce.

Results showing the ensonified area of seabed have been presented in two- and three dimensions for cylindrical, spherical and truncated cone (Manta) shaped objects, illustrating some of the stealth properties of the Manta compared to the other shapes. The three-dimensional results have a direct application as the method in three dimensions will be applied to compute the second order field using physical optics solution and will be the topic of the future work.

References

Section 7

Reflection from the seabed
THE DEVELOPMENT OF A DIVER DEPLOYED X-RAY ATTENUATION MEASUREMENT (XRAM) DEVICE TO MEASURE THE DENSITY GRADIENT \textit{IN SITU}

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The value for the reflection coefficient from a sand/water interface can have a significant impact in the modeling of the acoustics of shallow water communications, anti-submarine signal processing and buried mine detection. However, depth dependent density can have a considerable influence on the measured value for the reflection coefficient, particularly at high frequencies. Therefore, an accurate \textit{in situ} measurement of the bulk density of the transition layer is critical to the interpretation of reflection data. Previously, bulk density measurements were either taken from scans of cores which disrupted the natural grain assembly or conductivity probes in which the density is measured indirectly. For this study, a novel means of directly determining the density gradient \textit{in situ} using x-ray attenuation was developed. The system is small, lightweight and diver deployed allowing a greater flexibility in density measurements. Calibration measurements of materials with varying densities as well as laboratory measurements of the transition layer of a sand/water interface will be presented. Issues involved with the applicability of the current device and future developments will be discussed. [Work supported by ONR, Ocean Acoustics]

1 Introduction

Accurate measurement and interpretation of the reflection coefficient from the ocean bottom is important in a diverse range of applications spanning communications, signal processing, buried mine detection and inversion for sediment properties. The importance of obtaining an accurate reflection coefficient value is magnified in littoral environments where multiple-bounce interactions with the sediment layer are possible.

One complicating factor in interpreting sand/water reflection coefficients is the presence of depth-dependent density gradients in the sediment. Kimura and Tsurumi showed that, at high frequencies (~150 kHz) and low angles of incidence, a 12 dB difference was observed between the reflection coefficient generated from a model assuming uniform density and two models in which the density varied exponentially with depth [1]. Therefore, a method to measure these density gradients accurately could have a major impact on the interpretation of measured reflection coefficient data.

Several methods have been proposed to measure sediment density gradients. In the
interest of preserving sediment structure, it is preferable to take measurements in situ. The In-situ Measurement of Porosity (IMP) device developed at the University of Washington measures a 3D matrix of electrical conductivity as a function of depth [2]. These measurements can be mapped to density. Unfortunately, conductivity can also be affected by other sediment parameters such as tortuosity which can complicate data analysis. In addition, the device itself is too large for diver deployment and requires engineering support.

In this paper a novel means of obtaining sediment density gradient measurements in situ using a diver-deployed X-Ray Attenuation Measurement (XRAM) device is presented. The system is small, light and requires only ten minutes per site to measure density in the top six inches of the sediment. Therefore, a single diver can make a rapid assessment of the statistical variation of sediment density over an area of the ocean bottom.

2 Background

2.1 The X-Ray Attenuation Measurement (XRAM) device

A picture and diagram of the XRAM device are shown below in Figure 1.

![XRAM picture and diagram](image)

The entire device is approximately twenty inches high including a six-inch long sediment
A DIVER DEPLOYED X-RAY ATTENUATION MEASUREMENT (XRAM) DEVICE

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The small size and low weight of the XRAM make it easy for a single diver to maneuver. Its cylindrical body contains a PC-104 stack running LabView, the x-ray source, a preamplifier for the x-ray detector, and the system batteries which supply power for up to 4 hours before requiring a recharge. The source state, detector position and data acquisition are under computer control and, after acquisition, the data can be transferred via wireless link to a second computer for analysis.

A computer-controllable cold-cathode source was chosen so that it would be non-radiating when not in use. The source emits x-rays at energies ranging from approximately 5 keV to 30 keV with maximum emission at 10 keV. Physically, the source is about seven inches long and emits photons in a 120 degree cone which illuminates the entire sediment probe. The source was selected for its compact size, low heat dissipation and reasonable price. The size and heat dissipation issues are important for making a compact underwater device. The price makes it affordable. The x-ray detector was chosen so that it also had maximum efficiency at 10 keV. Physically, the detector has a 1 cm$^2$ cross-section and fits easily into the sediment probe.

2.2 Model Equations

A theoretical model of x-ray absorption in sediment was developed for comparison with data acquired with the XRAM. The most basic model of x-ray attenuation in an absorbing media makes the following assumptions [3,5]:

1. The beam of emitted x-rays is perfectly collimated.
2. The x-rays are monoenergetic of energy $E$ and initial intensity $I_0$.
3. The x-rays traverse an absorber of mass thickness $x$ before striking a detector of perfect efficiency at energy $E$.

If the above conditions are satisfied the intensity of the x-ray at any point in the absorber attenuates according to a simple exponential law given by

$$I = I_0 e^{-\mu \rho x},$$

where $\mu/\rho$ is the mass attenuation coefficient for the absorbing medium. However, the XRAM violates these conditions. Therefore, the model must be adjusted to account for spherical spreading, the broadband nature of the source and the different path lengths to each point on the detector. A $1/r^\alpha$ spherical spreading law is used to account for the non-collimated source. Integration is also performed across the detector face and through the energy spectrum. With these adjustments the model equation becomes

$$I = \frac{1}{r^2} \int_0^\infty \int_{\alpha_0}^{\alpha} I_0(E)D(E)e^{-\frac{\mu x(A)}{\rho}} d\alpha dE,$$

where $I_0(E)$ and $D(E)$ are the energy dependent source spectrum and detector efficiencies, $x(A)$...
is the mass thickness for each point on the detector face, and $A_d$ is the surface area of the detector. Given the density and depth-dependent porosity of an attenuating material, the mass thickness can be calculated for each detector position on the sediment probe. Values of the mass attenuation coefficient ($\mu/\rho$) for various materials were obtained from NIST [4]. For example, the mass attenuation coefficient for water is plotted in Figure 4 on a log-log scale.

3 Data Analysis

3.1 Liquids

To simplify analysis, data were first taken in three liquids and then compared to the model response. The chief simplification afforded by a liquid is that the medium can be assumed to be homogeneous and isotropic which simplifies the calculation of mass thickness. The three measured liquids were

- Water (H$_2$O): $\rho = 1$ g/cm$^3$
- Methanol (CH$_4$O): $\rho = 0.792$ g/cm$^3$
- Castor oil (C$_{21}$H$_{40}$O$_5$): $\rho = 0.956$ g/cm$^3$

Figure 2 shows the detector response plotted with respect to the path length through both water and methanol. A higher detector response corresponds to less attenuation so the higher response in the methanol can be explained by its lower density.

![Figure 2. Attenuation vs. Path Length to Detector for Water and Methanol](image-url)
If a medium with known density (such as water) is used to calibrate the system, the relative density of an unknown attenuating medium can be determined. Also, as illustrated in Figure 3, if the detector response is plotted with respect to the amount of attenuating mass between the source and detector then the system response for water and methanol are identical. In other words, the data for water and methanol indicate that x-ray attenuation is proportional to attenuating mass regardless of the attenuating medium. Using this plot, a unique mapping between attenuating mass and detector output can be made through which the density of the unknown medium can be found. Unfortunately, when attenuation was measured in Castor oil the data did not agree with these conclusions. As the dash-dot curve in Figure 3 shows, the Castor oil data suggest a different dependence on attenuating mass than implied by the water and methanol data.

In order to explain the discrepancies between the methanol/water and Castor oil data, the mechanisms responsible for x-ray attenuation were investigated further.

3.2 X-Ray Attenuation Mechanisms

At the energies generated by the XRAM, there are two relevant mechanisms of x-ray absorption; the photoelectric effect and Compton scattering. As can be seen in Figure 4, the mass attenuation data consists of two distinct linear regions which are indicative of the two mechanisms. The photoelectric effect dominates at lower energies. Here the x-ray ejects an inner shell electron which is replaced by an outer shell electron producing a photon of lower
energy. The energy of the x-ray must be greater than the binding energy of the inner shell electron. Compton scattering dominates at higher x-ray energies. In this mechanism, x-rays interact with an outer shell electron which is ejected from the atom. The incident x-ray is scattered in a different direction with a greater energy. Compton scattering is dependent only on the number of atoms in the transmission path. The photoelectric effect is also dependent on molecule size.

Therefore, if density is to be determined independent of material type, the x-ray energy should be in a region dominated by Compton scattering. Unfortunately, as Figure 4 shows, the XRAM source lies in the lower energy region which is dominated by the photoelectric effect. Due to the dependence on molecule size, comparison between attenuating media of grossly different molecular mass will be difficult. From the chemical formulas for the three tested media it is apparent that the molecular mass of Castor oil (C_{21}H_{40}O_{5}) is significantly greater than the mass of either water or methanol (H_{2}O, CH_{4}O). This may explain the discrepancy in the mass to attenuation mapping. However, the molecular weight of sand (SiO_{2}) is on the order of water and methanol. Therefore, reliable analysis could be performed on data taken across a sand/water interface.

![Figure 4. Photoelectric- and Compton-dominated Regions of the X-Ray Spectrum](image)

3.3 Sand / Water Interface Data

Data were taken across an interface between water and saturated SiO_{2} beads in order to simulate the conditions of a sand/water interface on the ocean floor. A plastic bucket was filled with water before SiO_{2} beads were slowly poured into the bucket until a 1.5 cm layer of water
remained at the top. In an effort to remove air from the saturated sand, the mixture was then rocked for thirty minutes before inserting the XRAM probe.

Figure 5 shows both the experimental and model responses for the sand/water interface experiment. To model the saturated sand, the best fit was found with a porosity of 0.4 and the location of the interface was modeled as being at 1.7 cm instead of 1.5 cm. This 2 mm shift is probably due to an uneven sand interface or measurement error when the bucket was filled with the SiO$_2$. Agreement between the model and experimental data is nearly perfect up to the interface. After the interface the experimental data is somewhat higher than the model response although it still tracks the general shape of the model. This slight discrepancy can be accounted for by trapped air in the mixture or depth dependent porosity. This effect will be investigated in subsequent publications.

4 Discussion

The X-Ray Attenuation Measurement (XRAM) device is a novel approach to measuring sediment density in situ via x-ray attenuation. X-Ray attenuation can be used to measure density gradients in the first few centimeters of oceanic sediment. These gradients can have a significant effect on reflection coefficients. Data taken in homogeneous liquids suggest that if the attenuation is dominated by the photoelectric effect (as is the case with a low energy x-ray source), the sediment mass attenuation coefficients must be similar to water in order to obtain accurate results. This requirement may be avoided by using a source of higher x-ray energy such that Compton scattering is the dominant attenuation mechanism.

In the sand/water interface experiment, good agreement was obtained between a model
and the experimental data up to the point of the interface and the data disparity after the interface is congruent with expected complicating experimental effects such as trapped air or density gradients. In the near future, further experimental studies will be completed in which the porosity of a suspended sediment is varied so that porosity inversion may be performed.

Acknowledgements

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References

MEASURING SEABED REFLECTIVITY FROM AMBIENT NOISE: RESULTS FROM TRIALS AT UK SITES

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Under the UK MoD REA research programme, work has taken place to demonstrate the concept of measuring the seabed reflection coefficient from ambient noise using a system comprising a vertical line array suspended below a freely drifting buoy. Data collection trials have been conducted at four sites around the UK coast with different seabed types. The measured reflection coefficients have been compared with reference geoacoustic data for the sites. Significant variation between sites is seen in the measured reflection coefficients and good agreement with the reference datasets is observed. Transmission loss has been measured at two of the sites, using a dedicated sound source, and has been compared with modelled transmission loss, using the measured reflection coefficients as inputs for transmission loss modelling. Good agreement between measured and modelled transmission loss is observed.

1 Introduction

SEA have been undertaking research for the UK MoD into geoacoustic inversion of ambient noise using a short vertical line array (VLA) suspended below a freely drifting surface buoy. The results of a trial in the North-West Approaches to the UK were published previously [1] and trials have now taken place in three further locations. The aim of the trials was to demonstrate that the seabed reflection coefficient can be successfully measured from ambient noise in different locations and under different environmental conditions.

The basis of the method of measuring the seabed reflection coefficient from ambient noise is discussed in [2] and [3]. The seabed reflection coefficient is measured from the vertical directionality of the ambient noise field, which is resolved using standard plane-wave beamforming techniques applied to noise sampled on a vertical line array.

The VLA Buoy used for the trials was developed by QinetiQ under contract to SEA and with requirements and design input from SEA. The surface buoy contains the electronics pod, which houses the embedded PC, hard disk, array interface unit and GPS unit, as well as the UHF aerial for GPS and non-acoustic data telemetry to the trials ship. Mission programming is achieved via Ethernet link between the electronics pod and a standard PC. The reinforced suspension cable for the array contains the power and data cores. An elastic rope (bungee) and set of damper discs act as a surface motion isolation mechanism. A weight attached to a short elastic rope hanging from the bottom of the array ensures that the array remains vertical in the water.

For each trial reference geoacoustic data was obtained in order to model the reflection coefficient for comparison to the measured reflection coefficient. As well as
recording ambient noise for reflection coefficient measurement, the signal from an omnidirectional sound source was measured as the source was towed away from the VLA Buoy. The purpose of this was to measure the transmission loss for subsequent comparison to modelled transmission loss using the measured seabed reflection coefficient for transmission loss modelling. Successful modelling gives additional confidence in the measured reflection coefficient and illustrates the operational use of the data, i.e. prediction of acoustic propagation.

Trials took place off the south and north-east coasts of England (south of Weymouth and east of the port of Blyth), and in a relatively sheltered area on the west coast of Scotland. The seabed type varied from low loss (muddy sandy gravel) to high loss (soft mud).

2 Blyth trial

This trial took place in August 2004. The deployment location was approximately 10 miles east of the port of Blyth. Reference geoacoustic data for the area was provided by the British Geological Survey. The area is characterised by a layer of silts and muddy sand overlying a layer of very soft mud with additional layers of muds, glacial clays and marls below. The thickness of the upper layer is uncertain but is estimated to be between 0 and 5m. Geoacoustic parameters (estimated from the geophysical properties) have been provided for the layers as well as estimated average thicknesses. The modelled reference reflection coefficient is shown in Figure 1. The modelled effect of the VLA beamformer has been included for direct comparison with measured data, hence the resolution degradation at low frequencies.

![Figure 1: Reference reflection loss (dB per bounce) for Blyth site](image)

The wind speed during the trial was approximately 10 knots. Very limited whitecapping was observed. Despite the low wind speed there was significant swell (~2m peak to peak). Limited ship monitoring was available from the ship’s radar: two ships were sighted during the deployment at ranges of three and seven miles. The water depth was 67m and the centre of the array was at a depth of 38m.

As with all trials datasets the period of wind noise least contaminated with shipping noise was identified and three minutes of data processed. Figure 2 shows the array
response, from which shipping noise is clearly visible at the lower frequencies. Above ~1kHz the noise field is dominated by wind however, and we expect to be able to derive the reflection coefficient. The reflection coefficient is shown in Figure 3. The white area to the left of the plot is where the reflection coefficient cannot be measured as sound does not reach the array from the sea surface at these angles due to the presence of a downwardly refracting sound speed profile. The lack of resolution at low frequencies is due to the inability of the beamformer to resolve the noise field at low frequencies (as modelled in Figure 1), though the reflection coefficient is well resolved down to ~1kHz.

Agreement with the reference reflection coefficient of Figure 1 is excellent. The critical angle in the measured coefficient is slightly lower towards the top end of the band than that of the reference coefficient, being closer to 25° than 30°, but considering that the reference geoaoustic parameters are estimated from the geophysical properties the agreement is very good.

Figure 2: Array response at Blyth site

Figure 3: Reflection loss (dB per bounce) at Blyth site
It was not possible to obtain a transmission loss dataset during the Blyth trial as during the deployment period the swell gradually increased and the VLA Buoy had to be recovered earlier than planned for safety reasons.

3 Weymouth trial

This trial took place in October 2004. The deployment location was approximately 15 miles south of Weymouth. Reference geoacoustic data for the location was provided by QinetiQ. The seabed comprises a thin layer of muddy sandy gravel overlying a bedrock of Kimmeridge Clay, and is expected to be uniform within ~2km of the deployment location. The upper layer is expected to be less than 0.5m thick. The modelled reference reflection coefficient (including the modelled effect of the beamformer) is shown in Figure 4 with the upper layer thickness set at 0.5m.

The wind speed during the trial was between 20 and 25 knots (usually closer to 25 knots) with swell of around 1.5m peak to peak. The array was deployed with the centre at 20m depth. No sound speed profile measurement was available during this trial and isovelocity conditions were assumed (a reasonable assumption with a rough sea in shallow water – the water depth was 50m). Several ships were observed during the deployment. For the period processed to provide the results shown below, there were two large vessels both at a range of ~6nm.

The array response is shown in Figure 5, which clearly shows a wind dominated noise field above ~1500Hz. The reflection coefficient is shown in Figure 6. The critical angle of ~40° is in very good agreement with the reference reflection coefficient of Figure 4. The measured reflection coefficient shows evidence of layer structure but the clear pattern of the reference reflection coefficient is not visible – as the reference data specified an upper layer thickness of anywhere between 0 and 0.5m this is not surprising.

