Remote sensing of water waves: wave flume experiments on regular and irregular waves

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Abstract
Laser scanning technology is a form of remote sensing which has shown, in feasibility studies, that a water surface can be measured rapidly and accurately without in-situ sensors. The adoption of a terrestrial laser scanner (TLS) for wave measurements is an innovative use of state-of-the-art technology usually employed for surveying and high precision surface modelling. An experimental setup for the measurement of waves in a wave flume is detailed and the results of remote sensing of wave parameters are described. The experiment conducted involves a unique method for measuring wave parameters such as wave height, wave period and wavelength. The experiments function as a source of reliable laboratory controlled data, however it also provides a platform for the development of laser scanning technology for field measurements.

Keywords: Remote sensing, terrestrial laser scanner, wave measurement

1. Introduction

In the study of wave profiles, wave shape and other spatially dependant wave characteristics, one must rely on specialised laboratory techniques or an extensive array of field instruments in order to collect sufficient data. This paper describes the use of a Terrestrial Laser Scanner (TLS) as a relatively simple yet powerful tool for aiding such studies.

Remote sensing of wave parameters can have a number of advantages over traditional in-situ methods. In-situ methods are well established and contribute much of the experimental and field data of wave parameters used in research. Water wave research generally makes use of wave staffs (Carvalho & Parente [1]), pressure transducers (Bishop & Donelan [2]) and wave buoys (Barstow & Krogstad [3]). There are a wide range of in-situ instruments that are commonly deployed in coastal waters (IOC [4]) while capacitance wave probes meet the requirements for most laboratory experiments. The direct measurement of wave parameters, and in particular water elevation, using these devices generally provides reliable data due to their ease of validation.

However, an in-situ device is limited to measurement of only one location and therefore cannot itself provide spatial profiles. Some techniques can be employed to work around this limitation, such as fixing such a device to a moving platform (Brevik [5]), however there is no simple method that can be easily adopted for research in the field. Therefore to determine the spatial evolution of wave profiles arrays of in-situ devices are required. For flume experiments this can be relatively easy to incorporate as installation and cost are generally not limiting factors. However, this may not be the case in the field as the size of the area to be monitored can require a large number of sensors. The expense of installation would mean the array would likely be fixed at a certain location. This is the main disadvantage of the use of in-situ devices compared to remote sensing techniques for measurement of spatial profiles.

Remote sensing has grown over the last half a century as technology has improved and as innovative uses became available. Simply removing the sensor from the water whilst retaining the performance of in-situ devices has opened up new research avenues and allowed studies to take place that were previously unfeasible. Remote sensing has been applied to velocity measurements through particle image velocimetry (Liu et al [6]), wave elevation time series through acoustic gauges, and construction of water surface geometry through photogrammetry. Although these methods perform as intended, they cannot combine measurements in both a large spatial domain and over a period of time.

Satellite altimetry is another method of remote sensing and can determine water surface elevation. Comparison between traditional tide gauges and satellite altimetry is drawn in Woppelmann [7]. It is shown that a combination of both methods is necessary for large scale remote sensing, however due to the large spatial distances measured by satellite, only mean values for wave heights are recorded. Radar is another example of a remote sensing technique that has evolved into a sophisticated wave analysis tool. X-band radar systems such as WaMoS II can be used to determine accurate wave parameters (Nieto Borge et al. [8]), however there is limited accessibility to these systems in industry.

Considering all remote sensing techniques currently available for researchers it is evident that visible light based instruments may be most suitable for high accuracy and relative portability.

LIDAR (light detection and ranging) is one such technique based on laser technology for spatial measurements of distant targets.

The basis of LIDAR is the time-of-flight principle in that the time taken for a pulsed laser system to emit and receive the echo of a laser pulse determines the distance to the target. LIDAR was first introduced for use in the coastal environment following on from research undertaken by Hickman & Hogg [9] in 1965. The LIDAR systems were attached to aircraft allowing relatively fast bathymetric surveys over large areas. Airborne LIDAR systems have since been developed around the world, including by the Royal Australian Navy LADS system in Australia by the Defence, Science and Technology Organisation.

Studies involving laser technology for wave elevation, such as the reliability study described in van Unen [10], have shown that as a fixed instrument a laser based remote sensing device can perform as well as traditional methods. Remote sensing at large distances (up to 1km) is proposed in Maslov et al. [11] with the use of shore based LIDAR mounted on a high structure. One concern with using LIDAR for ocean water measurements is the reflectivity of the water surface. However, particulate matter such as plankton, capillary waves on the water surface and foam can all increase the intensity of the return signal (Belmont [12]).

