IMAGING SPACE DEBRIS AND SMALL TARGETS
with Space-Based Radars and Dynamic Satellite Constellations – First Tests

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Space debris is causing steadily increasing risks but many objects are not identified, limiting the scope of removal missions. We propose a dynamic satellite constellation with multiple EM receivers and transmitters, enabling multi-aspect imaging of targets through bespoke signal processing (beam-steering, synthesis of virtual apertures and dynamic beamforming to create virtual pencil beams to interrogate volumes of interest). This adaptive and modular architecture is used to build the first experimental stage toward a scaled demonstrator, using different radar transceivers and adaptive processing of echoes from moving targets. The algorithms developed are intended to be used aboard satellite nodes, with potential distribution of the most demanding tasks amongst neighboring nodes. This laboratory work is supplemented with analyses of US and European orbital debris databases, to identify the LEO portions most at risk from collisions, and to match the expected orbits and velocities of debris with the detection capabilities of the satellite constellation (ranges, fields of view, reaction times afforded by different configurations). These calculations inform the types of radars needed (frequencies, powers), whether in space and part of the constellations, or ground-based and used as sources of opportunities. Orbital constraints are used to match the number of nodes in the dynamic constellations with their respective positions, depending on propulsion modes and other considerations (general situational awareness). Focused on Near-Earth application, this method can be adapted to other areas (e.g. space mining). This approach aims to make future missions more affordable, de-risking space activities, protecting assets and preparing for future regulations.

Keywords: Space debris, Satellite constellations, Adaptive imaging, Multistatic dynamic focusing

1 BACKGROUND

1.1. Space Debris

Access to space is increasing, along with the number and type of stakeholders, from national and international space agencies to corporations, universities and other entities. This results in an increasing density of assets in the most desirable orbits e.g. Low Earth Orbit (LEO) and Geostationary Orbit (GEO). As orbits overlap or drift, as space assets deteriorate or lose function and/or propulsion, the number of space debris has steadily increased over the last decade. In 2009, the hypervelocity collision between satellites Kosmos-2251 and Iridium 33 occurred in Low Earth Orbit. Initial NASA estimates of 1,000 pieces of debris larger than 10 cm, and many smaller ones, were updated with later cataloguing of > 2,000 debris large enough to be tracked from Earth. The intentional destruction by China of one of its own satellites in 2007 created > 2,000 large debris (as catalogued at the time) and an estimated 150,000 debris particles, a large portion of which was still in orbit 10 years later. Influential as it was, this was not an isolated case, as other countries had acted similarly in the past. In 2018 and earlier (for example 2016), cracks apparently caused by space debris affected the International Space Station, sometimes affecting the integrity of life-sustaining systems. ISO regulations [1] were designed to reduce the growth of space debris by ensuring that spacecraft and launch vehicle orbital stages are "designed, operated and disposed of in a manner that prevents them from generating debris throughout their orbital lifetime". But even successful launch of assets in space is not without challenges, creating debris ranging in size from spent propulsion stages to flakes of paint or bolts. Some will drift and be destroyed in the atmosphere, but others can stay in orbit for years or decades. These ever increasing numbers and densities will ultimately lead to what is known as the "Kessler effect" [2], with collisional cascading becoming frequent enough that access to space becomes problematic.

Current catalogues count more than 18,000 objects large enough to be tracked from the ground: these objects are mostly mapped from their radar cross-sections, with the inherent limitation that radar sensitivity drops below critical sizes or at higher altitudes [2]. Smaller debris (1 – 10 cm) are conservatively estimated to number 670,000 objects. The number of even smaller debris, still dangerous enough when impacting at very high velocities (> 7.5 km/s), is unknown but likely to be even larger. Regularly, ground telescopes discover other objects of varying sizes, up to full satellites [3]. There are new initiatives to better monitor space debris, although preliminary analyses showed they would still be physically limited through association with ground-based surveys [1, 4]. Furthermore, emerging technologies to dispose of space debris (e.g. *RemoveDEBRIS*

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from SSTL) will best work when provided with a map of debris showing more than their positions, but also their compositions (and hence potential dangers to other space activities: foam moving at a slow relative speed will for example be much less damaging than part of a satellite on a direct collision course).