The measured reflection coefficient is similar both in terms of critical angle and loss levels to that measured in the North-West Approaches [1] – this is perhaps to be expected since both locations are characterised by an upper layer with similar geophysical properties (‘gravelly muddy sand’ for the North-West Approaches site and ‘muddy sandy gravel’ for the Weymouth site).
A transmission loss dataset was collected at this site. This actually took place during a previous trial at the same site during which the wind speed was 10 knots. No sound speed profile measurement was available and isovelocity conditions were assumed.

An omnidirectional sound source generating a 3.15kHz sine wave was towed along a 5km track. The trials vessel moved at a constant low speed in order to obtain a constant source depth. A depth sensor was used to record the source depth, which was 5.7m. The output from the uppermost hydrophone of the array (depth 35m) was averaged over contiguous 10s windows, corresponding to range intervals of 20m (vessel speed 2ms\(^{-1}\)). Transmission loss was modelled every 20m in range using a ray model, with the measured seabed reflection coefficient of Figure 6 used in the modelling.

Measured and modelled transmission losses are shown in Figure 7. Agreement between the curves for the first 2.5km (i.e. up to fifty times the water depth) is very good. A spherical spreading curve is included for comparison, and the transmission loss is clearly considerably lower than spherical spreading (around 10dB lower at 2.5km), as would be expected in an environment with a highly reflective seabed.
The measured transmission loss trend changes dramatically after 2.5km, and beyond ~2.8km the transmission loss is close to spherical spreading levels. The reason for this is unknown, but if the sound source was providing constant power for the entire period as is thought to be the case, the change must be due to an environmental feature. One of the references used in providing the reference geoacoustic data for the trial location shows a geological boundary approximately 2km west of the initial Buoy deployment location (the trials vessel was moving west), at which the bedrock changes from Kimmeridge Clay to Corallian Beds. There is currently not enough information to determine whether this is the cause of the change in transmission loss trend, but it is interesting that the change occurs at approximately the range at which the boundary is thought to lie.

4 Scotland trial

This trial took place in November 2004. The site was a relatively sheltered area approximately halfway between the island of Raasay and the mainland. The water depth was ~158m at the Buoy deployment location, with variable water depth in the vicinity. A detailed geoacoustic model for the area was not available but the seabed is known to consist of very soft mud, which was confirmed by the British Geological Survey.

The wind speed during the trial was around 10 knots. A little whitecapping was visible and there was almost no swell. Four small fishing vessels were observed during the deployment period at ranges varying from 1.7nm to 3.1nm.

A sound speed profile was measured approximately 3km west of the deployment location which showed a roughly linear increase in sound speed between 1496.1ms\(^{-1}\) at the sea surface and 1498.1ms\(^{-1}\) at a depth of 147m, i.e. a weakly upwardly refracting profile. The centre of the VLA was at a depth of 36m.

The array response is shown in Figure 8. The noise field is clearly wind dominated although a little shipping noise is visible in the horizontal at all frequencies. The reflection coefficient of Figure 9 shows a low critical angle of ~15° with high loss above the critical angle. This fits in well with expectations for a soft mud seabed.
Transmission loss was measured at this site using the same methods as at the Weymouth site. Here the 10s averages correspond to range intervals of 15m as the vessel speed was 1.5ms\(^{-1}\). The source depth was 7.2m and the receiver depth (uppermost hydrophone of the array) was 34m. Transmission loss was modelled every 15m in range using the measured reflection coefficient of Figure 9. Due to the variable water depth, a range-dependent bathymetry profile was used in the modelling.

The measured and modelled transmission losses shown in Figure 10 are in excellent agreement. The transmission loss trend in this environment is clearly different to that at the Weymouth site, with transmission loss here much closer to spherical spreading as would be expected for a high loss seabed.
5 Conclusions

Seabed reflection coefficients have been successfully measured from ambient noise at three locations around the UK coast. The reflection coefficients were measured in a variety of environmental conditions with both wind and shipping noise present. Good agreement with reference reflection coefficients modelled from ground-truth geoacoustic data is seen. Transmission loss has been modelled using the measured reflection coefficients, and has shown good agreement with measured transmission loss.

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References

EFFECT OF ENVIRONMENTAL VARIABILITY ON THE AMBIENT NOISE NOTCH

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When plotted as a function of elevation angle, the ambient noise directivity as observed on a vertical array often exhibits a notch at broadside. Elementary modeling suggests that this notch should become more pronounced as the gradient of the sound speed profile is increased. A strong sound speed gradient, however, also suggests the possibility of strong environmental fluctuations due to internal waves. The acoustic mode coupling induced by internal waves has the potential to fill the ambient noise notch. In the present study, a model for the ambient noise notch is developed. The emphasis is on shallow water scenarios in the 1 to 5 kHz band. The model uses the Dozier-Tappert modal transport theory extended to include energy loss due to interaction with the seabed. Model results are shown to be in good agreement with measurements made during the 2001 East China Sea Experiment.

1 Introduction

During typical summertime conditions, an acoustic duct is often formed in shallow water. The duct is bounded from below by an acoustically fast seabed and from above by a mixed layer of warm water. Sound trapped in this duct propagates at relatively shallow angles and with relatively little loss of energy. Noise sources like the wind and shipping are typically located near the sea surface and so outside the duct. This un-ducted ambient noise travels at steep angles and tends to be absorbed by the seabed. Consequently, if one placed a vertical array near the seabed and listened to the ambient noise from distant shipping, the received energy would not be omnidirectional. When plotted as a function of elevation angle, the beamformed ambient noise will typically exhibit a notch at broadside to the array. Tang [1] showed the notch for ambient noise data collected between 500 and 5000 kHz in the 2001 East China Sea component of the ASIAEX experiment.

In the present paper, we develop a physics-based model for the beamformed ambient noise. The model includes the effects of environmental variability due to random background internal waves and estimates the mean output for a beamformer. The Dozier-Tappert modal transport theory is used to describe the statistics of the measured noise field. Calculations show how internal waves partially fill the ambient noise notch. Good agreement is obtained between noise notch predictions and data taken in the East China Sea.
2 Model

The propagating acoustic field in the ocean waveguide can be described by a normal mode expansion. If the ocean is range dependent through such environmental factors as internal waves, it may be necessary to include coupling between the modes as they propagate. Dozier and Tappert [2] developed a transport theory valid for deep water that included mode coupling for the statistical moments of the mode amplitudes. Evans recently used the formulation to model the ambient noise notch for deep-water, low-frequency scenarios [3]. The basic Dozier-Tappert formulation can be extended to consider bottom interaction, an important factor for shallow-water applications [4,5]. Thorsos et al. [6] found good agreement between bottom-interacting transport theory and numerical calculations based on the wide-angle parabolic equation for a 3 kHz shallow water problem. In the present case, we use bottom-interacting transport theory to develop a model for the average output of a vertical array doing beamforming in shallow water at a few kilohertz. Shallow water internal waves introduce range dependence into the problem and are shown to affect the average level of the ambient noise notch.

The time-harmonic pressure field at depth $z$ due to a point source at range $r$ can be expanded in its normal modes,

$$ p(r,z) = \sum_n (\xi_n r)^{-1/2} A_n(r) \Phi_n(z), \quad \text{(1)} $$

where each $\Phi_n$ is a normal mode with complex amplitude $A_n$ and associated horizontal wavenumber $\xi_n$. The factor $r^{-1/2}$ accounts for cylindrical spreading. Because the environment is assumed random due to internal waves, the mode amplitudes are random. Construct the $N$-element column matrix $\Gamma$ with elements $\Gamma_n = <A_n^2>$. Neglecting cross terms, bottom-interacting transport theory permits one to write the matrix differential equation

$$ \frac{d\Gamma}{dr} = -S\Gamma. \quad \text{(2)} $$

Elements in the transport matrix $S$ describe the coupling between pairs of acoustic modes. The solution to Eq. (2) can be written using the matrix exponential

$$ \Gamma(r) = \exp(-Sr)\Gamma(0). \quad \text{(3)} $$

Our interest is coupling between the acoustic modes induced by shallow water internal waves. The internal waves can be expanded in terms of their normal modes $W_j$, each of which satisfies

$$ \frac{\partial^2 W_j}{\partial \xi^2} + \frac{N^2(z) - \omega^2}{\omega^2 - \omega_i^2} K^2 W_j = 0. \quad \text{(4)} $$
An important point is that the buoyancy profile $N(z)$ used to calculate the internal wave modes in Eq. (4) is strongly related to the background sound speed profile used to calculate the acoustic modes in Eq. (1); the oceanographic and acoustic models must be tightly linked in a realistic calculation [7,8]. The remaining quantities in Eq. (4) are the inertial frequency $\omega_i$ (known from the latitude), the internal wave frequency $\omega$ and the horizontal wavenumber $K$.

Given the internal wave modes, elements in the transport matrix $S$ are calculated by evaluating coupling integrals of the form [2,4,5]

$$s_{jmn} = \int N^2(z)W_j(K_{mn})\Psi_m(z)\Psi_n(z)dz.$$  \hspace{1cm} (5)

Equation (5) makes use of the resonance approximation where the internal waves are evaluated at horizontal wavenumber $K_{mn} = \xi_m - \xi_n$.

For realistic environments, both the acoustic and internal wave modes must be calculated numerically, as must the integral in Eq. (5). Notice that the internal wave modes must be recalculated for each pair of acoustic modes that are coupled; if there are $M$ retained acoustic modes, then the internal wave modes must be calculated $M(M-1)/2$ times. Consequently, if there are $J$ retained internal wave modes then there are $JM(M-1)/2$ integrals to evaluate. While the number of integrals may be large, the calculations are straightforward and can be performed using standard closed quadrature routines. It should be noted that the integrations are independent of both the internal wave energy and the bottom loss. The effect of these important parameters on the mean output of the beamformer can therefore be studied without having to recalculate the coupling integrals.

Equation (3) gives the mean intensity for the acoustic modes due to a single source after propagating through a random internal wave field. For the ambient noise problem of current interest, there will be many noise sources. The ranges and depths of these discrete noise sources can be modeled as independent random variables. Since the pressure spreads cylindrically [Eq. (1)], an extra factor of $r^{-1}$ should be included in the expression for the intensity moment, Eq. (3). Then averaging over the source’s range and depth yields

$$\left\langle r^{-1}\Gamma(r)\right\rangle_{r,z} = \left\langle e^{-S r}r^{-1}\right\rangle_{r,z} \left\langle \Gamma(0)\right\rangle_{z}.$$  \hspace{1cm} (6)

Given the probability density functions for the source range and depth, the ensemble averages in Eq. (6) can be evaluated either analytically or numerically.

In practice, the ambient noise might be measured over a vertical array and then Fourier transformed. A beamformer applies a steering vector to each frequency bin of interest and the magnitude-squared of the output is plotted as a function of beamformer look direction. Equation (6) can consequently be used in estimating the average output of the beamformer.

3 Model/Data Comparision

Ambient noise data were collected in the East China Sea during May and June 2001 as part of the ASIAEX experiment [1]. Nearby fishing boats, distant shipping and the wind
all contributed to the noise field. The data were collected on a 31-element vertical array with 21.43 cm spacing. The bottom array element was 7.5 m above the seabed in water 105 m deep. The array was located below the thermocline with the sound speed essentially constant over the depths spanned by the array. Data were sampled at 12 kHz with emphasis on the noise field between 500 Hz and 5 kHz.

Figure 1. Sample beamformer output from East China Sea Experiment. Result calculated over a single 0.5 s window.

Figure 1 is an example showing the output from a simple Bartlett beamformer. The data have been bandpass filtered and Fourier transformed over a 0.5 second window. The red-green-blue color scale has a 30 dB dynamic range. The vertical streaks in the figure can be removed by averaging in frequency over different bins or by averaging in time over different windows. Even without averaging, the noise notch at zero degrees is clearly visible. The noise peaks are concentrated around plus and minus ten degrees look direction. A vertical slice through Fig. 1 gives the beamformed noise at a particular frequency. The depth of the notch relative to the peaks varies with frequency but is typically less than ten decibels.

To model the experiment using the procedure outlined in the previous section, some basic information about the environment must be either known or estimated. Figure 2(a) shows the measured sound speed profile. The surface mixed layer extends down to about 30 m depth. Together with information about the seabed, the profile can be used to calculate the acoustic modes. At 3 kHz, 150 modes are retained. These are more modes than actually propagate in the water column, but the higher order modes act as a mechanism through which energy can be lost due to mode coupling [6]. The measured bottom loss was 0.75 dB/m/kHz. Figure 2(b) shows the buoyancy profile estimated from the sound speed profile using the method outlined by Reynolds and Levine [8]. For horizontal wavenumbers based on the resonance approximation, Eq. (4) is solved numerically yielding the internal wave modes. Reasonable values for other internal wave parameters can also be estimated. Because the internal wave field is dominated by low order modes in shallow water, the characteristic mode number \( j_\ast \) is set to zero. Based on other experiments [7,8], a reasonable value for the internal wave strength is \( bE_{GW} = 0.1 \text{ m} \). Twenty internal wave modes are retained.
Figure 2. (a) Measured sound speed profile. (b) Estimated buoyancy profile.

Figure 3 compares the measured and modeled beamformer performance at 3 kHz. Each curve is normalized to have 0 dB peak response. The measurement shows a 7 dB notch and represents an average over a 20 Hz band centered at 3 kHz. Two model predictions are shown. The dashed line represents a calculation where internal waves are ignored; the environment is treated as being range independent and described by the background sound speed profile in Fig. 2(a). The range-independent calculation accurately predicts the location of the peaks in the beamformer response, but predicts a 13 dB notch that is much deeper than observed in the data. The dotted line represents a calculation where internal waves have been included. This calculation is within 2 dB of the measured level in the notch.

Figure 3. Beamformer performance. Measured data compared to model predictions.
4 Summary and Discussion

Warm water near the sea surface often creates a sound speed duct that traps sound between the surface mixed layer and the sediment. Noise sources like distant shipping are located outside of this duct. Environmental variability, however, can act to couple the sound produced by noise sources into the duct. A consequence is that an expected notch in the ambient noise beam pattern can be partially filled. In the present paper, a model has been developed for the beamformed ambient noise field. It is shown how internal waves of realistic strength could produce the partial filling of the ambient noise notch observed in experimental data.

Acknowledgements

The authors thank Dr. Dozier for providing a copy of Reference [4]. The ASIAEX experiment was supported by the Office of Naval Research.

References

THE EFFECT OF CENTIMETRE SCALE IMPEDANCE LAYERING ON THE NORMAL-INCIDENCE SEABED REFLECTION COEFFICIENT

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The frequency dependence of the normal incidence amplitude reflection coefficient $R$ of the seabed is considered for a range of frequencies ranging from 2 kHz to 1 MHz, and for sediment types between medium silt (grain diameter 25 µm) and coarse sand (700 µm). Published in-situ measurements of $R$ at low frequency (up to about 10 kHz) and laboratory measurements of $R$ at high frequency (150-1000 kHz) are both consistent with theoretical predictions using the Rayleigh reflection coefficient. However, in-situ measurements of $R$ at intermediate frequency (8-150 kHz) are lower than the Rayleigh-derived values by up to a factor of three or so. In-situ measurements of sediment density (or porosity) show that a thin transition layer exists between water and sediment, within which the impedance varies on a depth scale of order 10 mm. The expected frequency dependence due to such layering is greatest when the acoustic wavelength is of the same order as the transition layer thickness. Thus, high sensitivity to frequency of in-situ $R$ can be expected for frequencies of a few tens of kilohertz. The extent to which this mechanism can explain the acoustic measurements is explored. It is found that $R$ does indeed vary with frequency and grain size in the expected frequency range, and that this variation is consistent with the theoretical expectation based on available measurements of layer thickness as a function of grain size.

1 Introduction

It is known that there exists a correlation between the seabed reflection coefficient $R$ at normal incidence and the mean grain size of the sediment ($M_z$). [1, 2, 3, 4] This relationship is exploited by recent articles [5, 6] to produce maps of grain size, from measurements of $R$. A common idealisation is to characterise the seabed using only its sound speed and density, with $R$ equal to the Rayleigh reflection coefficient, independent of frequency. The well-established link between grain size and impedance [7] would thus explain the observed correlation.

In practice the seabed is never perfectly uniform, but layered, and this layering introduces a dependence on frequency if the product of wave number and transition layer thickness is of order unity, or greater [8]. By ‘transition layer’ is meant the region in which the density increases rapidly but continuously from a value of 1.0 g cm$^{-3}$ in water to between 1.4 and 2.0 g cm$^{-3}$ in the sediment, depending on the type of sediment. [7] The thickness of this layer is typically of order 10 mm, and the effect of seabed layering

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on this scale is the subject of this article. In particular, the extent to which this layering might be responsible for the $R-M_z$ correlation is explored.

The paper is structured as follows: Sections 2 and 3 describe, respectively, previously published measurements of the normal-incidence reflection coefficient in the frequency range 1-1000 kHz and of the *in-situ* transition layer thickness on a scale of 1-100 mm. The measurements are reconciled with theoretical effects of the layering in section 4, followed by some conclusions in section 5.

2 Measurements of reflection coefficient

Measurements from published literature, of the seabed reflection coefficient at normal incidence, are plotted in Figure 1 as a function of frequency between 1 kHz and 1 MHz. Apart from the measurements of Breslau at 12 kHz, none of the measured reflection coefficients outside the frequency window between 20 kHz and 200 kHz are lower than 0.2 in magnitude. Also shown (horizontal lines) are theoretical values of the Rayleigh coefficient, calculated using the correlations from Ref. [7], for integer values of $M_z$ (in phi units [9]) between 1φ (top line) and 7φ (bottom line). The same dark to light colour coding is used for both measurement and theory.