Commercial LIDAR instruments are available for applications such as manufacturing, military use and meteorology. A terrestrial laser scanner (in application 'terrestrial laser scanning'), or TLS, is a specialised instrument that is generally used for surveying purposes in mining and industrial fields. The high accuracy of TLS is useful for tasks such as volume estimates and post-construction surveys.

The main advantage of TLS over other LIDAR techniques is that it can provide extensive spatial data from a relatively compact and portable design. An initial feasibility study by Harry et al. [13] of commercially available TLS determined that it is possible to detect a water surface using the laser based instruments, however certain conditions such as appropriate surface reflectivity is required. The experiments detailed in this paper follow on from this feasibility study and focus on TLS for wave measurements.

2. Experiment setup

The experiments were carried out within the UNSW Water Research Laboratory's 1m wave flume. The flume is approximately 35m long, its width is 0.9m and its total depth is 1.4m. To produce breaking waves in the flume a sloping timber beach face (1:10 slope) was installed with the beach intersecting the water level at approximately 18m from the generator end. Therefore only half of the length of the wave flume was necessary. A water depth, h, of 1m was set for all runs. A Canadian Hydraulics Centre GEPDAP/NDAC general purpose software system is used to control the drive signal for the wave paddle. The wave generator is a paddle type hydraulic piston that moves laterally to produce both regular and irregular waves.

Four capacitance wave probes were used for the experiment to measure water surface elevation at specific points along the flume. Capacitance wave probe data was logged at with the GEDAP/NDAC system at a frequency of 120Hz. Figure 1 illustrates the general layout of the flume including placement of the capacitance probes and the TLS. The distances of each wave probe (WP1, WP2, WP3 and WP4) from the TLS are approximately 10.7m, 9.4m, 7.9m and 5.45m respectively.

The TLS used for wave measurements was a Leica ScanStation2 mounted above the flume so as to provide a clear view of the length of the flume. The TLS can record three-dimensional spatial data of targets within the specified line of sight. The TLS opto-mechanical design produces rapid changes in the vertical angle of the emitted laser pulses. This combined with a gradual rotation

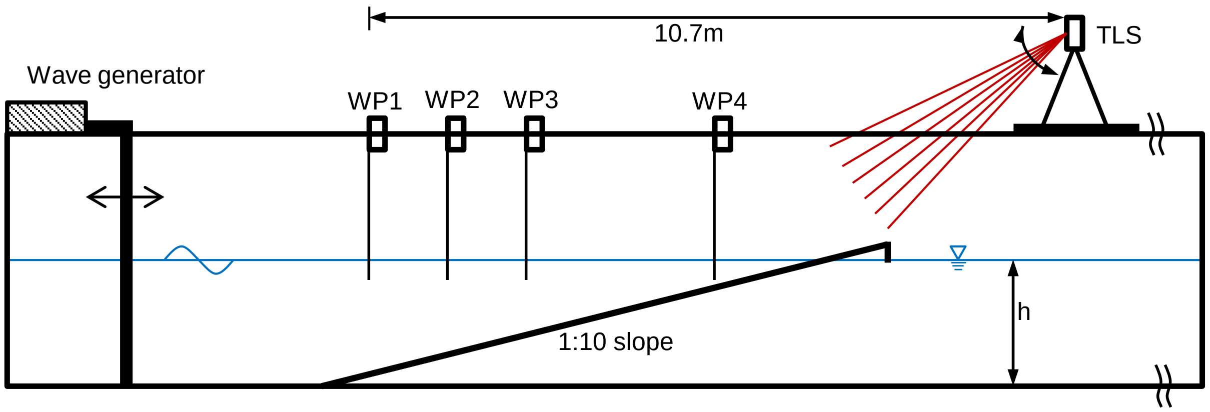

Figure 1 Diagram illustrating the experiment setup. The TLS is mounted above the wave flume to increase the visible water surface.

of the TLS unit in the horizontal plane allows a view of all targets surrounding the TLS. Spatial resolution was set at 5cm (H) x 1cm (V) @ 20m range. Therefore for locations toward the TLS the resolution increases.