Figure 1. Amplitude reflection coefficient vs frequency, colour-coded by grain size: measurements (dots) and Rayleigh reflection coefficient (horizontal lines). The sequence of dots connected by straight lines indicates the measurements from Ref. [10].
Notice that the Rayleigh reflection coefficient tends to overestimate the measured values. This discrepancy was noted by Chotiros et al [10] and attributed by them to a poro-elastic mechanism, explained using Biot theory. An alternative explanation is pursued here connected with the layering in the uppermost few centimetres.

For measurements at a fixed frequency, it can be seen that the reflection coefficient tends to increase with increasing grain diameter (decreasing $M_z$ in phi units). This trend is most apparent from the 12 kHz data from Ref. [1]. Source references for all data points are shown in Table I.

Table I. Source references for reflection coefficient measurements in order of increasing frequency.

<table>
<thead>
<tr>
<th>frequency $f$ (kHz)</th>
<th>grain size $M_z$ ($\phi$)</th>
<th>$R$</th>
<th>location</th>
<th>reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>1.2 to 2.7</td>
<td>0.27 to 0.39</td>
<td>New Jersey Shelf</td>
<td>Goff et al [3]</td>
</tr>
<tr>
<td>2.0</td>
<td>1.3</td>
<td>0.35</td>
<td>Florida Panhandle</td>
<td>Schock [11]</td>
</tr>
<tr>
<td>8.5 to 17.5</td>
<td>2.25</td>
<td>0.21 to 0.36</td>
<td>Biodola Gulf</td>
<td>Chotiros et al [10]</td>
</tr>
<tr>
<td>12</td>
<td>0.9 to 7.8</td>
<td>0.13 to 0.39</td>
<td>various</td>
<td>Breslau [1]</td>
</tr>
<tr>
<td>20</td>
<td>5.3</td>
<td>0.071</td>
<td>Arafura Sea</td>
<td>Mourad &amp; Jackson [12]</td>
</tr>
<tr>
<td>25 to 30</td>
<td>3.0</td>
<td>0.18</td>
<td>Quinault Range</td>
<td>Mourad &amp; Jackson [12]</td>
</tr>
<tr>
<td>30</td>
<td>4.8</td>
<td>0.089</td>
<td>Puget Sound</td>
<td>Mourad &amp; Jackson [12]</td>
</tr>
<tr>
<td>150</td>
<td>2.2</td>
<td>0.20</td>
<td>laboratory</td>
<td>Kimura &amp; Tsurumi [13] (Fig. 6)</td>
</tr>
<tr>
<td>150</td>
<td>3.5</td>
<td>0.07</td>
<td>Shimizu Harbour</td>
<td>Kimura &amp; Tsurumi [13] (Fig. 7)</td>
</tr>
<tr>
<td>411</td>
<td>4.3</td>
<td>0.38</td>
<td>laboratory</td>
<td>Wang et al [14]</td>
</tr>
<tr>
<td>500</td>
<td>2.0</td>
<td>0.31</td>
<td>laboratory</td>
<td>Drevet et al [15]</td>
</tr>
<tr>
<td>500 &amp; 1000</td>
<td>-1.9 to -0.1</td>
<td>0.28</td>
<td>laboratory</td>
<td>Nolle et al [16]</td>
</tr>
</tbody>
</table>

3 Measurements of transition layer thickness

Given that, in reality, the impedance does not change discontinuously, could some of the frequency dependence be explained by layering in the top few centimetres? To answer this question some in-situ measurements of layer thickness are examined to see if they can be related to grain size. To avoid dealing with the complete impedance profile, the layer is parametrised in terms of a single parameter, $z_{0.9}$, defined as the depth at which the change in impedance (sediment impedance minus water impedance) reaches 90% of its asymptotic value in the sediment. [4] In practice it is usually the density (or porosity) that is measured, rather than the impedance.
Measurements of \( z_{90} \) are plotted in Figure 2 vs grain size. There is a weak trend shown by the solid line (a least squares fit), the equation of which is

\[
\log_{10}[z_{90} \text{ (mm)}] = 0.09M_z + 0.8 . 
\]  

(1)

Although the spread around this trend is large - roughly a factor of 3 in thickness - from the graph it appears that \( z_{90} \) and \( M_z \) are positively correlated, but it is clear that the correlation is a weak one. The numerical value of the correlation coefficient is 0.4, giving an indication of the confidence in the trend. The probability of this value (or higher) arising by chance is 26%. The median value of \( z_{90} \) is close to 10 mm.

Figure 2. *In-situ* measurements of layer thickness vs grain size in phi units (Cl: clay; EB: Eckenförde Bay; FP: Florida Panhandle; MK: Marquesa Keys; PC: Panama City; PM: Punta della Mariella; PV: Portovenere; Sa: sand; Te: Tellaro; VA: Venere Azzurra). See Ref. [4] for source references.

4 Effect of layer thickness on the reflection coefficient

If the layering is important, \( R \) can be expected to be related to the parameter \( f z_{90} \), where \( f \) is the acoustic frequency. [8] To test this expectation, Figure 3 shows a graph of \( R \) vs \( f z_{90} \), using Eq. (1) to estimate \( z_{90} \) for *in-situ* measurements of \( R \). The correlation equation is not appropriate for laboratory measurements because these tend to be made with carefully prepared compacted sediment samples. For these a small, but otherwise arbitrary, value is chosen for \( z_{90} \), equal to 0.5 mm. Up to an \( f z_{90} \) value of about 500 m/s, the graph shows a clear trend of decreasing reflection coefficient with increasing \( f z_{90} \).
consistent with the theoretical prediction calculated using the method of Ref. [17] (solid lines). See Ref. [4] for details of the implementation.

Of particular interest is the frequency dependence apparent in the Chotiros data at frequencies around 10 kHz (see Figure 1), or \( f_{90} \) around 100 m/s using the value of \( z_{90} \) determined from the correlation equation (10 mm). This compares with a strong frequency dependence expected from theoretical considerations at the higher value of \( f_{90} \approx 200 \) m/s (from the same graph). The discrepancy can be explained by assuming that the correlation underestimates the true \( z_{90} \) value by a factor of 2, well within the scatter of Figure 2. Thus, the trend in Chotiros’s data (a decreasing reflection coefficient from 0.35 at 8.5 kHz to 0.21 at 17.5 kHz) can be explained in terms of a layered fluid medium, with a layer thickness of \( z_{90} \approx 20 \) mm, without the need to invoke Biot theory.

![Figure 3. Reflection coefficient vs frequency layer-thickness product (\( f_{90} \)), colour-coded by grain size: measurements (dots) and theoretical predictions (curves).](image)

It is unfortunate that few calibrated measurements of \( R \) are available for \( f_{90} \) larger than about 500 m/s, making it difficult to test the predictions beyond this point. However, the supply of data at high frequency using uncalibrated echo sounders is more plentiful. Figure 4 shows the reflection coefficient from three such data sets, [6] plotted vs \( f_{90} \) values (estimated using Eq. (1) again) up to about 3000 m/s. A logarithmic y axis is used in order to compare relative levels more easily. The solid lines show the same theoretical predictions as in Figure 3. The three uncalibrated data sets are: 150 kHz data from a site in the North Sea, displaced upwards relative to the theoretical curves for
clarity; 66 kHz data from the same North Sea site, aligned roughly with theory; and 38 kHz data from a location close to the Norwegian port of Stavanger, displaced downwards.

For each of the three data sets there is a single unknown factor that converts the uncalibrated measurement to the true reflection coefficient. This means that meaningful comparisons of relative values can be made within each data set, but not between them. Taking the 150 kHz data as an example there is a clear negative correlation between $R$ and $fz_90$ whose slope follows that of the theoretical prediction. A similar behaviour is seen at 38 kHz and 66 kHz. Because of the uncertainty associated with the $z_{90}-M_z$ correlation, the agreement in slope between theory and measurement is probably fortuitous. Nevertheless, the overall impression from examining Figure 4 is that, for the frequency range covered by these data, the changes in the reflection coefficient with grain size, at a fixed frequency, can be largely explained by the variations in layer thickness expected from Eq. (1), even without considering the effect of the associated changes in impedance contrast. A likely explanation for this observation is that, at high frequency, the reflection coefficient becomes sensitive to the impedance gradient in the transition layer, a quantity that is closely related to the layer thickness.
Conclusions

- The known correlation between normal-incidence reflection coefficient and sediment grain size can be explained at low frequency by the known link between impedance and grain size. However, at high frequency (above 20 kHz) the impedance contrast on its own is not sufficient.

- There appears to exist a (weak) correlation between sediment grain size and the thickness of the interface between water and sediment. For sand sediments the measured layer thickness values tend to be around 10 mm or less, whereas for silt and clay most of the layer thickness values are greater than 10 mm. The observed dependence of the high-frequency reflection coefficient on frequency and grain size is found to be consistent with this correlation. However, the weakness of the grain size-layer thickness correlation reduces the significance of this conclusion. In order to investigate further the significance of the correlation it is necessary to obtain additional high quality measurements of density vs depth. After completing the work presented here, the author became aware of one additional fine-scale density profile measurement from the ASIAEX experiment. The measurement gives a layer thickness of about 2 cm [18] for a grain size of 3.5 $\phi$ [19]. This point lies close to the regression line and is therefore not expected to change any of the conclusions.

- A firm conclusion is that at high frequency the normal-incidence reflection coefficient is sensitive to the impedance gradient, and hence to the transition layer thickness. This sensitivity should be taken into account for interpretation of echo sounder measurements.

Acknowledgements

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References


Section 8

Bubbles
BUBBLE ACOUSTICS IN SHALLOW WATER: POSSIBLE APPLICATIONS IN NATURE

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Gas bubbles are the most potent naturally-occurring entities that influence the acoustic environment in liquids. Upon entrainment under breaking waves, waterfalls, or rainfall over water, each bubble undergoes small amplitude decaying pulsations with a natural frequency that varies approximately inversely with the bubble radius, giving rise to the 'plink' of a dripping tap or the roar of a cataract. When they occur in their millions per cubic metre in the top few metres of the ocean, bubbles can dominate the underwater sound field. Similarly, when driven by an incident sound field, bubbles exhibit a strong pulsation resonance. This paper discusses three examples of how bubble acoustics may find applications in Nature. The first of these is the determination of bubble size distributions through inversion of the sound fields that bubbles generate on entrainment. This can be used not only in testing models of bubble cloud evolution under breaking waves, but also in extraterrestrial environmental assessment. The second application lies in the possible enhancement by humpback whales of the efficiency of the bubble nets they use in fishing. The third speculates on the apparent conundrum, that unless dolphins employ better signal processing than humans currently do, then when they use bubble nets to hunt they are, in this visually confusing environment, nullifying their own most spectacular sensory apparatus. It demonstrates how exploitation of nonlinearities provides routes massively to enhance the contrast between targets and bubble clouds which would otherwise hide them from sonar. Whether dolphins use such techniques is unknown, but the potential to improve human sonar in bubbly waters is clear.

1 Extraterrestrial exploration of bubble acoustics in Nature

After a 7-year journey on NASA's Cassini spacecraft, the European Space Agency’s Huygens probe landed on Saturn’s largest moon, Titan, on January 14. It takes a moment to understand the step-change in knowledge that took place on that day. The surface of the planet is obscured with smog, and while we could envisage the possibility of seas, waves and waterfalls, and the equivalent of Earth’s water cycle based on liquid methane and ethane, when the investigation of this paper began, we had no sure knowledge that these existed [1-3]. Huygens was ingeniously designed to cope with a range of terrains, from liquid to solid, and this investigation addressed two possibilities: if the descent had ended with a splashdown in liquid; or (perhaps less likely) if the landing site had been close to a methane-fall. The characteristics of acoustic sensors tally well the constraints of space travel: acoustic instrumentation is low-cost, rugged and durable, has low power consumption, and generates signals of low bandwidth compared to the imaging systems.

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more usually exploited off-world. Indeed, whilst eventually Huygens managed to transmit for several hours on the surface, many expected only 3 minutes of battery life would remain after landing. Huygens was designed with an acoustic capability [4].

![Figure 1](image)

(a) Mosaic of three frames from Huygens indicates convergent flow from a high ridge area to a major river channel. (b) Impression by artist (David Seal) of Titan's surface as Huygens parachutes down. A “methane-fall” flows from the cliff at left, and methane clouds are visible. Smooth ice features rise out of the methane/ethane lake. (Credits: ESA/NASA/JPL/University of Arizona). (c) Power spectral densities for bubble entrainment noise, expressed in dB, simulated for Earth and Titan (based on Southampton University stream) (after [7]). Waterfall and splashdown sounds can be accessed via www.isvr.soton.ac.uk/fdag/uaua.htm.

Whilst it is recognised that acoustic technology could never replace imaging, the possibility was explored as to what could be gained were only the acoustic systems to be operational after landing: “If there is a splash and not a crunch when the probe lands, that would make Titan the first known body other than Earth to have an ocean open to an atmosphere. This would mean there could be babbling brooks and streams; and a beach at minus 180 degrees C” [5]. In the first stage [2], an appropriate model for the emission of bubbles was chosen and used to invert the sound of a terrestrial waterfall (the Salmon Leap, at Sadler’s Mill, Romsey, Hampshire, UK). The Salmon Leap bubble population was then used to estimate the sound that a methane-fall would make, if there were one on Titan which had the same entrainment statistics (not an unreasonable suggestion given the fluid parameters [2]). The reconstructed power spectrum for the terrestrial waterfall agreed with the measured Salmon Leap data, allowing some credibility to be given to the predicted spectrum for Titan. Recordings of these sounds, and similar predictions of possible splashdown sounds, can be accessed via the web page (Fig. 1). Nevertheless, the inversion was conducted without reference to the higher order moments [6], and the associated discrepancies were evident in listening-test comparisons of the measured and reconstructed Salmon Leap data. In addition, whilst the general shape of the predicted spectrum for Titan agreed with back-of-the-envelope calculations [2] and appeared to be physically sensible, the absolute spectral levels seemed to be too high. Therefore a second study completed the same prediction, but using a more stringent inversion routine and on a different waterfall [7]. This clarified the issue of the anomalous excitation amplitude.
2 Possible acoustic exploitation of bubble nets by cetaceans

Marine mammal calls often propagate through bubbly water, be they generated under breaking waves or wakes, though biological decomposition, or even by the mammals themselves. Two circumstances are of particular interest: the possible use of acoustic signals to trap prey in bubble nets; and the ability of dolphin sonar to operate in bubbly water (such as the surf zone) that would confound the best man-made sonar, despite the fact that the dolphins possess ‘hardware’ which is comparatively mediocre [8].

![Figure 2](image)

Figure 2  (a) Aerial view of a humpback bubble net (photo graph by A. Brayton, reproduced from [9]). (b) Schematic of a whale insonifying a bubble-net (plan view; sound speed is least at the mid-line of the net wall). (c) Four whales insonify bubble net (inner circle inner boundary of the net wall (outer one is obscured by rays) – image by T.G. Leighton and S.D. Richards). See Leighton et al. [2] for details.

2.1 The bubble nets of humpback whales

For many years there has been speculation as to the mechanism by which humpback whales (*Megaptera novaeangliae*) exploit bubble nets to catch fish [10]. It has been known for decades that single whales, or groups, dive deep and then release bubbles to form the walls of a cylinder, the interior of which is relatively bubble-free (Fig. 2(a)). The prey are trapped within this cylinder, for reasons previously unknown, before the whales lunge feed on them from below. It is usually assumed that prey are contained by the bubbles alone. However it is certainly known that when humpback whales form such nets, a proportion (as yet unquantified) of them emit very loud, ‘trumpeting feeding calls’, the available recordings containing energy up to at least 4 kHz. Leighton et al. [10] proposed that these whales may be using such calls to enhance the ability of their bubble nets to trap the fish, in the following manner. A suitable void fraction profile would cause the wall to act as a waveguide. Assume the scales permit the use of ray representation. Fig. 2(b) shows how, with a hypothetical tangential insonification, the mammals could generate a ‘wall of sound’ around the net, and a quiet region within it (Fig. 2(c)). The natural schooling response of fish to startling by the intense sound as they approach the walls would, in the bubble net, be transformed from a survival response into one that aids the predator in feeding [3]. The frequencies in the feeding call are indeed in the correct range to excite resonances in fish swim bladders and, given
their sensitivities, presumably such excitation could discomfort the fish sufficiently for it to return to the interior of the net.

Fig. 2(c) plots the raypaths from four whales whose beampatterns are represented by a $10^5$ fan of 281 rays, for a bubble net in which the void fraction increases linearly from zero at the inner and outer walls, to 0.01% at the mid-line of the wall. The proposed ‘wall of sound’ and quiet interior are clearly visible. Even if the whales do not create sufficiently directional beams and insonify tangentially, the bubble net might still function through its acoustical effects. The ‘wall of sound’ effect in Fig. 2(c) is generated from those rays which impact the wall at low grazing angles. Those rays which never impact the wall do not contribute to the ‘wall of sound’. If rays of higher grazing angle impact the net, they may cross into the net interior, though their amplitudes would be reduced by the bubble scattering, and attenuation alone would generate a quieter region in the centre of the net.

The actual acoustics of the cloud will of course be complicated by 3D effects and the possibility of collective oscillations; and even, speculatively, bubble-enhanced parametric sonar effects [10] which might be utilized by whales, for example to reduce beamwidth or generate harmonics, sum- and difference-frequencies etc. These effects are discussed elsewhere [10].