Of significant note is the requirement of a particulate matter dispersed within the water or on the water surface. Initial test runs had confirmed that clear water is not a suitable medium for reflection of the laser pulses. Two methods were employed for preparing the water in the flume. The first is the use of kaolin forming clay dispersed throughout the water body which required regular stirring. The second is the combination of the kaolin forming clay and small foam balls (<2mm diameter) that remain on the water surface. It is assumed that this combination could represent a high energy surf zone (including significant white wash) in the field.

A mixture of regular and irregular waves was included in the experiment. Data for a total of 15 runs was obtained. Irregular waves use a JONSWAP spectrum to imitate a random sea state. Table 1 lists all 15 runs and their corresponding start conditions. Each run is approximately 11.5 seconds long.

3. Results

There are two important aspects of the results obtained with the TLS, validation against wave probe data and the application of the data as wave profiles for analysis. Prior to analysis of these results there was significant processing of the data for all of the runs.

The TLS records to what is called a point cloud which is a data set of coordinates in three dimensions of each laser pulse that is emitted and received by the scanner. The data obtained from the Leica instrument is first processed through Leica Cyclone software before a point cloud can be exported. Intensity of points is determined during a scan which allows real-time filtering to remove points outside a certain intensity range. For all scans carried out during the experiment, the intensity limits were automatically set by the software. Further processing was required in MATLAB to arrange the point cloud into separate vertical scan lines that travel the length of the flume. This is required as the Cyclone processing optimises the point cloud assuming that only static objects are to be scanned whereas for the experiment propagating waves are the target.

Table 1 Details of all runs

Run	H (m)	T (s)	Wave type	Water Status
1	0.3	2.02	Regular	clay
2	0.3	2.02	Regular	clay
3	0.3	2.02	Regular	clay
4	0.3	1.65	Regular	clay
5	0.3	1.65	Regular	clay
6	0.3	1.65	Regular	clay
7	0.3	1.65	Regular	clay
8	0.3	1.43	Regular	clay
9	0.3	1.43	Regular	clay
10	0.21	1.62	Irregular	clay
11	0.21	1.62	Irregular	clay
12	0.21	1.62	Irregular	clay
13	0.21	1.62	Irregular	clay
14	0.3	2.02	Regular	foam balls
15	0.3	2.02	Regular	foam balls

3.1 Validation

Validation of the point cloud against the capacitance wave probes was achieved by first separating individual scan lines (to produce wave profiles) and then extracting the scan data at the corresponding location of the four wave probes.

The frequency of the TLS to record each scan line depends of the selected viewing angle, however for all runs this remained constant to provide an average frequency of 3.5Hz. Due to the non-uniform spatial distribution of the scanned wave profiles the closest point along the x-axis, within 5cm of the wave probe location, was chosen for comparison at each time interval. Figure 2 shows the water elevation time series for Run 8. The water elevations are in relation to the still water level that was accurately determined based on an initial survey of the wave flume containing water and the kaolin forming clay.

There is good agreement of the scan data with most corresponding wave probe points. Data is lacking at on the back face of each wave as the shallow angle does not provide a strong enough return signal. The relatively low number of scans within each run period does not allow a comprehensive analysis of each run. In order to quantitatively determine the accuracy of the TLS the entire data set must be considered.

In Figure 3 the TLS elevation data at the four wave probe locations for all runs are plotted against their corresponding wave probe measurements. A total of 1346 data points are plotted. A linear regression analysis for this data results in a coefficient of determination (R^2) value of 0.7924. The average elevation difference between the TLS data and the wave probe data for all runs is approximately 0.9mm. It can be observed that there are a number of points that notably deviate away from agreement. This can be caused by obstruction to