2.2 Dolphin use of bubble nets

Dolphins, especially Odontoceti, have been observed to be adept at hunting in bubbly water, possibly using acoustics. This is in despite of the fact that Odontoceti possess relatively mediocre acoustic transduction hardware [8]. In contrast, modern precision naval active sonar systems are confounded by the overwhelming reverberation signals recorded in bubbly water. Leighton [3] argued that Odontoceti might overcome their hardware disadvantage by means of novel signal processing. Leighton et al. [11] propose the use of various forms of “Twin Inverted Pulse Sonar” (TWIPS), which exploits nonlinear bubble oscillations to reveal linearly scattering objects present in the acoustic field. This paper presents the results of a simulation wherein TWIPS is applied, in the presence of a cloud containing 35 million oceanic bubbles, successfully to reveal the presence of a linearly scattering object approximately equivalent to one small fish.

3 Modelling sonar enhancement in bubbly water using TWIPS

To verify the potential for TWIPS to reveal a linearly scattering object within a bubble cloud, a simulation was developed, incorporating three primary inputs: a bubble cloud, a target, and an input signal. Details are given in [11]. When present, the target is located at the centre of the cloud and assumed to scatter linearly. This paper uses target strengths of -20 and -25 dB (the latter would be equivalent to an Atlantic cod (Gadus morhua) [12] of length 330 mm broadside on to a 100 kHz acoustic beam). The bubble cloud is assumed to be a sphere of radius 1 m, containing around 35 million bubbles following the population size distribution as measured by Meers et al. [13], such that the void fractions (the ratio of the volume of gas within a cloud to the total volume occupied by the cloud) on the order of $10^{-7}$ (i.e. $10^{-5}$ %). The cloud is dynamic, evolving as a consequence of turbulence, buoyancy etc. [3], although the number of bubbles is constant. The insonifying wavetrain is shown in Fig. 3. It consists of two pulses, identical
except that the second (the ‘negative’ pulse) has opposite polarity to the first (the ‘positive’ pulse). The amplitudes and frequencies can be found in [11]. By splitting the backscattered time series in half and then subtracting the two half-time-series one from another, scatter from the target can be enhanced with respect to scatter from the bubbles.

Figure 3  The incident wave

Figure 4  Diagram of simulation geometry for transducer, target
and spherical bubble cloud.

Figure 5  Simulated monostatic
backscatter from the seawater containing
a 1 m radius spherical bubble cloud
containing, at its centre and 10 m from
the transducer, a target (target strength
TS = -25 dB). The signals each show a
typical return (‘positive’ pulse only). The
signal from the target is buried in
bubble noise: the time window in which
its echo is received is labelled. See [11]
for details.

Figure 6  TWIPS2a has been applied to two cases: the
bubble cloud on its own (solid line); the bubble cloud
with a target of strength TS = -25 at its centre (dashed line)
(the data from Fig. 5). The target, which was not
discernable in Fig. 5, now gives a signal more than an
order of magnitude greater than the scatter from the

The scattered pressure for monostatic operation was calculated from a region of seawater containing spherical cloud of bubbles of radius 1 m, centred on the target (which was at range 10 m from the transducer) (Fig. 4), in order to determine which sonar system could detect whether a target was present in the cloud. The data presented here are for a single return only, with no averaging. A typical echo is shown in Fig. 5: although the time window where the contribution from the target is labelled, it is not possible to see that target. An example time series from one form of TWIPS (TWIPS2a [11]) is shown in Fig. 6: the scatter from the single target fish is more than an order of magnitude greater than from the entire cloud of 35 million bubbles.
Figure 7 Fifty pulse pairs (shown in Fig. 3) were projected at the cloud, spaced at intervals of 10 ms, and the echoes processed using (a) conventional sonar deconvolution techniques, (b) TWIPS1 and (c) TWIPS2b. The left plot in each panel shows the case when there is no target present, and the right plot shows the case when a target is inserted at the cloud centre (TS = -20 dB). The cloud, of 1 m radius, contains 35 million bubbles, and evolves appropriately between each ping, as described earlier. (a) A single average was formed from the two pulses that make up each pulse pair, such that 50 averages are available for plotting. Each average was plotted as a time history on a one-dimensional line, with a greyscale such that the amplitude of the signal at the corresponding moment in the time history was displayed. These processed echo time histories were then stacked, one above each other, to form an image. (b) TWIPS1 processing of the 50 pulse pairs (no averaging) are displayed similarly, by stacking the consecutive grey-scale time series one above the other. They were projected at the cloud, spaced at intervals of 10 ms. The TWIPS1 processed echoes were plotted, each as a time history on a one-dimensional line, as in (a). (c) TWIPS2b processing is used (no averaging) and the image displayed as in (b).

In current sonar signal processing, averaging and correlation are used to amplify signals which are consistently found in the same temporal location. Experience has shown that this technique does not yield useful results in the complex, dynamic acoustic environment encountered in a bubble cloud. For the same set of incident pulses, conventional sonar processing was compared with two forms of TWIPS: TWIPS1 and TWIPS2b. TWIPS covers a range of processing techniques, with different capabilities. All are designed to enhance contrast of targets in bubble clouds, both by increasing the
scatter from the target and, very importantly, at the same time suppressing the signals from the bubbles. TWIPS1 is designed always to enhance target contrast, producing a reliable enhancement with every ping. TWIPS2b gives much greater contrast enhancements, but not with every ping: the particular form demonstrated here ‘glints’ on about 10% of pings. However the contrast enhancement is much greater than occurs with TWIPS1. It is particularly useful for sources that have the luxury of insonifying a region with multiple pings.

The implications for sonar imaging can be illustrated by plotting such time histories on a one-dimensional line, with a greyscale such that the amplitude of the signal at the corresponding moment in the time history is displayed: white corresponds to high detected amplitudes, and black corresponds to low detected amplitudes. For conventional sonar (Fig. 7(a)), TWIPS1 (Fig. 7(b)) and TWIPS2b (Fig. 7(c)), 50 pulse pairs were projected at the cloud, spaced at intervals of 10 ms. The processed echoes were then stacked, one above each other, to form an image. As a stationary feature in the display, detection of the target in every ping would correspond to the observation of a vertical white line which is visible when the target is present, but absent from the corresponding sonar plot when the target is absent. The left hand plots in the individual panels of Fig. 7 correspond to the cloud when there is no target present, and the right hand plots of each panel in Fig. 7 correspond to the bubble cloud when the target (TS = -20 dB) is present. In comparing the results, resist the temptation to compare against each other the ‘target present’ plots in (a)-(c). Rather, mimic the consideration of a sonar operator: Recalling that the same echo can be processed by conventional and TWIPS techniques simultaneously, consider the difference between the left and right plots in each panel, and ask whether a sonar operator or dolphin could tell, from the left panel, that a target was absent; and from the right, whether there is a possible target to investigate.

Standard sonar processing fails to detect the target: There is insufficient difference between the two plots in Fig. 7(a) because scatter from the bubbles masks the presence of the target. TWIPS1 detects the target on almost every occasion, such that there is a vertical line on the right of Fig. 7(b) compared to the plot on the left (where, importantly, it has suppressed the bubble signal). As stated earlier, TWIPS2 is designed to work spectacularly for about 10% of pings. This feature is shown in Fig. 7(c), in that for some pings it fails to detect the target is present at all. However when it does detect one, the amplitude is very high (see plot on the right); when the target is not present (left hand plot), it rarely delivers a high amplitude return, very effectively suppressing the returned signal. The plots all have a linear greyscale and no thresholding has been applied.

4 Discussion and Conclusions

The results suggest that the physics will allow nonlinear acoustics to be exploited to enhance the detection of linearly-scattering targets within bubble clouds. Whether or not dolphins have developed this faculty, is unknown. It is intriguing that they can generate pulses at amplitudes >50 kPa at ranges of 1 m (even to the point where there are some suggestions that they may be self-inducing long term hearing damage). Furthermore some species (e.g. *Platanista minor* and *Platanista gangetica*) which can echolocate in highly turbid environments, have lost the ability to use their eyes. As a platform, dolphins can approach a target and insonify it with many pulses, the short ranges not only promoting
the possible exploitation of nonlinearities, but also allowing relatively small changes in
the location of the source to insonify a target from significantly different angles, e.g.
through head motion. Resolution of this mystery will require careful (preferably open-
water) measurements of dolphin sonar pulses in turbid and bubbly environments, taking
particular care with measurements of phase. As a result of limitations in state-of-the-art
manufactured sonar systems, the spectacular ability for dolphins to detect objects in
acoustically complex environments is employed currently by the US Navy for mine-
hunting. The development of technology that matches this extraordinary skill set will
offer other options.

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AN OVERVIEW OF RECENT LABORATORY MEASUREMENTS ON DISPERSION AND ATTENUATION IN BUBBLY LIQUIDS, AND SCATTERING FROM ARTIFICIAL BUBBLE CLOUDS

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Effective medium (EM) models are commonly used to describe the acoustics of bubbly liquids. Regarding linear sound propagation, this approach has been successful for low void fractions and broad bubble size distributions, at frequencies away from the individual bubble resonance frequency (IBRF). For narrow size distributions at frequencies near IBRF, previously reported sound speed and attenuation measurements are not well-described by EM models. Due to high attenuation in the medium and the difficulty of independently characterizing bubble populations, experimental verification of competing models has not been achieved. An impedance tube technique was developed to overcome these difficulties and used to investigate narrow bubble size distributions at IBRF. Agreement with existing theory to a greater degree than previously reported was observed up to a void fraction of $5.4 \times 10^{-4}$, within the uncertainty of the bubble population parameters. Regarding free-field scattering from clouds of freely rising bubbles, EM models have typically been found effective up to the cloud’s monopole resonance frequency. Measurements of scattering from bubble collections that had a well-defined shape were conducted. An EM scattering model was found to describe the measurements at frequencies up to three times the cloud’s monopole resonance frequency and up to 55% of the mean bubble resonance frequency.

1 Introduction

Bubbles and bubble clouds near the ocean surface add greatly to the complexity of shallow water acoustics, but as recently as 1965, a standard textbook in underwater acoustics stated that large numbers of bubbles did not occur regularly in the ocean, except in the wakes of ships [1]. It is now well known that the upper layers of the ocean can contain as many as $10^6$ bubbles per cubic meter, even in calm seas [2]. Supersaturation of sea water by spring warming, snow, rain, and wave breaking are all known to produce bubbles at or near the surface [3]. In addition, marine plant photosynthesis, decomposition of organic material, and geological processes contribute to the continual presence of bubbles throughout the water column [2]. Perhaps the most
Acoustically relevant bubbles are those produced by spilling and plunging breakers, which can form into plumes and clouds [4] and can migrate, via turbulence [5] and Langmuir currents [6], into a variety of spatial distributions and be transported to depths as great as 30 meters. These bubble clouds can cause attenuation as high as 60 dB per meter [2] and persist for minutes at a time [4]. Measurements have shown that bubble clouds have high target strengths, of order \( -1 \) dB [7, 8]. In addition to these naturally occurring bubbles, highly organized and persistent bubbles are also found in the wakes of ships. Bubbles and bubble clouds also generate noise [9], and exhibit strong nonlinear effects [10, 11].

Sound propagation below IBRF, and sound propagation at and above IBRF, through bubbles with a broad bubble size distribution (BSD) and void fractions below about \( 10^{-4} \), is fairly well understood [12]. Propagation through narrow size distributions of bubbles excited near IBRF and at higher void fractions is not well understood [12-14]. The high attenuation, of order 10 dB/cm in this regime, and the difficulty in obtaining bubble size measurements of sufficient accuracy has left competing models unverified by experiment [13, 14]. Due to the complex shape of natural bubble clouds, and the difficulty of independently monitoring cloud size, shape and bubble content, there is an absence of single-cloud scattering data suitable for systematic model comparison above the cloud’s monopole resonance frequency [8].

In this paper, we review recent laboratory scattering and propagation experiments [15, 16] that were conducted on well-characterized bubble populations in order to facilitate meaningful model comparison with a minimum of fitted parameters. The measurements were found to compare favorably to existing effective-medium propagation and scattering models. The propagation experiments focused on frequencies near IBRF and show increased model agreement compared to previously reported data [12]. The frequency range of the scattering experiments was sub-IBRF, but in the resonance regime associated with collective oscillation of the bubble cloud. Some of the scattering experiments show better model agreement than one might expect, given the limitations of the effective medium model that was used.

2 Propagation Measurements: Sound Speed and Attenuation

2.1 Description of the Experiment

Near IBRF, high attenuation prohibits time-of-flight and standing wave measurements, so an impedance tube technique was used [17]. Frequency-dependent sound speed and attenuation within the bubbly liquid were inferred from measurements of the effective plane wave specific acoustic impedance \( z_s \) at the surface of the bubbly liquid. The experiments reviewed here are described in detail elsewhere [16], but an overview of the apparatus and procedure are given.

A schematic diagram of the impedance tube system is shown in Figure 1. The bubbles were generated directly at the measurement plane of the impedance tube, by either a single needle, which was lowered down into the impedance tube, or with a bubble injection manifold (BIM) that fit inside the impedance tube and deployed multiple needles. The needle and the BIM can be moved between the impedance tube and two other systems (not shown in Figure 1) that were used to determine the BSD and
the void fraction. The experimental procedure was composed of four parts. First, the impedance tube was calibrated. The needle or BIM was then installed in an optical apparatus for the measurement of the BSD. For needle-generated bubbles, void fraction was also measured in the optical apparatus. For BIM-generated bubbles, the BIM was moved to a third apparatus for void fraction measurement. Finally, the needle or BIM was installed in the impedance tube and the surface impedance $z_s$ of the bubble layer was measured.

Impedance tube construction, calibration and operation have been described previously [17]. Briefly, the system consists of a thick-walled stainless steel tube with two custom fabricated wall-mounted hydrophones. The system was designed to admit waves that are plane (to a high degree of approximation), despite some coupling between the fill-material and the tube wall. The acoustic source was a Kildare Corporation TP-400/A tonpilz. The bubbly liquid was contained within a sample holder. Pseudo-random noise signals were generated and received with a Hewlett-Packard HP89410A vector signal analyzer. A Crown CE-1000 amplified the excitation signal and the hydrophone signals were conditioned with a charge amplifier. The transfer function between the two hydrophones was measured with the HP89410A and the data were transferred to a laptop computer for storage and processing. The surface impedance $z_s$ of the bubbly liquid is related to the measured transfer function using Eq. (1) of [17], and a set of calibration functions. High attenuation prevented surface reflections from the top of the bubbly layer, hence $z_s = \rho c_m$. The bubbly mixture density $\rho$ was known and phase speed and attenuation were obtained from $c_m$.

2.2 The Propagation Model

The measurements are compared to a model for linear sound propagation put forth by Commander and Prosperetti [12]. For circular excitation frequency $\omega$, the complex sound speed in the bubbly mixture $c_m$ is given by

\[
\frac{c_m^2}{c_o^2} = 1 + 4 \pi i \int_0^\infty \frac{ap(a)da}{\omega_o^2 - \omega^2 + 2ib\omega},
\]  

(1)
where the host liquid has sound speed $c_l$, density $\rho_l$, viscosity $\mu$, surface tension $\sigma$ and equilibrium pressure $P_\infty$. The number of bubbles per unit volume with equilibrium radius between $a$ and $a + da$ is $P(a)da$. The bubbles have equilibrium internal bubble pressure $P_{b,e} = P_\infty + \frac{2\sigma}{a}$, and damping coefficient

$$b = \frac{2\mu}{\rho_a a^2} + \frac{P_{b,e}}{2\rho_l a^2} \frac{\omega}{\omega^2 a^2 c_l}.$$  \hspace{1cm} (2)

The three terms are due to viscous, thermal and acoustic dissipation effects, respectively. The terms $\Phi$ and $\omega_0$ are defined in [12] and relate to the gas thermal behavior and the bubble resonance frequency, respectively.

The comparison between sound speed and attenuation measured with the impedance tube and the predictions of Eq. (1) are presented for a number of void fractions in Figure 2. A complete description of the data analysis is beyond the present scope but is discussed elsewhere [16]. The dominant source of uncertainty in the entire experiment is with the probability distribution function $P(a)$, and is due directly to uncertainty in individual bubble radius ($\pm 10\%$), the finite number of bubble observations, and

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Figure 2. Model/data comparison for sound propagation in bubbly liquid at four void fractions. In each of the sub-figures a) through d), the upper frame is phase speed $V$ (m/s) and the lower frame is attenuation $A$ (dB/cm). In a), a single needle was used to produce the bubbles, otherwise the BIM was used. The large open circles represent data obtained from the void fraction resonator.
instability in the bubble production system (which led to non-stationary population statistics). For a given void fraction, a truncated normal distribution was fit to the observed bubble size measurements and a predicted sound speed and attenuation was calculated. Some of the statistical distribution parameters, such as mean bubble radius and standard deviation, where then adjusted to best fit the measured attenuation curve. This adjustment was well within the range of the bubble size measurement uncertainty itself. Void fraction was not adjusted. The best-fit bubble population statistics that were used in the model predictions are shown in Table 1.

Good agreement near IBRF is seen in all cases. The predicted and measured peak attenuation are within 1 dB and the shape of the measured and predicted attenuation curves are very similar. There is a deviation between measured and predicted phase speed above IBRF. At and below IBRF, the bubbly liquid is acoustically soft compared to the walls of the impedance tube, but above IBRF, as the phase speed increases, the bubbly liquid becomes acoustically hard compared to the walls. This causes elastic waveguide effects to become prominent, one of which is a reduced phase speed relative to the unconfined value. Therefore, the phase speed measured in the impedance tube, is reduced relative to the free field value predicted by Eq. (1). This effect is expected and is further discussed in [16]. Near IBRF though, elastic waveguide effects are at a minimum, and the data shown in Figure 2 are consistent with behavior in the free field.

Table 1. The bubble population statistics used to form \( p(\alpha) \) in Eq (1), as plotted in Figure 2. A truncated normal distribution was used, described by the population minimum, mean and maximum bubble radii, and the population standard deviation, respectively.

<table>
<thead>
<tr>
<th>Void fraction, VF</th>
<th>( a_{\text{min}} ) (mm)</th>
<th>( a_0 ) (mm)</th>
<th>( a_{\text{max}} ) (mm)</th>
<th>( s ) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.2 ( \times 10^{-5} )</td>
<td>0.627</td>
<td>0.636</td>
<td>0.645</td>
<td>0.005</td>
</tr>
<tr>
<td>3.3 ( \times 10^{-4} )</td>
<td>0.58</td>
<td>0.60</td>
<td>0.75</td>
<td>0.031</td>
</tr>
<tr>
<td>4.1 ( \times 10^{-4} )</td>
<td>0.58</td>
<td>0.62</td>
<td>0.71</td>
<td>0.038</td>
</tr>
<tr>
<td>5.4 ( \times 10^{-4} )</td>
<td>0.58</td>
<td>0.64</td>
<td>0.75</td>
<td>0.035</td>
</tr>
</tbody>
</table>

### 3 Scattering from Artificial Bubble Clouds of Canonical Shape: Bubbly-Liquid-Filled Compliant Cylinders

Obtaining knowledge and control of naturally occurring bubble cloud shape, size and bubble content with sufficient accuracy for systematic investigation of scattering properties, including comparison with model predictions, has not been achieved. Monopole scattering from artificially generated, acoustically compact bubble clouds has been investigated [8]. For excitation frequencies well below IBRF, such clouds scatter sound as if they were effective fluid spheres, with effective density and sound speed given by Wood’s mixture rule [18]. Above the monopole resonance frequency, these clouds were not acoustically compact and did not exhibit fluid-sphere scattering. To extend the frequency range of investigation, clouds of canonical shape were used. Thin-walled rubber tubes provided both a means to be filled with bubbly liquid, and a structure for which the scattering formulation was known.
3.1 Description of the Experiment

The experiments were conducted in a large indoor tank. A 3-m length of thin-walled latex-rubber tubing was deployed horizontally in the tank and served as the scattering target. A bubbly fluid generator (BFG), described in [15], was used to produce a large volume of microbubble-filled liquid that could be pumped through a closed fluid circuit that contained the target. Void fraction was monitored above the tank’s water surface, several meters down-line from the target; not to determine absolute void fraction, but to verify that the void fraction remained constant throughout the experiment. BSD was also measured down-line, with a flow-through photographic imaging cell. Void fraction and BSD directly within the target was not monitored. Time-resolved incident and reflected acoustic pulses were recorded for a range of frequencies and two tube sizes, and echo level was determined from the measured acoustic pulses. A complete description of the measurement procedure and data processing is given in [15]. Results for the larger of the two tube sizes over a frequency range from 5–20 kHz have already been reported [15]. Results for the smaller tube and an extended frequency range are reported here.

3.2 Overview of the Scattering Model

The majority of the bubbles produced by the BFG were below resonance size for the experimental excitation frequencies and Wood’s equation [18] was used to describe the sound speed and density of the bubbly liquid within the tube. Doolittle and Überall’s scattering formulation [19] for an elastic-walled, fluid-filled cylindrical shell was then used to predict the amplitude of the scattered wave

\[ P_{sc} = P_0 \sum_{m=0}^{\infty} A_m H_m^{(1)}(kr) \cos(m\theta) \]

where \( P_0 \) is pressure amplitude of the incident wave, and \( A_m \) are determined from the boundary conditions, geometry and material properties, including those of the bubbly liquid. \( H_m^{(1)} \) is an \( m \)-th order Hankel function of the first kind and \( k \) is the wave number in the surrounding fluid. Time dependence \( \exp(-i\omega t) \) is suppressed. Shear and compressional elastic waves are allowed in the tube wall, and compressional waves are prescribed inside the tube. These are expressed in a form similar to Eq. (3), with one unknown coefficient for the internal wave and two for each component of the elastic wave. Satisfaction of appropriate boundary conditions at the inner and outer shell radii leads to six linear equations with six unknown coefficients. Finally, Cramer's rule is used to find \( A_m \) for each value of \( m \), yielding \( P_{sc} \). Three terms were used for all the calculations presented below, which satisfied a convergence criterion of a maximum deviation of 0.1 dB from one mode to the next. Echo level was then calculated with

\[ EL = 20 \log_{10} \left( \frac{P_{sc}}{P_0} \right) \]

3.3 Results

Echo level measurements and the predictions of Eq. (3) are presented in Figure 3. Eq. (3) is for plane wave excitation, but the source did not generate plane waves. To
account for this frequency-dependent geometric effect, the echo level of a reference target was used for calibration. The air-filled tube (VF = 1 in Figure 3) served as the reference target. The geometric effect will be modeled from first principles in future work. No additional fitted parameters were used for the water-filled case (VF = 0). Best-fit void fractions were obtained for the two intermediate cases. No other adjustable parameters were used.

Good agreement between model and measurement is seen for the two intermediate void fractions between 20 and 60 kHz. A likely cause of greater deviation below 20 kHz is the presence of a bimodal BSD that differed from the one measured in the flow-through imaging chamber. A larger concentration of resonance-size bubbles than shown in Figure 3 could be responsible for the increased echo level. Above 60 kHz, IBRF effects could be invalidating the Wood-limit description of the bubbly liquid.

4 Conclusions

The experiments reviewed in Section 2 support the use of a single-scattering effective medium model [12] to describe the propagation of sound in bubbly liquid with a relatively narrow bubble size distribution, near the individual bubble resonance frequency, up to a void fraction of $5.4 \times 10^{-4}$. Knowledge of the bubble size distribution must be an order of magnitude more precise in order to absolutely verify Eq. (1), or any model. The experiments presented in Section 3 support the use of an effective medium model to describe scattering from bubble clouds, at frequencies above the monopole resonance frequency of the cloud, up to $ka$ of order 2, and 55% of the mean bubble resonance frequency.
Acknowledgements

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HIGH-FREQUENCY ACOUSTIC SCATTERING AND ABSORPTION EFFECTS WITHIN SHIP WAKES

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Clouds of small air-bubbles injected and mixed into the near-surface ocean within vessel wakes can create significant acoustic scattering and extinction. Recent high frequency (100 kHz) sidescan sonar measurements on a moving vessel showed persistent strong backscatter features and significant dropouts in sea-surface reverberation behind the wakes. Details of the sonar measurements and features of ship wakes recorded during these sonar trials are reviewed. Estimates of typical wake width, persistence, backscatter strength, and effective extinction are presented for the case of straight-running and turning vessels at speeds up to 20 knots.

1 Introduction

Surface ship wakes are a significant underwater acoustic feature due to the injection of clouds of small air-bubbles, with their accompanying backscatter and extinction properties. These bubbles are created by propeller cavitation, breaking of the ship's bow and stern waves, and air entrainment in the turbulent boundary layer around the hull. After initial injection, these bubbles are re-distributed by wake flows and turbulence and subject to buoyancy, coalescence, and dissolution processes, dissipating over periods of 10 to 15 minutes. Several previous studies [1-4] have documented the basic properties of ship wakes, wherein the bubbly wake penetrates to depths up to 2 times the ship's draft and spreads horizontally to widths up to 5 times the ship's beam. In addition to their obvious naval importance as a surface ship signature, wakes are ideal for testing models on bubble dynamics and high-frequency propagation in bubbly media [4,5].

This work describes results from a 100 kHz side-looking sonar sampling the wake of a maneuvering vessel from a distance of approximately 500 m. While previous studies have generally focused on vertical profiling within the wake, hence only sampling a limited volume, this work looks at the macroscopic features of the wake employing a relatively distant side-looking sonar in a surface-grazing geometry. This is the same geometry as would be used in an obstacle avoidance sonar from a ship or autonomous vehicle, where confusion of target ship and its wake needs to be addressed. Looking perpendicular to the wake yields a backscatter profile that initially widens and grows in strength as the wake deepens, then dissipates over a period of 10 to 15 minutes. A key feature of this geometry is that acoustic extinction in the near side of the wake affects sampling of farther regions. Overall, this wake study was undertaken to determine how wake backscattering is affected by vessel speed and maneuvers.
2 Observational Methods

The sea trials were conducted with a medium-sized, twin-propeller vessel in Bedford Basin, Nova Scotia on March 11th, 2004. The focal point of the trials was the DRDC Atlantic Acoustic Calibration Barge (ACB), where a 100 kHz sonar system was mounted. During the day, the ship performed a total of 24 pre-defined runs in the vicinity of the ACB at 10, 15 and 20 knots, with a 400 to 500 m closest point of approach (CPA). Three distinct types of runs were performed: straight-line, 90° turns, and full-circle turns (the turns were always away from the ACB). At or just prior to CPA the ship heading was nearly perpendicular to the sonar beams. These sonar measurements sought to quantify the scattering strength and persistence of the bubbly wake at various speeds and during maneuvers. The runs were conducted at least 15 minutes apart to allow the previous wake to drift away from the CPA and dissipate. Two differential GPS systems were installed on the vessel bow and stern near the vessel center-line, from which vessel speed and heading, and range and bearing from the sonars on the ACB, could be calculated. The wind conditions generally increased from 10 to 20 knots during the day, producing significant white-capping in the later runs. The water depth in the vicinity of the ACB was roughly 45 m.

This work utilized a four-channel, 100-kHz sidescan sonar system capable of operating up to 750 m slant range [6]. For these trials a simple 1 ms gated-CW pulse was used, providing 72-cm acoustic resolution. Each channel was coherently sampled at 20,000 samples per second, providing 3.7 cm sampling resolution, with 16-bit (92 dB) dynamic range. A time-varying gain was utilized to partially compensate for geometric spreading and absorption losses. Maximum sampling ranges between 600 and 750 m were utilized, allowing pulse repetition rates between 0.8 and 1.0 pings per second. The 100-kHz sidescan transducers had fan-shaped beams 3° x 60° (to -3 dB points), mounted with their wide (60°) beam apertures oriented vertically, with the main axes horizontal. The four transducers were oriented at approximately 5° azimuthal increments to provide a wider overall coverage area and slightly different incidence-angle looks at the vessel. The four transducers were mounted on a rotating calibration station at the ACB, oriented towards the vessel CPA. The transducer depth was 8.4 m. During these trials a lower-frequency (20 – 40 kHz) sonar was also operated from the ACB, occasionally inducing acoustic interference in the 100 kHz system. Attempts were made to filter out this cross-talk, with partial success.

The fact that these trials used a surface-grazing geometry at ranges up to 500 m suggested that acoustic propagation effects might be important. During the trials several sound velocity profiles were collected from the ACB, with conditions on March 11th showing a generally upward-refracting profile with a distinctly colder surface layer in the upper 2 m. A simple ray-tracing analysis was used to quantitatively predict the transmission loss from the source to the target, using the measured sound speed profile, a 500 m sonar-to-ship separation, and assuming a wake located in the upper 5 m. Two near-surface, refracted eigenrays were identified: a direct path and a singly surface-reflected ray. The modeling found that these two near-surface rays generally produced a 0.5 dB propagation enhancement relative to spherical spreading. However, it is believed that ambient bubble layer losses (from natural white-capping) would reduce the intensity of the surface-reflected ray, such that simple spherical spreading appears a reasonable assumption. Additionally, note that the relatively wide vertical aperture allows reception
of seabed backscatter beyond roughly 100 m range, which is responsible for some of the reverberation in vicinity of the vessel wakes.

Calibration of the high-frequency backscatter sonars was accomplished using echoes from a 0.914 m outside diameter, hollow steel sphere (6.4 mm shell thickness) moored approximately 250 m SE of the barge, approximately 3 m below the surface. Using well-known analytic models for spherical shell backscatter, the target strength \( TS \), \( 10 \times \) common logarithm of the backscatter cross-section in \( m^2 \) was calculated as a function of frequency. The predicted sphere \( TS \) at 100 kHz, corrected for the finite band-width of the transmitted pulse (1 ms duration), was -11.5 dB (re \( m^2 \)). This is similar to the \( TS \) predicted under a rigid body assumption of \( 10 \times \log_{10}[\text{radius}^2/4] = -12.82 \text{ dB} \).

The sphere echoes appeared as small but distinct intensity peaks near 245 m range. The transducer mounting was rotated manually until the target sphere echo (at known range and heading) appeared to have maximum intensity in one of the channels. Then ping data was recorded and averaged over 400 separate pings at a fixed sonar heading, and the process repeated for each of the four channels. Then, the total systemic calibration coefficient, \( K \), for each channel was extracted through application of the standard sonar equation, specifically

\[
K = TS_{\text{sphere}} - 20 \log_{10}[A_{\text{rms}}] - 2TL + TVG \quad \text{(in dB)}
\]

where \( A_{\text{rms}} \) is the averaged sphere echo amplitude, \( TL \) is the acoustic transmission loss, given by the sum of spherical spreading (\( 20 \log_{10}[\text{range}] \)) and an acoustic absorption term (\( \alpha = 0.021 \text{ dB/m} \) at 100 kHz under these water conditions), and \( TVG \) is the time-varying gain. The sonar \( TVG \) was determined by averaging sonar data with the transmit power turned off. A re-arrangement of Eq.1, with an added term to account for the insonified volume of the sonar, is then used to calculate the estimated volumetric backscatter strength (described below).

### 3 Sidescan Sonar Observations

Although a variety of runs were performed, the contrast between straight-line and 90°-turning maneuvers at 20 knots is the most illuminating. Figures 1 and 2 present example wake images for these two cases. In the straight-line run (Fig. 1) echoes from the vessel hull can be seen following a hyperbolic trajectory centered on the CPA. Fig. 1 also shows an intense noise event (vertical line) coincident with the vessel mid-section passing through CPA, presumably due to propeller cavitation. The hull echo and noise line are less prominent in the 90°-turn image (Fig. 2), however some other similar turning runs do show such features clearly. Constant-range reverberation lines in both images are seabed echoes. Surface reverberation appears as cloudy, diffuse bands drifting slowly towards the sonar, more prominent in Fig. 2.

The straight-line run (Fig. 1) shows three distinct wake features: a central core beginning near the CPA and spreading to a width roughly equal to the ship beam over the first 250 s, an outer wake edge more rapidly expanding towards the sonar, and an inner wake line expanding to an intermediate across-track range. The central core is a typical feature of twin-screw vessels, and its relatively high intensity is presumably due to deeper bubble penetration in the central down-welling zone. The disappearance of the wake central core after time = 280 s has been noted previously by several investigators [3,4], and is possibly due to higher concentrations of larger diameter bubbles which rise
to the surface relatively quickly. The outer wake edge expands and intensifies to a define a wake half-width of roughly 4 ship beams by the right-hand edge of the image, some 480 s after passage of the vessel. Note that although this straight-line wake should be approximately symmetric about the CPA, the further side of the wake beyond CPA range does not appear in the sonar image, either in the central core or the outer edge. This is presumably due to strong acoustic extinction effects in the near side and central core of the wake. Also, the apparent disappearance of the wake central core after time = 280 s may be partly attributable to this effect.

![Figure 1](image)

**Figure 1** 100 kHz sidescan intensity (arbitrary dB) vs. normalized cross-track range and time showing wake evolution for a straight-line run at 20 knots starting 1407UT, 11 March 2004. Cross-track range relative to CPA and normalized by vessel beam.

A similar, yet stronger acoustic extinction effect appears in the 90°-turning run (Fig. 2), where the central core is only visible for roughly 100 s after CPA and there is a distinct signal drop-out at ranges beyond the outer wake edge at times >150 s. In this turning maneuver the wake outer edge now expands to at least 8.5 times the ship beam towards the sonar, and is much more intense in early portions of the wake formation. A characteristic of sharp turns with a vessel of this size is the creation of an overturning horizontal vortex as the vessel slides partly side-ways through the water [4,7]. This vortex rotates outward along the surface, creating a strong convergence and downwelling zone that migrates outwards from the turn, with a relatively smooth divergent surface region behind it. Similar to the straight-line run there are no wake features at ranges beyond CPA, although it should be noted that this wake is inherently asymmetric. Note a distinct drop-out in reverberation in behind the wake edge (cross-track range near -1 to -3 ship beams) beginning at roughly 150 s.
ACOUSTIC SCATTERING EFFECTS IN SHIP WAKES

Figure 2 100 kHz sidescan intensity (arbitrary dB) vs. normalized cross-track range and time showing wake evolution for a 90°-turn run at 20 knots starting 1526UT, 11March 2004. Cross-track range relative to CPA and normalized by vessel beam.

Figure 3 Comparison of normalized wake width (width / beam) vs. wake age in ship-lengths for straight-line, 90°-turn, and full-circle wakes at 20 knots. Dashed lines show corresponding fitted curves of the form width = A[1 – B*exp(-t/t_0)].

The overall width of the wake can be extracted from these images, as summarized in Figure 3. Clearly, the outer wake edge in the two turning runs expands to roughly twice that observed for the straight-line run, with quantitatively similar behavior for the 90°-turn and full-circle maneuvers. Due to the expected symmetry of the straight-line run,
this width is one-half of the total width, and is consistent with wake width and time scales observed previously [3,4]. It is presumed that the turning-maneuver wakes show enhanced spreading due to greater horizontal migration of the overturning vortex. All three wakes show a time-evolution consistent with an exponential-decay approach to a maximal value, with time constants ranging from 137 s (straight-line) to 338 s (90° turn).