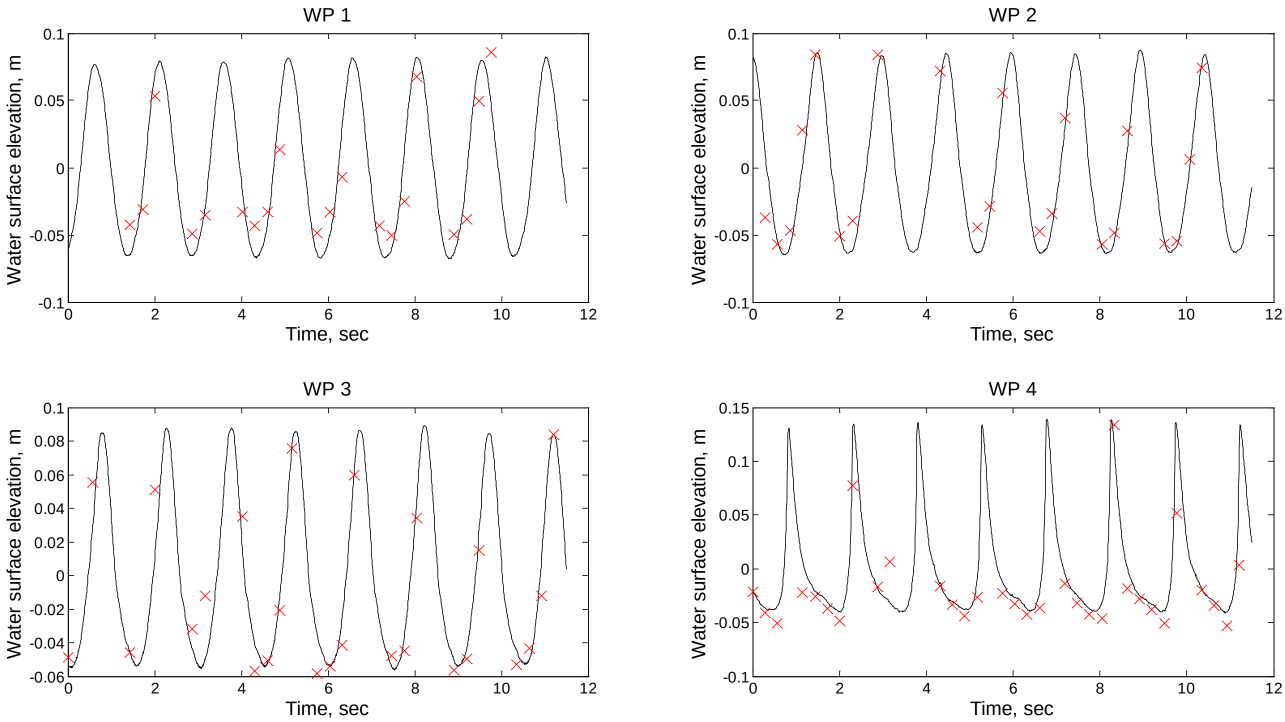

Figure 2 Comparison between wave probe data (solid line, -) and the corresponding TLS data (crosses, x) for Run 8.

the TLS line of sight by a wave probe or interference from the flume walls.

In Figure 3 it can also be observed that there is a greater concentration of data points at elevations below 0m. This can be attributed to the relatively large number of data points at WP4 (closest to scanner). There is good agreement between the TLS data wave probe data from the breaking point and towards the beach slope. This can be observed in Figure 2 for the WP4 comparison where there are a greater number of points gathered from the trough of the wave as opposed to the upper half of the wave face.

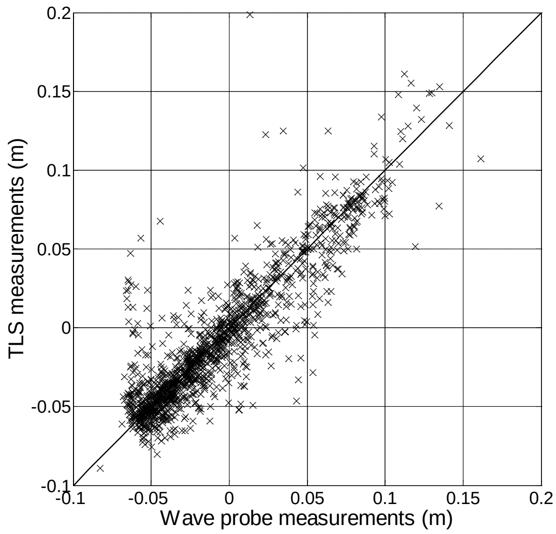

Figure 3 X-Y scatter plot of scanned points (all runs) against wave probe measurements.

3.2 Wave parameters and wave crest profile

To realise the full potential of TLS as a research tool for wave measurements, the focus needs to move away from analysis of one dimensional time series to the use of the entire data set within the spatial limits of the point cloud. As has been demonstrated in the previous section, the results for TLS measurements under experimental conditions can be relied upon.

The TLS measurements allow for not only the determination of basic wave parameters such at wave height and wave period, but also for the construction of the time evolution of wave profiles. A series of consecutive wave profiles can be measured for two-dimensional surface elevation motion analysis. For the experiments presented here, only qualitative observations are made due to the short run periods.