![Profiles of averaged volumetric backscatter strength at two points in the wake evolution of the straight-line run at 20 knots (data shown in Fig. 1). Cross-track distance relative to CPA and normalized by vessel beam. (a) early wake 20 s after CPA, and (b) late wake 300 s after CPA. Both profiles averaged over 10 s (solid line), and compared to background reverberation averaged over 30 s just prior to CPA (dashed line).](image)

Figure 4 Profiles of averaged volumetric backscatter strength at two points in the wake evolution of the straight-line run at 20 knots (data shown in Fig. 1). Cross-track distance relative to CPA and normalized by vessel beam. (a) early wake 20 s after CPA, and (b) late wake 300 s after CPA. Both profiles averaged over 10 s (solid line), and compared to background reverberation averaged over 30 s just prior to CPA (dashed line).

The sonar calibrations allow estimates of the apparent wake target strength and other acoustic characteristics. In this horizontal sonar geometry only depth-integrated wake backscatter can be extracted. From previous studies with vertically profiling echo-sounders [3,4] similar vessel wakes were found to have a roughly uniform volumetric scattering strength from the surface to 5 - 8 m depth. In this case we shall calculate a depth-averaged volumetric scattering strength, $<S_v>$, assuming the total volume of wake insonified by the sonar is one ship draft in depth by 3.0° horizontal angle by 72 cm in range (one pulse-length). Cross-wake profiles for the two run types are shown in Figures 4 and 5. At a fixed sonar frequency and assuming a particular size distribution of the micro-bubbles, the total extinction cross-section, $s_e$, is proportional to the volumetric backscatter cross-section (linear equivalent of $S_v$) [8]. Specifically in the near-surface region at 100 kHz the ratio between extinction and backscatter cross-sections is approximately 60. Then the extra transmission loss due to bubbles is

$$TL_{bub} = 4.34 \int_{\text{path}} s_e \cdot dl$$

(2)

where $l$ is distance along the acoustic path. Since the depth variation in $s_e$ is not known, only simple estimates of $TL_{bub}$ can be produced. Furthermore, since some portion of the observed backscatter is due to seabed reverberation, which is not subject to wake extinction, it is not appropriate to blindly apply extinction corrections to the profiles.

Figures 4 and 5 show 10-s averaged profiles at two times in the wake evolution compared to the background reverberation prior to CPA. In Fig. 4a the early wake is
dominated by the central core near CPA, with a $<S_v>$ reaching a maximum near -17.0 dB (re m$^{-1}$), more than 22 dB higher than the background. The remainder of the profile, being dominated by seabed reverberation, is largely unchanged. The one-way path-integrated bubble loss (Eq.2) across this wake core is 17.8 dB, or 35.6 dB for the two-way loss appropriate for backscattering. Clearly this extinction effect is responsible for the lack of wake signal beyond CPA, and a diminished scattering strength in the far side of the central core. At later times (Fig. 4b) the outer wake edge dominates, with $<S_v>$ averaged over -3.6 to -2.8 ship beams reaching -27.5 dB (re m$^{-1}$). This is again roughly 20 dB above the reverberation, with a two-way integrated bubble loss of 15.0 dB. In Fig. 4b the central core has either dissipated or been rendered invisible by extinction effects in the outer wake edge, or both.

Figure 5 Profiles of averaged volumetric backscatter strength at two points in the wake evolution of the 90° turn run at 20 knots (data shown in Fig. 2). Cross-track distance relative to CPA and normalized by vessel beam. (a) early wake 45 s after CPA, and (b) later wake 200 s after CPA. Line definitions similar to Fig. 4.

In the 90° turning maneuver (Figure 5) the wake profiles are dominated by the outer wake edge almost immediately after CPA, with scattering strength and extinction much stronger than the straight-line run. In Fig. 5a the early wake formation is dominated by a strong outer wake edge centered at -2.5 ship beams with $<S_v>$ = -15.2 dB (re m$^{-1}$). This creates a bubbly region roughly 0.8 ship beams wide with a one-way integrated bubble loss of 89.8 dB. Clearly acoustic signals cannot penetrate such a feature. Even at later times (Fig. 5b) where the outer wake edge has spread and dispersed somewhat, the peak $<S_v>$ near -5.2 ship beams still reaches approximately -20 dB (re m$^{-1}$), with a one-way integrated bubble loss of 22.8 dB. In the later wake profile, there is a reverberation drop-out of roughly 5 to 10 dB at ranges from -3 to +1 ship beams, presumably due to acoustic extinction in the outer and inner wake lines. The remaining $<S_v>$ profile in this drop-out zone is composed of seabed reverberation and systemic noise contributions.
4 Concluding Remarks

When viewed in a horizontal, surface-grazing geometry at relatively high acoustic frequencies (>20 kHz), ship wakes are a significant acoustic target. These high-resolution sonars captured the evolution of a central core roughly one ship beam wide and several outer wake lines. Overall the wakes were observed to dissipate over 12 to 15 minutes, depending on the vessel speed and maneuvering state. At 20 knots the outer wake edge expanded to a half-width of 3.8 ship beams wide in a straight-line run, and expanded to more than 8.5 ship beams during a 90°-turning run. The stronger outer wake edge in the turning maneuvers is believed to be due to the creation of an overturning horizontal vortex as the vessel slides partly side-ways through the turn. This vortex rotates to the outside of the turn along the surface, creating a strong convergence and down-welling zone that migrates outwards, with a relatively smooth divergent surface region behind it. Similar vortex formation has been observed previously [4,7] in the case of straight-line runs. In general only minor differences were observed between 90°-turn and full-circle maneuvers. Assuming the wake to be roughly uniform up to 1 ship draft in depth, peak volumetric backscatter strengths exceeded –15 dB (re m⁻³), with predicted one-way acoustic extinction losses in the range 15 to 90 dB. These extinction losses are presumed to be responsible for a lack of observed wake features at ranges beyond the CPA.

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References

MEASUREMENTS OF THE ATTENUATION AND SOUND SPEED IN BUBBLY FRESH AND SALT WATER

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Bubble clouds were created that filled a 144 cubic meter water tank, wherein acoustic signals were transmitted and recorded over a wide range of frequencies. The latest mean-field theoretical dispersion formulae were tested under a variety of environmental conditions. Paramount amongst the environmental parameters were the bubble size distribution, void fraction, temperature, and surface tension. In these sets of experiments, void fractions from roughly 0.019% to 0.39% were investigated. Particular attention was paid to tracking the phase of the transmitted signal at several propagation distances, as the frequency progressed toward resonance. This yielded phase speed measurements in an essentially free-field environment using a modified version of phase spectral analysis technique.

1 Introduction

The mechanisms that control an individual bubble’s interaction with an external harmonic linear pressure field have been understood for some time; the water-gas interface surface tension, water viscosity, bubble gas thermal dissipation, and acoustic re-radiation. The path from the theory of a single bubble interaction to the theory of multiply scattering ensembles of bubbles is still an area of active research. Standard approaches result in a mean field model wherein an averaging process has been applied to the bubbly system under consideration. The averaged system is parameterized in terms of the size distribution of the bubbles and the total fractional volume.[1]

From the experimental aspect of the problem, there have few experiments conducted on a scale large enough to properly verify and validate the theoretical models. A proper set of experiments to carry out this effort would require nearly free-field conditions, where all aforementioned environmental parameters could be monitored, if not precisely controlled. Much of the experimental data collected hitherto has been in sound tubes,[2] wherein the phase velocity of the medium could be easily measured. However the similitude of sound tube experiments to forward scattering in the open ocean is questionable.

In this paper, we present and analyze data collected at the U.S. Naval Research Laboratory’s Salt Water Tank Facility. Acoustic signals were broadcast from 3kHz to 100kHz through moderately dense bubble clouds with void fractions from approximately 0.019% to 0.39%. The times-of-flight and attenuations of the signals to three separate distances were measured. The phase velocities were estimated and were found to validate existing theories.
2 Experimental Setup

2.1 Environment

The Naval Research Laboratory has built an above ground square tank with a 1cm thick steel liner. The tank measures roughly 6 meters on a side with a height of 4 meters. On each of the four vertical faces three large acrylic windows measuring 130 centimeters wide by 250 centimeters high by 7.5 centimeters thick were mounted in the liner. These windows were used throughout the experiment to provide optical access to events within the tank. The water depth was kept a constant 3 meters, and all experiments were carried out at the physical center of the tank.

Fresh water was used to conduct our initial experiments within this facility. The bulk properties of the liquid-air mixture depend on the surface tension at the bubble interface. It was of some importance to keep the number of chemicals added to the water to a minimum, thus a high power ultra-violet filtration system was employed along with a particle filtration system capable of removing particles down to 10 microns. During the portion of the experiment where bubbles were introduced, no chemicals other than those present in drinking water were introduced. Periodically, water was sampled from the tank and the surface tension was checked using a tensiometer, and was found to be a constant value of 69.98 dynes/cm

The bubble generation system was comprised forty aeration tubes that were aligned in rows spaced approximately 15 centimeters apart. Each tube measured 5 meters long by
3 cm diameter and was placed on an anodized aluminum stand built to mount the tubes in
eight banks of five approximately 7.5 cm above the floor of the tank. To free fluid
circulation around the bubbler mounts were manufactured in such a way as to allow flow
around the mounts to move in a relatively unimpeded manner. Taking into account the
typical rise time of a bubble and the highest void fractions investigated in this experiment
the maximum volume of air introduced into the bottom of the tank through the bubblers
was approximately 0.39% of the total volume of the water or 72 liters per second. This
resulted in a significant upward flow of the bubble/liquid mixture in the center of the
tank. The vast majority of the bubbles were dispersed upon reaching the water’s surface.
Some did remain in the liquid and followed the general circulation downward on the
edges of the bubbler system.

![Bubble Size Distribution](image)

Figure 2. This figure depicts the bubble size distribution for the conglomeration of experiments
carried out for a void fraction of 0.39%. The distribution did not deviate from this significantly for
any void fraction.

2.2 Broadcast Signal

The broadcast signals were chosen based on the fidelity of the sources and the desire to
limit the signal bandwidth. Fifty cycles were broadcast at each frequency. A tapered
cosine envelope was applied to each signal before entering the power amplifier in order
to remove any spurious transients generated by abrupt changes in signal voltage applied
to the transducers. The recorded signals were band pass filtered at ±200 Hz from the
carrier frequency and 16 bit digitized at a sampling rate of 1 MHz. Depending on the
frequency signals were transmitted through 3 cm, 5 cm, or 10 cm spherical transducer.

3 Analytical Methods

The phase spectral method of Sachse was used to determine the phase velocity of the
propagated signals.[3] In this method one assumes that the total phase \( \phi \) at the broadcast
radial frequency \( \omega \) is given by the relation

\[
\phi(\omega) = k_r(\omega)L + \phi_0(\omega) .
\]  

(1)
Here $k_r$ is the real part of the complex wave number, $L$ is the distance of propagation in meters and the value of $\phi_0(\omega)$ is determined by the phase at the source. Solving for the phase velocity $V(\omega)$, defined as the ratio of $\omega$ over $k_r(\omega)$ one finds

$$V(\omega) = \frac{\omega L}{\phi(\omega) - \phi_0(\omega)}. \quad (2)$$

Validation of a model used to predict phase velocities could then proceed by assuming the experimental results should asymptotically approach the theoretical values far above bubble resonance. The carrier frequency would then be gradually lowered until one observed the passing of the phase function through $2\pi$ radians. Thus if at the highest measured frequency $\omega_\infty$ theoretical and experimental values match for given number of complete cycles $N_\infty$, then the phase velocity will be given by

$$V(\omega_\infty) = \frac{\omega_\infty L}{\phi(\omega_\infty) - \phi_0(\omega_\infty) + 2\pi N_\infty}. \quad (3)$$

The frequency at which either $\phi$ or $\phi_0$ is observed to pass through zero for the $n^{th}$ time will result in

$$V(\omega) = \frac{\omega L}{\phi(\omega) - \phi_0(\omega) + 2\pi(N_\infty - n)}. \quad (4)$$

The resulting curve of $V(\omega)$ is then compared with the theoretical curve as in Fig. 3.

Experimentally the time of arrival was determined by using the correlation function of the signal recorded on the monitoring hydrophone with the signals recorded at several different distances from the source. An arrival was considered to occur at the maximum of the correlation function if the delay time could be identified as preceding that of the first reverberant echo. Once the time delay was determined for each hydrophone, a section of the data equal to the length of the initial pulse and beginning at the arrival time was extracted from the larger data record. This subset of the data was then zero padded to the sampling rate, windowed with a Blackman-Harris window function and finally a fast Fourier transform was taken. The phase of the signal was identified as the complex phase of the frequency bin containing the carrier frequency of the initial pulse.

The time of the arrival of the signal denoted by $t_a$ is given by,

$$t_a = \frac{L}{V_s}, \quad (5)$$

where $V_s$ is called the "Signal Velocity."

It must be stressed that $V_s$ is not the group velocity $U = \partial \omega / \partial k$. Of course, $V_s$ must asymptotically approach the group velocity $U$. However, in frequency regimes where the attenuation is classified as anomalous, $V_s$ differs significantly from $U$. 
4 Discussion

Measured values for the phase velocity showed remarkable agreement with the theoretical results of Commander and Prosperetti from the highest frequency broadcast (approximately 100kHz) to slightly above the region of anomalous absorption (approximately 12kHz).[1]

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References

AN ANALYSIS OF GRAVITY WAVE FOCUSING IN THE LITTORAL ZONE

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One of the unique environmental factors impacting acoustic propagation in the littoral zone is the presence of shoaling surf. Surface gravity waves act as acoustic mirrors, creating high-intensity cusps and caustics in the reflected sound field. The focal points of sound move through the water column as the gravity waves shoal, and can disrupt the performance of underwater communications systems. The Doppler and phase shifts associated with the surface focusing micro-paths have been measured and can be described by deterministic models. Analytical calculations of the focusing properties of shoaling gravity waves are described and used to predict the motion of the focal regions through time.

1 Introduction

Acoustic propagation in the very near shore is complicated by the presence of shoaling and breaking gravity waves. Coastal oceanographers divide the very near-shore into three zones: the outer region, which extends from deep water to the onset of wave breaking, the transition region, which covers a horizontal range of approximately 10 water depths after initial breaking, and the inner region [1]. The transition and inner regions contain extensive clouds of wave-induced bubbles, which persist in the water column from 10’s to 100’s of seconds after injection and can have a significant impact on acoustic propagation and underwater ambient noise [2,3]. Although episodic rips can transport these clouds seaward, most of the bubbles remain in the transition region and have little impact on propagation in deeper water, which is dominated by reverberation and surface focusing effects.

Experiments to measure the impact of gravity wave focusing on acoustic communications in the surf zone have been reported [4,5] and show that the focusing effects can be modeled deterministically using measurements of the shoaling wave field.

In this paper, we present a scattering analysis of gravity wave focusing based on the Kirchhoff approximation in the Helmholtz scattering integral [6]. Analytical expressions are derived for the motion of the focal point for a specified geometry and wave properties (radius of curvature and velocity) assuming that the wave crest can be approximated as section of hemispherical shell.

2 Scattering Calculations

The first step in the scattering analysis is to assume that, over a horizontal extent equivalent to a few Fresnel zones, the crest of a shoaling gravity wave can be adequately
modeled as a section of a hemispherical shell. This geometry is illustrated in figure 1, which also shows the variables used in the scattering calculations. The y-axis is parallel to the shore line, the x-axis points inshore and the z-axis points toward the sea floor. The origin of the coordinate system is located at the peak of the wave and in a plane that contains the source and receiver.

Figure 1. Geometry for the scattering calculations. The surface \( \Gamma \) represents the wave crest, which is assumed to be invariant along the y-axis.