The data quality of a selection of measured wave profiles can be observed in Figure 4. The three profiles cover the range of tests types, in particular, regular waves with clay, irregular waves with clay and regular waves with foam balls. The profiles of clay water only demonstrate the effect of incidence angle of the laser pulse and the water surface. The front face of individual waves which are closer to perpendicular to the direction of the laser pulses are accurately measured, however acute angles such as the rear slope do not provide a return signal. Also there is no observed difference between regular or irregular wave data quality, although there is a possibility that smaller waves may be shadowed by larger waves blocking the line of sight.

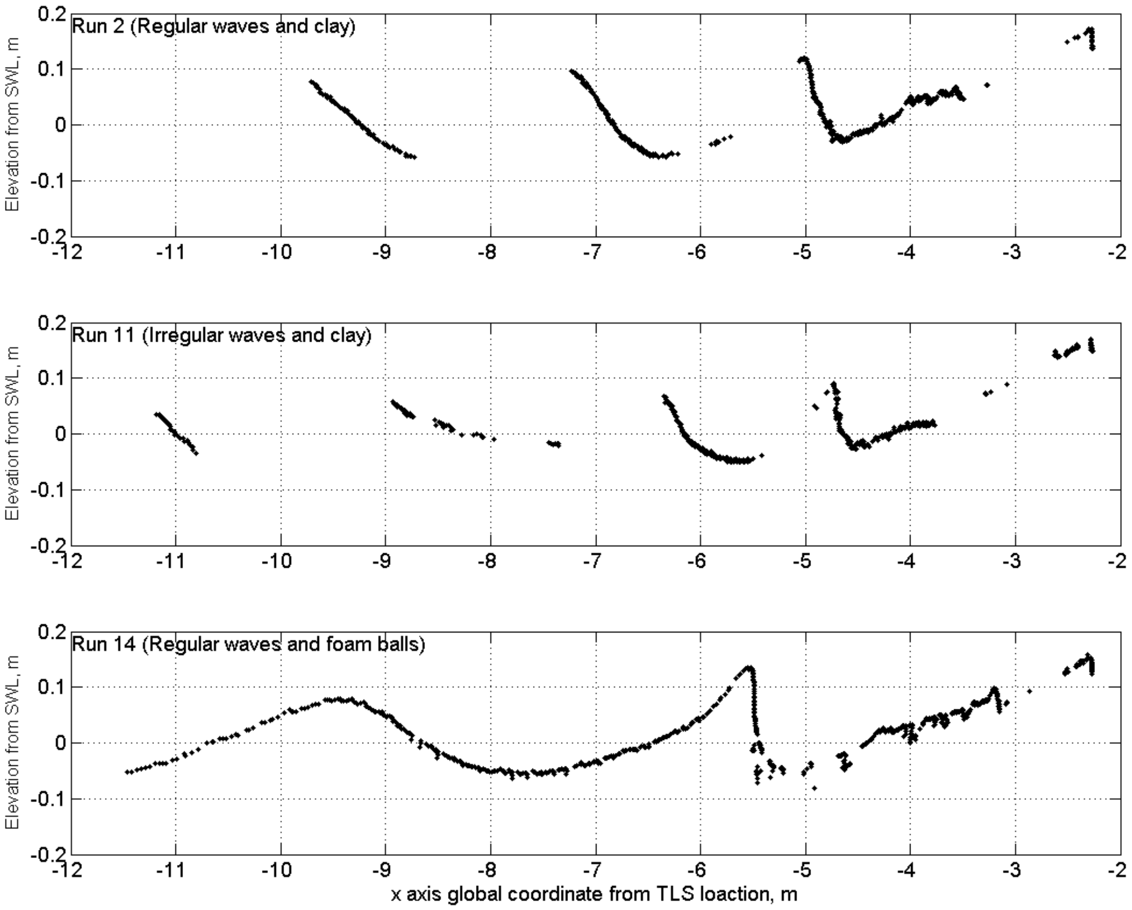

Figure 5 Spatial water surface profiles for Run 2, Run 11 and Run 14. Note that the wave conditions are given in Table 1

The third wave profile in Figure 4 shows the difference of a highly reflective surface, in this case white foam balls, compared to the conditions of the first two profiles. The third wave profile contains more data points that were within reflection intensity limits of the scanner allowing the measurement of a full wave profile rather than approximately half a wavelength of the clay conditions. However, for this experiment set up the use of foam balls for runs more than approximately 10 seconds is not recommended as they tend to build up due to the wave motion and expose the water surface.