The starting point for the analysis is the Helmholtz-Kirchhoff scattering integral. From Ogilvy [6]:

\[
\psi(r) = \psi^{inc}(r) + \int_{\Gamma} \left( \psi^{sc}(r_0) \frac{\partial G(r, r_0)}{\partial n_0} - G(r, r_0) \frac{\partial \psi^{sc}(r_0)}{\partial n_0} \right) dS_0 \quad (1)
\]

where \( \psi \) is the total field, \( r_0 \) is the position vector on the scattering surface, \( r \) is the field evaluation point, \( n_0 \) is the unit outer normal to the surface, \( G \) is the free space Green’s function, the superscripts \( sc \) and \( inc \) respectively denote incident and scattered field components, and \( dS_0 \) is an element of the scattering surface. Note that

\[
\frac{\partial \psi}{\partial n_0} dS_0 = n_0 \cdot \nabla \psi dS \quad (2)
\]

where \( \cdot \) denotes dot product, and that \( \psi^{inc} \) is a function of the source position. The boundary conditions on the pressure release surface are given by:

\[
\psi^{inc}(r_0) + \psi^{sc}(r_0) = 0, \quad (3)
\]

and
\[
\frac{\partial \psi^{inc}(r_n)}{\partial n_0} = \frac{\partial \psi^{sc}(r_n)}{\partial n_0} \]

Substituting (3) and (4) into equation (1) for the scattered field yields:

\[
\psi(r) = \psi^{inc}(r) - \int_{x_0} \left( \psi^{inc}(r_0) \frac{\partial G(r, r_0)}{\partial n_0} + G(r, r_0) \frac{\partial \psi^{inc}(r_0)}{\partial n_0} \right) dS_0
\]

Gathering the partial derivative terms together results in a simple expression for the scattered field:

\[
\psi(r) = \psi^{inc}(r) - \int_{x_0} \frac{\partial (\psi^{inc}(r_0)G(r, r_0))}{\partial n_0} dS_0.
\]

From equation (2), this can be written as:

\[
\psi(r) = \psi^{inc}(r) - \int_{x_0} n_0 \cdot \nabla (\psi^{inc}(r_0)G(r, r_0)) dS_0.
\]

2.1 Case I. Symmetry along the y-axis with a point source

Consider a point source placed located at \( r_s = (x_s, y_s, z_s) \) above a pressure-release cylindrical shell defined by \( z = \eta(x) \) (figure 1). The scattered field at a point \( r_r = (x_r, y_r, z_r) \) is given by:

\[
\psi^{inc}(r_r) = -\int_{-L}^{L} \hat{n} \cdot \nabla \left( \frac{\exp(ikR_s)}{R_s} \frac{\exp(ikR_r)}{R_r} \right) dx dy,
\]

where \( \hat{n} = \hat{n}(r) \) is a unit normal on the scattering surface, \( \nabla = \left( \hat{x} \partial / \partial x + \hat{y} \partial / \partial y + \hat{z} \partial / \partial z \right) \), where the symbol \( \hat{a} \) denotes a unit vector in the direction of \( a \), \( 2L \) is the aperture of the scattering shell and

\[
R_s = \left( (x-x_s)^2 + (y-y_s)^2 + (z-z_s)^2 \right)^{1/2},
R_r = \left( (x-x_r)^2 + (y-y_r)^2 + (z-z_r)^2 \right)^{1/2}.
\]

Note that the gradient function is to be evaluated on the scattering surface, both source and receiver are placed in the \( y = 0 \) plane, and the source strength implied by equation (8) is \( 4\pi \) at unity distance from the source. Later we will need the surface derivative functions, which are given by:
\[ \eta = R - \gamma, \quad \frac{d\eta}{dx} = \frac{x}{\gamma}, \quad \frac{d^2\eta}{dx^2} = \frac{\gamma + x^2/\gamma}{\gamma^2} \] (10a,b,c)

where \( \gamma = (R^2 - x^2)^{1/2} \) and \( R \) is the radius of curvature of the shell. These calculations will be restricted to the special case of both source and receiver in the \( y = 0 \) plane. Taking this to be the case, the kernel of the integrand in equation (8) can be expressed as

\[ \hat{n} \cdot \nabla \left( \frac{\exp(ikR_s) \exp(ikR_r)}{R_s} \right) = -A\sin(\theta) + B\cos(\theta) \] (11)

where \( \tan(\theta) = x/(R^2 - x^2)^{1/2} \) and

\[ A = \frac{x - x_s}{R_s R_r} \exp(ik[R_s + R_r])(ikR_s - 1) + \frac{z - z_s}{R_s R_r} \exp(ik[R_r + R_s])(ikR_r - 1) \]

\[ B = \frac{z - z_s}{R_s R_r} \exp(ik[R_s + R_r])(ikR_s - 1) + \frac{z - z_s}{R_s R_r} \exp(ik[R_r + R_s])(ikR_r - 1) \] (12)

The first integral over \( y \) in equation (8) can be evaluated using a stationary phase analysis. For an isolated point of stationary phase, the asymptotic form for the integral

\[ I = \int_a^b f \exp(i\lambda\phi)dx \] (13)

is given by

\[ I_1 = f_1 \left( \frac{2\pi}{\lambda\phi_1} \right)^{1/2} \exp(i\lambda\phi_1 + i\text{sgn}(\phi_1)\pi/4) \] (14)

where the subscript \( 1 \) indicates that the function is to be evaluated at the point of stationary phase \( \phi'(x_1) = 0 \), and a superscript dash and double dash respectively indicate single and double differentiation with respect to \( x \). Substituting equation (11) into equation (8) yields a point of stationary phase at \( y = 0 \), and the asymptotic form

\[ \psi^{sc}(\mathbf{r}_s) = -\int_L f_1 \left[ \frac{2\pi}{k(1/a + 1/b)} \right]^{1/2} \exp(i\pi/4) \exp(ik(a + b))dx \] (15)

where
GRAVITY WAVE FOCUSSING IN THE LITTORAL ZONE

\[
f_1 = -\sin(\theta) \left[ \frac{x-x_s}{a^3 b} (ika-1) + \frac{x-x_s}{b^3 a} (ikb-1) \right] + \cos(\theta) \left[ \frac{\eta-z_s}{a^3 b} (ika-1) + \frac{\eta-z_s}{b^3 a} (ikb-1) \right]
\]

and

\[
a = \left( (x-x_s)^2 + (\eta-z_s)^2 \right)^{1/2}, \quad b = \left( (x-x_s)^2 + (\eta-z_s)^2 \right)^{1/2}
\]

2.2 Case II. Phase analysis for symmetry along the y-axis

The phase variation of the integrand in equation (15) is determined by

\[
\phi = a + b,
\]

which has first and second derivatives:

\[
\phi' = \frac{\gamma_s}{a} + \frac{\gamma_r}{b}, \quad \phi'' = \frac{a\gamma'_s - \gamma_s a'}{a^2} + \frac{b\gamma'_r - \gamma_r b'}{b^2},
\]

where \(\gamma_{s,r} = \left( (x-x_{s,r}) + (\eta-z_{s,r}) \eta' \right)\) and \(a, b\) are defined in equation (17). The first derivative is zero at \(x = 0\) provided

\[
\phi'(x = 0) = \frac{-x_s}{R_{r0}} - \frac{x_r}{R_{r0}} = 0.
\]

which is equivalent to saying that the stationary phase contribution occurs along a line of specular reflection. At \(x = 0\) and along the specular reflection line,

\[
\phi''(x = 0) = \frac{(1-z_s/R)R_{r0} - x_s^2/R_{r0}}{R_{r0}^2} - \frac{(1-z_r/R)R_{r0} - x_r^2/R_{r0}}{R_{r0}^2} = 0
\]

at the focus. Making use of equation (20), this condition can be solved for \(R_{r0}\) to yield

\[
R_{r0} = \frac{2}{R} \frac{z_s}{R_{r0}} - \frac{1}{R_{r0}}.
\]

If \(x_r = 0\), then equation (22) simplifies to
\[
\frac{1}{R_{r0}} = \frac{2}{R} - \frac{1}{R_{s0}}, \tag{23}
\]

which is the thin lens equation. In general, there is a focus provided \( R_{r0} > 0 \), which restricts values of \( R_{s0} \) for a given \( z_s \). The condition is:

\[
R_{s0} > \sqrt{\frac{z_s R}{2}}. \tag{24}
\]

2.3 Case III. Symmetry along the y-axis with a distant point source

When the source is located many wavelengths from the scattering boundary, and the receiver is located at least a few wavelengths away, the approximations \( ka \gg 1 \), \( kb \gg 1 \) and \( a = R_{s0} = (x_s^2 + z_s^2)^{1/2} \) can be used, in which case the scattering integral simplifies to

\[
\psi^{sc}(r_s) \approx -\int_{-L}^{L} f_1 \left[ \frac{2\pi}{k(1/R_{r0} + 1/b)} \right]^{1/2} \exp(i\pi/4) \exp(ik(a_1 + b)) dx, \tag{18}
\]

where

\[
f_1 = \frac{ik}{bR_{r0}} \left[ \cos(\theta) \left( -\cos(\theta_{r0}) + \frac{\eta - z_s}{b} \right) - \sin(\theta) \left( -\sin(\theta_{r0}) + \frac{x - x_s}{b} \right) \right], \tag{19}
\]

and

\[
a_1 = R_{s0} - x \sin(\theta_{r0}) - \eta \cos(\theta_{r0}). \tag{20}
\]

The source angles in equation (19) are defined by \( \sin(\theta_{r0}) = x_s / R_{s0} \) and \( \cos(\theta_{r0}) = z_s / R_{s0} \). The phase of the integral is given by:

\[
\phi = k \left( R_{s0} - x \sin(\theta_{r0}) - \eta \cos(\theta_{r0}) + \left( (x - x_s)^2 + (y - y_s)^2 \right)^{1/2} \right). \tag{21}
\]

The main contribution to the scattering integral comes from points of stationary phase \( x_1 \), which are solutions of \( d\phi / dx = 0 \). If the second derivative of phase is also zero at \( x_1 \), then the point corresponds to a focus. Making the appropriate substitutions yields:
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\[
\frac{d\phi}{dx} = -\sin(\theta_{s0}) - \frac{d\eta}{dx} \cos(\theta_{s0}) + \frac{1}{b} \left[ (x-x_s) + (\eta-z_s) \frac{d\eta}{dx} \right]
\]

\[
\frac{d^2\phi}{dx^2} = -\frac{d^2\eta}{dx^2} \cos(\theta_{s0}) + \frac{1}{b} \left[ 1 + \left( \frac{d\eta}{dx} \right)^2 + (\eta-z_s) \frac{d^2\eta}{dx^2} \right] - \frac{1}{b^3} \left[ (x-x_s) + (\eta-z_s) \frac{d\eta}{dx} \right]^2
\]  

(22)

Both the first and second phase derivatives are zero when \( x = 0 \) and

\[
\theta_{s0} = -\theta_{s0}, \quad R_{r0} = \frac{R}{2} \cos(\theta_{s0}),
\]

which defines the condition for a focus (this can be shown by direct substitution).

For a wave crest passing over a source in the surf zone, we have \( z_s \) constant and \( x_s = vt \), where \( v = (gh)^{1/2} \) is the wave crest velocity in water depth \( h \). Note that \( x_s = 0 \) when \( t = 0 \). It follows immediately that \( \theta_{s0} = \arctan(vt / z_s) \) and

\[
x_f = \frac{R}{2} \cos(\theta_{s0}) \sin(\theta_{s0}), \quad z_f = \frac{R}{2} \cos^2(\theta_{s0}),
\]

where \((x_f, z_f)\) is the focal point of the crest for a specified distant source angle.

Figure 3 shows the variation in focus position for three shoaling gravity waves calculated using equation (24). Time \( t = 0 \) corresponds to \( x = 0 \) and the maximum depth of the focus. As the wave shoals, the focal point moves monotonically upwards toward the surface and generally shoreward, although gently curving wave crests, corresponding to large radii of curvature, can result in a focus that backtracks over a portion of its trajectory.

3 Discussion

Analytical expressions for the position and trajectory of the focal region associated with scattering from shoaling wave crests in the surf zone have been derived. The movement of the focus through the surf zone is found to depend on the radius of curvature of the wave crest, which acts as a kind of spatial filter determining the range of closest approach between the focus and the source. Certain source-receiver geometries and wave radii of curvature do not result in a focus, and the condition for a focus to occur is given by equation 24.
Figure 3. Variation of focal position with time for three wave crest radii of curvature. Equal time increments have been taken between successive points.

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References

THE EFFECT OF THE BUBBLE SPACING ON PASSIVE ACOUSTIC TRANSMISSION ALONG BUBBLE CHAINS

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An experimental investigation is conducted on the passive acoustic emission by a bubble chain composed of discrete bubbles. Different bubbly chain configurations are generated by forcing air with different flow rates through two different nozzles immersed in water. The aim was to examine the effect of the spacing between neighboring bubbles on the channeling of acoustic energy along the bubble chain. The acoustic energy was created naturally by the detaching bubble at the bottom of the chain. The analysis of the data in the frequency domain is obtained by means of time-frequency Wigner-Ville distributions. For different chain configurations, the evolution and the attenuation of the energy of the resonant bubble frequency is evaluated. The modulation of the pressure and the frequency response under different conditions are also presented. It is shown that there is a significant reduction of the attenuation of the analyzed acoustic signals in the direction along the chain. The detected irregularity is more pronounced as the spacing between the bubbles in the chains is decreased. This produces a strong un-attenuated channeling of acoustic energy along the closer-spaced bubble chain.

1 Introduction

The sound naturally emitted by bubbles in fluids is a significant phenomenon, and the ability to determine the size and number of bubbles has practical applications in many areas. The detection and the measurement of the bubble size and population can be obtained by use of optical methods (Leighton et al. [1]), conductivity probes (Chanson [2], Watson et al. [3]) or by the interaction of an acoustic field with the bubble (Minnaert [4], Choi and Yoon [5], Manasseh et al. [6]). The acoustic field may be externally imposed or passively emitted by the bubbles themselves. According to the Minnaert’s formalism the frequency \( f_0 \) of the acoustic signal emitted by a single, linearly-oscillating bubble is correlated with the bubble radius \( R_0 \) (assuming the bubble is spherical and is under adiabatic conditions) by:

\[
f_0 = \left( \frac{1}{2 \pi} R_0 \right) \left( 3 \gamma P_\infty \rho \right)^{1/3};
\]

where \( P_\infty \) is the absolute liquid pressure, \( \gamma \) is the ratio of specific heats for the gas, \( \rho \) is the liquid density.

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Acoustic estimation of bubble populations (i.e. the size and space distribution) in liquids is usually done by simultaneous measurement of backscatter and attenuation (Medwin [7]). The number density of such bubble population can be then calculated under an assumption that there is no interaction between the scatterers, and that the measured intensity at the receiver is the sum of the intensity coming from each scatterer in isolation. However, depending on the experimental conditions these two assumptions may be underestimating the interaction effects, which will lead to inaccurate results. Some of the important parameters are: the wavelength of sound, the size of the bubbles, the distance between neighboring bubbles, and the distance from the scatterer to the point where the sound is measured (the position of the receiver).

Thus, a deeper understanding of the bubble-sound interaction is crucial for accurate numerical modeling and the prediction of the acoustical feedback. The choice of the appropriate model for a bubble system is a topic that has been investigated by many researchers, focusing primarily on coupled-oscillator approximations. Important studies include those of Zabolotskaya [8], Oguz and Prosperetti [9], Tolstoy [10], Feuillade [11] and Twersky [12]. The focus of this work is to investigate of the propagation of sound along chains of uniformly produced same-sized bubbles but with different spacing between subsequent bubbles.

2 Experimental system and data acquisition technique

The experimental set-up used in this investigation is illustrated in Fig. 1. The tank designed for the experiments is 950 mm × 560 mm in base and 1500 mm deep. The internal orifice radius of the nozzles used for the bubble chain configurations were 2.500 ± 0.025 mm and 1.000 ± 0.025 mm, supplied with air via a precision pressure regulator at 13.0 ± 0.5 kPa pressure. The nozzle orifice used for bubble production in both cases was 1.2 m below the water surface. The way a bubble is produced is very important for the subsequent behavior of the emitted sound pulse. For this investigation, it is particularly important to avoid any bubble collision at the moment of release should be avoided. Experiments were conducted for the bubble production rates such that the produced bubbles from different nozzles had the same diameter.

A set of two Brüel & Kjaer type 8103 hydrophones was used. The hydrophone signals were pre-amplified by Brüel & Kjaer type 2635 charge amplifiers and digitised by a National Instruments Data Acquisition Card type 6024E. For these experiments because a high resolution of the scanned field was required the positioning of the scanning hydrophone was automatically controlled using a robot arm (S-Model 10, Type A05B-1024-B202, Fanuc Ltd).

The acoustic pressure in the form of voltage output was stored in separate files using a program built on a LabView platform (National Instruments Corporation). The program consisted of one main program for controlling the robot and two sub-programs for the data acquisition. The logging block diagram is presented in Fig. 2. The first sub-program is StreamTone (CSIRO), and this version was modified for two-channel recording. CH0 was connected to the fixed hydrophone and CH1 was connected to the filter and the moving hydrophone. The second program is the High Speed Data Recorder, which was created for recording non-filtered and non-triggered (continuous) data from the third channel: CH2, connected to the moving hydrophone.
The acoustic center of the first (fixed) hydrophone was at a horizontal distance of 60 mm (point A" in Fig. 3) from the nozzle axis (0-0') and at the same vertical level with the nozzle orifice. This position was maintained for all of the experiments while the Bubble Production Rate (BPR) was varied. The second (scanning) hydrophone was positioned on a 38 × 31 grid (20 mm point to point distance) within the vertical plane left from the line A-A' (containing the nozzle axis 0-0').

The positioning of the second hydrophone was automatically controlled, ensuring an accurate grid positioning. Two channels, one for the fixed and one for the scanning hydrophone, were logged at 30 kHz (the time between two data points is $\Delta t = 3.333 \times 10^{-5}$ sec) each with a 12-bit resolution. The acoustic pressure from both hydrophones in the form of a digitized voltage was recorded at every grid-point. The digitized waveforms contained 1024 data points for each bubble pulse, thus the recording period $T$ is 34.13 ms. Between 36 and 40 bubble pulses were recorded at each point. The software started...
to record data once a certain voltage trigger level was reached; the signal from the fixed hydrophone was used as the trigger because the signal near the nozzle is highly repeatable (as shown by Manasseh et al. [6] and Nikolovska et al. [13]). As soon as the triggering occurred, data was recorded on channel CHO and CH1 simultaneously. This provided simultaneous acquisition of the sound signal near the source and in the far field. Once the StreamTone program had completed the recording the second program was initialized to record data from channel CH2 continuously for two to three seconds, ensuring that 30 to 60 bubble pulses were recorded (this depended on the BPR). After completing data recording at a certain point the main program is initiated the motion of the robot to the next grid point. The grid coordinates were entered in a separate text file that was read by the main program.