Wave shape, wave steepness and breaking depth can be easily observed from these wave profiles, which traditionally can only be measured with specialised instruments. Furthermore, measuring these parameters is certainly more difficult to do in the field without this technology. This is perhaps the main advantage of TLS for wave measurements, the instrument can simplify what would traditionally be a difficult task to undertake in the laboratory and the field

In addition to time evolution wave profiles, the TLS data can also be processed to construct maximum wave crest profiles (or trough profiles). Figure 5 shows the maximum wave crest profile for Run 2 and its relation to the beach slope. The wave crest profile was determined by plotting the maximum data point within 0.5m interval, however this can

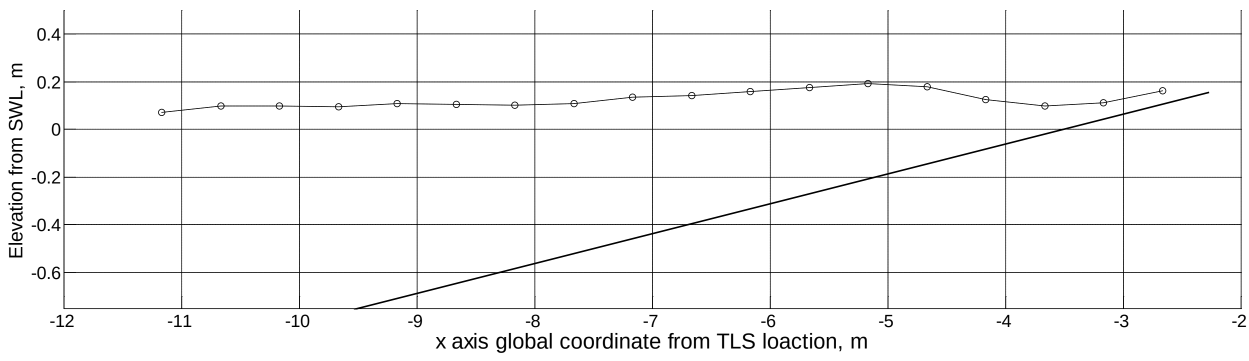

Figure 4 Maximum wave crest profile for Run 2 (dash line and circle) and beach slope (solid line)

be optimised with the use of a more suitable algorithm. It appears that the shoaling and setup are influencing the maximum wave crest profile and this would have to be confirmed in a more comprehensive study. Figure 5 also provides a clear indication of the breaking point.

4. Discussion

As the laser pulses emitted by the TLS require a target that exhibits diffuse reflection, the angle of incidence and the surface reflectivity need to be considered to ensure quality data is collected. This was tested by measuring the distance that the still water level was able to reflect the laser. At an incident angle of 15.5° and lower the water level could not be detected in the clay case. For the floating foam ball condition the minimum angle was at most 10.3°, however this was at the limit of foam ball coverage due to proximity to the wave paddle. It can be concluded that the minimum angle of incidence with a highly reflective surface is less than 10°. For field application this is a good result as there are generally only low instrument mounting positions on open beaches. It is would be preferable to set up in the field atop a sea wall or jetty for best performance.

In the experiment, each TLS run with the operation of the wave paddle had to be relatively short at approximately 11.5 seconds. This is due to the limitations of the ScanStation2 for time dependant data collection due to the scanner taking unexpected laser paths when processing a large number of data points in real-time. The main drawback of the Leica ScanStation2 is that there is no timestamp for each data point which would negate this problem. To synchronise the scan profiles and the wave probe data manual timekeeping of the scanner start and finish time was required.

As demonstrated in Figure 2 the scan data is not suited for creation of a time series of water elevation at one location due to the non-uniform distribution of points. To achieve this would require a much higher resolution, which is possible, however over large distances the point cloud would contain excess data that is not necessarily going to provide a significant gain. For construction of wave profiles however, the TLS performs very well and depending on the water surface conditions it can remotely sense profiles including the entire length of each wave.

5. Conclusions

The use of TLS for water wave measurement in wave flume experiments is a unique method that provides highly accurate spatial data, including that of a wave profile evolution. There is a great potential for comprehensive laboratory and field studies to develop the technology as a coastal engineering research tool.

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