3 Bubble-chain configurations investigated

In the following section a comparison is presented for two chain configurations made from different nozzles and at different bubble production rates. In both chain configurations the bubbles have the same radii (2.6±0.1 mm) but the spacing between the bubbles is different. When the chain is formed by the bigger 2.5 mm nozzle, the bubbles are formed at a lower production rate of 10 Hz BPR; thus, the bubbles were spaced further apart (20.5±0.2 mm). On the other hand, when the smaller 1 mm nozzle is used to form the chain, a higher production rate of 38 Hz BPR is used, consequently making the distance between the bubbles smaller (7.5±0.1 mm). For purposes of comparison the time and the space intervals are same in both cases. For the first case the profile of the sound pulse along the chain is shown in Fig. 4 (right). Distances are true radial distances from the tip of the nozzle. For clarity only five points are plotted: 6 cm, 19 cm, 36 cm, 54 cm and 72 cm in a vertical direction along a line parallel to the bubble chain (the axis A-A’ in Fig. 3). The trend is similar for all the points that lie between the points that are presented in these plots. The spacing between the first few bubbles on average is 20.5±0.2 mm. The average radius of the first three bubbles is 2.7±0.1 mm; thus the corresponding Minnaert’s [4] formalism is 1.28±0.05 kHz. The signal recorded at the nearest point to the nozzle has a peak frequency of 0.760±0.005 kHz.

The profile of the sound pulse along the chain generated by the 1 mm nozzle is plotted in Fig. 5 (right). The spacing between the first few bubbles on average is 7.5±0.1 mm. The average radius of the first three bubbles is 2.6±0.1 mm; thus the corresponding Minnaert frequency is 1.33±0.05 kHz. The signal recorded at the nearest point to the nozzle has a peak frequency of 0.84±0.01 kHz. For evaluation purposes the color scale used is same for both cases. Comparing Figs. 4(right) and 5(right),it is evident that in the case when the bubbles are further apart the average drop of the acoustic energy along the chain is more enhanced. When the bubbles are closer the sound is transmitted along the chain more efficiently; in other words, the energy of the sound from the bubbles’ detachment is more concentrated in the vicinity of the closer-spaced chain.

Figures 4 and 5 show the distribution of the $P_{\text{RMS}}$ in the investigated spatial plane near the bubble chain (the distance is in cm). The first case (Fig. 4 (left)) is for the chain with bigger spacing between the bubbles (around 20.5±0.1 mm) and as shown the intensity of the mean pressure is significant (the yellow surface) up to 34 cm (i.e. 63 bubble diameters) vertically away from the point of detachment and up to this region.
there are roughly 15 bubbles. The second case (Fig. 5 (left)) is when the spacing between the bubbles is smaller (around 7.5 ± 0.1 mm) and here the intensity of the \( P_{RMS} \) is remarkable (again comparing the yellow surface) up to 65 cm (i.e. 125 bubble diameters). For this case in this height there are on average 97 bubbles.

The average of the \( P_{RMS} \) for the whole scanned plane is almost same for the both cases, and its mean value is around 0.49 Pa for the first case, and around 0.45 Pa for the second one. This means that although the same energy is applied to the system, the distribution of that energy is strongly influenced by the presence of the neighboring bubbles in the chain and by the spacing between the bubbles.
Figure 6. Wigner-Ville distributions for the sound signals plotted in Fig. 4 and 5; the top map is of the signal that is recorded at the closest point to the nozzle, i.e. at radial distance 6 cm, and the map at the bottom corresponds to the point furthest away from the nozzle. Case of bubble chain generated with the 2.5 mm nozzle - spacing between the bubbles 20.5±0.1 mm (left) and with the 1 mm nozzle - spacing between the bubbles 7.5±0.1 mm (right)

Fig. 6 shows the variation of the signal energy through the time-frequency Wigner-Ville distribution (Cohen [14]). This gives the frequency evolution with time and also the attenuation of the corresponding frequencies. Following the peak energy of this frequency (the intense red surface in the Wigner-Ville maps) the speed at which the energy of this frequency travels is estimated to be around 82±6 m/s for the case with the big spacing between the bubbles and around 65±5 m/s when the bubbles are closer.

It can be noted that the speed at which the energy of the peak frequency travels along the bubble chains drops as the spacing between the bubbles in the chain is reduced. Nonetheless, the spreading of the group envelope is different, which can be explained by the fact that different frequency components (in a dispersive medium) have different phase velocities and different damping. Therefore, individual frequencies reach a certain point in the space at different times (which causes spreading of the group envelope along the time scale) and are attenuated at different rates (displayed as a narrowing of the group envelope along the vertical frequency scale).

Fig. 7 (left) emphasizes the difference in the $P_{\text{RMS}}$ profiles in horizontal and in vertical direction for the investigated bubble chain configurations. The influence of the neighboring bubbles and their spacing clearly modulates the distribution of the acoustic energy. Fig. 7 (right) compares the distribution of the attenuation of the bubbles resonant frequency (1.28 kHz); the calculation procedure is given in Choi and Yoon [5]. The difference between the attenuation of the measured sound pulse along the bubble chain is

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drastically decreased with the decrease of the spacing between the bubbles, i.e. from around \(-120\pm10\) dB/m for the big separation up to \(0\pm10\) dB/m as the bubbles are brought closer. However, the difference in the attenuation of the same frequency in horizontal is not very dramatic, around \(\pm20\) dB/m difference between the two chain configurations. These results indicate that the acoustic energy is ‘more efficiently’ transmitted along a denser chain configuration preliminary due to the presence and the separation of the neighboring bubbles.

Figure 7. The \(P_{\text{RMS}}\) (left) and the attenuation profiles (right). The dashed line is for the case with big spacing between the bubbles and the solid line is for the smaller one; the blue lines is the data along the chain (in vertical) and the red lines are the data away from the chain (in horizontal)

4 Discussion

The aim of the present study was to evaluate the influence of the spacing between neighboring bubbles on the distribution of the acoustic energy in the vicinity of bubbly streams. The investigated cases presented here have the following specifications: the bubbles are continually generated by the same system that ensures the size of the bubbles in one chain configuration is constant; the sound that is distributed along the chain has a frequency close to the resonant frequency of the individual bubbles; and the resonant frequency of the bubbles has a wavelength that is much bigger than the bubble radii and the spacing between the bubbles. By varying the airflow and by using different source nozzles, different bubble chain configurations were generated. For the cases presented here, the bubbles have same size but they are generated from different nozzles at different BPRs. The acoustic behavior of the bubble chains was evaluated by measuring the passive acoustic emission from these two bubble chain configurations. The following conclusions are drawn. In producing a bubble with a certain size but from a different nozzle the same energy is released (the mean \(P_{\text{RMS}}\) is same for both cases); and there is a significant change of the sound pressure profile along the line parallel to the axis of the bubble chain. This effect is strongly enhanced as the spacing between the bubbles is reduced and more bubbles are introduced in the chain; a clear example is given through the summarized \(P_{\text{RMS}}\) and attenuation profiles in Fig. 7.

The observed enhanced acoustic localization is not a consequence of geometric scattering from a large bubble or a cylindrical body (this is a case if we apply the homogenous medium theory, as investigated by Commander and Prosperetti [16], and approximate the bubble chain as a homogenous medium with a cylindrical shape), but as
shown through this study is due to the presence and the distance between neighboring bubbles.

The behavior observed while comparing a case of one bubble and a case of a chain of bubbles (Nikolovska et al. [15]) showed that the change of the acoustic properties (i.e. modulation of the sound pulse and localization of the acoustic energy) in the vicinity of the bubble chain results from the presence of the other bubbles in the chain. The results obtained through this experimental investigation indicate that the degree of channeling of the acoustic energy along the bubble chain is strongly dependent on the spacing between the neighboring bubbles in the chain. The Wigner-Ville maps (Figs. 6) show that reduced spacing between the bubbles facilitates the transmission of acoustic energy through a longer distance along the line of bubbles; this allows the signal's information to be transmitted away from the source in a direction along the bubbles to a distance dependent on the spacing between the bubbles.

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References

CAUSALITY CONDITIONS AND SIGNAL PROPAGATION IN BUBBLY WATER

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Acoustic signal propagation through sub-surface bubble clouds in the ocean can exhibit enormous variations depending on the acoustic signal frequency, bubble size distribution and void fraction. Existing theories predict large variations in phase speeds and attenuation that have been largely validated for frequencies well below bubble resonance. However, great care must be exercised when theoretically treating signal propagation at frequencies near resonance. We will discuss how the signal travel time is dependent on the behavior of the dispersion formula in the complex frequency plane and the range of validity of these formulae. Also we discuss necessary modifications to the current dispersion formulae to bring them into compliance with causality.

1 Introduction

Shallow water environments have persistently provided some of the most challenging scenarios for the application of acoustic propagation prediction methods in underwater acoustics. One of the most variable aspects of these systems is the presence of strong scatterers, whether they are bathymetric features like sediments or near surface variability such as fish or bubbles. To this end recent experiments conducted at the U.S. Naval Research Laboratory have been aimed at experimentally verifying and validating theoretical treatments of acoustic propagation through bubbly liquids. The pursuant data analysis has led us to ask a simple question, *what is the velocity of an acoustic signal in a bubbly liquid?*

In this paper we present a short discussion on the current theories of acoustic wave propagation in bubbly fluids. Specific attention is paid to the region of great interest, known as the anomalous absorption regime; that region generally marked by the highest absorption. The current mean-field theory models are linked to a large body of work carried out in the first half of the twentieth century concerning the causality conditions of electromagnetic wave propagation in the presence of dielectric material.[1,2,3] Using methods developed for the electromagnetic wave propagation, the velocity of propagation of an acoustic wave packet in a bubbly liquid was investigated. We point out an inconsistency of the current mean-field acoustic propagation theory that causes it to exhibit *acausal* behavior.
Figure 1. The left figure shows the geometric construction of the phase and group velocities for the experimental environmental conditions encountered. The right figure shows the specific paths of integration taken calculating the function in Eq.(1). The solid line (-) is used for \( k_r x < \omega t \), the dotted line (..) for the electromagnetic case, with \( k_r x > \omega t \), and the dash-dot (-.) for the acoustic bubbly fluid with \( k_r x > \omega t \).[1,2]

2 Phase Velocity, Group Velocity and Dispersion

We consider an acoustic signal to be a wave packet consisting of a sum of components each a one-dimensional harmonic wave moving in the positive \( x \)-direction at time \( t \), and position \( x \). Then the signal originating from \( x=0, t=0 \) can then be constructed via a Fourier integral, as

\[
f(x,t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} f(\omega') \exp\left[ -i\omega' t + ik(\omega')x \right] \, d\omega'.
\]  

In general, the wavevector \( k(\omega) \) will be a complex quantity, in order to take into account the transfer of energy from the wave as it propagates through the medium to the medium itself. However, we assume initially that the imaginary part of the wavevector is negligible in comparison to the real part, i.e., \( k_i \ll k_r \). The real part of the wavevector \( k_r(\omega) \), defines how the complex phase of the \( \omega \) component changes with position. This naturally leads to the definition of the phase velocity as the velocity an observer of the wave packet would have to maintain in order to observe the \( \omega \) component of the wave packet at a constant phase, i.e.,

\[
\psi(\omega) = k(\omega)x - \omega t = k_r(\omega)x - \omega t = \text{Const},
\]

thus \( v_p \) is given as

\[
v_p = \frac{\omega}{k_r(\omega)}.\]  

For dispersive systems \( k \) is a non-linear function of the frequency \( \omega \), and the components of Eq.(1) travel at different rates, each given by Eq.(3). In this case the different frequency components will add both constructively and destructively causing the wave packet to travel with a velocity different from the velocity of any of the separate
components. One can demonstrate by applying appropriate limiting procedures that the velocity of the wave packet or group velocity is defined as

\[ v_g^{-1}(\omega) = \frac{\partial k_r(\omega)}{\partial \omega} = \frac{1}{v_p} \left[ 1 - \frac{\omega}{v_p} \frac{\partial v_p}{\partial \omega} \right], \quad (4) \]

There are no \textit{a priori} requirements that place bounds on the value of the group velocity inherent included in the derivation of Eq.(4). This is graphically demonstrated in Fig. 1, where we have used the dispersion formula appropriate for the experimental work reported on in Ref. It can be seen in this figure that the slope of the curve that corresponds to the group velocity can be nearly infinite, positive, negative or zero. Thus the association of the group velocity with the propagation of energy of the wave packet is suspect, since it would seem to imply the instantaneous propagation of an acoustic signal.

The solution to this problem was determined at the turn of the twentieth century for the case of electromagnetic waves in the presence of dielectric materials by Sommerfeld and Brillouin, where the dispersion formula was given by[1,2]

\[ k_{\text{eff}}^2 = \frac{\omega^2}{c_0^2} \left( 1 + \frac{\alpha^2}{\omega_0^2 - \omega^2 - 2i\omega\beta} \right). \quad (5) \]

Sommerfeld and Brillouin demonstrated the path out of this conundrum lay in using theory of analytic functions in the complex plane. Provided the dispersion formulae have finite asymptotic limits, in essence \( \omega / k \to c_0 \) as \( \omega \to \infty \), the integral of Eq.(1) can be calculated using the saddle point method. Integration proceeds along the paths described in Fig. 1. If \( \text{Re}[k(\omega)x - \omega t] > 0 \) then the integration path can be closed in the upper half plane. Since, Eq. (5) is analytic in this region the integral along \( \Gamma_c \) must vanish, and the arc can be taken to infinity, making its contribution to the integral zero, leaving the integral along the real axis equal to zero. This proves that no signal can arrive faster than \( x / c_0 \) and the system is thus \textit{causal}.

For the case \( \text{Re}[k(\omega)x - \omega t] \leq 0 \), one must take the path of integration into the lower half plane where the square root of Eq. (5) is not analytic. However, one can show that the solution of the Fourier integral is dominated by the saddle points in the complex plane of the argument of the exponent in Eq. (1). These points are defined by the solutions to the equation

\[ \frac{d\psi}{d\omega} = 0 \Rightarrow \left( \frac{dk}{d\omega} \right) x = t, \omega \in \mathcal{C}. \quad (6) \]

For environmental conditions where \( k_i \ll k_r \) and \( k_i \ll 1 \), the solutions of Eq. (6) correspond to the points previously identified as the group velocity.
3 Mean-Field Dispersion Formula in Bubbly Water

Theoretical models of acoustic propagation in bubbly water must take into account three physical mechanisms for attenuation: viscosity, thermal transport, and radiation. Additionally, the interior pressure of the bubble will be different owing to the additional pressure due to the surface tension. When all of these are appropriately addressed the result can be summed over the distribution of bubble sizes. The resulting dispersion formulae are [3]

\( k_{\text{eff}}^2(\omega) = \frac{\omega^2}{c_0^2} + \frac{4\pi c_0^2}{r} \int_0^\infty \frac{r \rho_{\text{BSD}}(r)}{\omega_r(\omega, r)} dr - \omega^2 - 2i\omega b(\omega, r) \)  \( (7) \)

\( \omega_0^2(\omega, r) = \frac{p_0}{\rho r} \left( \text{Re} \left( \Phi(\omega, r) \right) - \frac{2\sigma}{p_0 r} \right), b(\omega, r) = \frac{2\mu}{\rho r^2} + \frac{p_0}{2\rho r^2} \text{Im} \left( \Phi(\omega, r) \right) + \frac{\omega^2 r}{2c_0} \)  \( (8) \)

where

\( \Phi(\omega, r) = \frac{3\gamma}{{(1 - 3\gamma)}^{1/2} \chi(\omega, r)} \left( \frac{i}{\sqrt{\chi(\omega, r)}} \coth \left( \frac{i}{\sqrt{\chi(\omega, r)}} \right) \right)^{-1} \)  \( \left\lbrack \chi(\omega, r) = \frac{D_\omega}{\partial r^2}, p_L = \frac{2\sigma}{r}, D_\omega = \frac{(\gamma - 1)k T}{\gamma_p p_\infty}, p_\infty = p_\infty + p_L \right\rbrack \)  \( (9) \)

\( \gamma \) is the ratio of specific heats of the gas, \( \sigma \) is the surface tension of the gas-water interface, \( c_0 \) is the quiescent sound speed, and \( p_\infty \) is the ambient hydrostatic pressure at the bubble’s depth.

Without loss of generality, we assume that the bubble size distribution \( \rho_{\text{BSD}} \) is monodispersed, i.e., all bubbles are identical. Then Eq.(7) is essentially equivalent to Eq. (5).
and we may apply the methods developed by Sommerfeld and Brillouin to signal propagation through bubble clouds. The asymptotic form of the dispersion formula is satisfied since \( \omega / k_{\text{eff}} \rightarrow c_0 \) as \( \omega \rightarrow \infty \). However, the contribution to the radiation absorption is \( i\omega^3 r / c_0 \), creates a pole in the upper half \( \omega \)-plane. By Cauchy’s theorem the complete integral along \( \Gamma_c \) is non-zero, yet the contribution from the upper arc is zero because of the asymptotic limit of Eq.(7). Thus for any time including those satisfying \( \text{Re}[k(\omega)x - \omega t] > 0 \) the integral of Eq.(1) will be non-zero. Thus the theoretical model must be acausal.

The error in the formulation comes from the fact that the formula for the radiation damping (the last term in Eq. (8)) is actually based on a series of low-frequency approximations. The correct formulation valid for all frequencies is [4]

\[
\beta_{\text{rad}} = \frac{1}{2} \frac{\omega^2 r}{c_0 - i\omega r}
\]

### 4 Discussion

The mean-field theory of acoustic signal propagation through a bubble cloud as originally set forth in the culminating work of Commander and Prosperetti [3] bears more than a passing similarity to the theory of electromagnetic wave propagation in the presence of a dielectric.[1,2] This is precisely because both theories originate from considering the underlying mechanism causing scattering and absorption to be approximated by a damped harmonic oscillator. Methods of analysis developed for the electromagnetic case were applied to the acoustic case, wherein the theory was shown to be acausal. A correction was applied to the theory with the result that the high-frequency behavior of the attenuation becomes independent of frequency, instead of decaying. The main impact the corrected theory will have on observational methods will be to drastically lower the estimates of the number of bubbles on the lower end of the distribution.

### Acknowledgements

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