1.2 Multistatic Imaging

The ideal approach to detecting and imaging space debris should therefore:

- Detect/image potential debris from as close as possible, i.e. in space and at altitudes commensurate with what is known or expected from these debris;
- Be able to identify objects from several angles, i.e. to minimise the effects of radar cross-sections varying with imaging angles (e.g. for tumbling objects);
- Be able to investigate large clouds with varying densities AND focus on objects smaller than the current resolution limit afforded by Earth-based radars.

Our patented approach therefore proposes [5] to use a collection of radar transducers acting as both EM transmitters and EM receivers (Fig. 1), imaging debris fields in 4 dimensions (space and time). For cost reasons, and for easier and faster deployment, this will rely on nanosatellites. This will also make post-mission disposal safer and easier, to avoid creating more debris. Starting from a "basic" configuration with transducers on both sides of a debris cloud, it is already possible to acquire both traditional backscatter measurements from individual objects or, varying signal beamwidth and duration, aggregate returns from the entire cloud or portions thereof. Future launches, or repositioning from nanosatellites in other swarms in the vicinity, can then add to the different multistatic points of view by growing the size of the complete constellation. Varying which satellite acts as a transmitter and which satellites act as receivers will allow varying these geometries, and define specific volumes at different times. This will give access to a full 4-D map of a debris field, useful to map its evolution, for example as it follows a particular orbit, is submitted to atmospheric drag or interacts with other clouds or larger objects (e.g. other satellites). As many of the debris are likely to be metallic or sensitive to solar radiation, their tumbling rates will also be affected by Yarkovsky–O'Keefe–Radzievskii–Paddack (YORP) effects, and this is a parameter of importance for future removal (and simulations of future behavior, e.g. using MASTER).

Each satellite can be accurately positioned, within the constellation and using global positioning networks (reaching to the altitudes envisaged). For both absolute and relative positioning, EM time-of-flight checks between nodes can also be used to refine positional information. Distributed processing between lighter "nodes" and larger satellites (with more processing power) can be used to focus on regions of particular interest. Beam steering focuses on diffractions, creating virtual pencil beams from which high-resolution imagery can be formed, yielding information on the sizes of individual targets and on their shapes (via multi-angle diffraction patterns).

2 FROM MISSION CONCEPT TO SCALED DEMONSTRATOR

2.1 Orbits of Interest

Databases such as DISCOS (*Database and Information System Characterising Objects in Space*) [8] contain information about the largest objects, and models such as MASTER (*Meteoroid and Space Debris Terrestrial Environment Reference)* [9] provide extremely useful information. In a first stage, they are used to define altitudes with the largest risks of collisions (Fig. 2). We aim to target the capability gaps of existing systems [10] in terms of altitudes and in terms of object sizes. The approach of uncontrolled targets for future removal requires extremely accurate knowledge of trajectories, rotation rates and general aspect (whole or fractured, single target or cluster). This will in particular be affected by orbit decay [11, 12] and atmospheric drag [13]. In a first instance, we will be investigating LEO space debris.

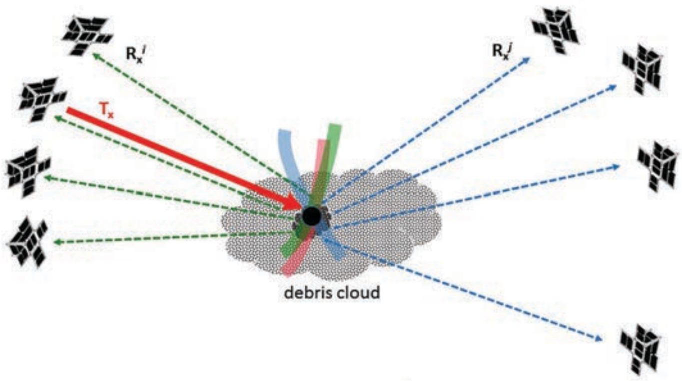

Fig.1 Satellite constellations enable imaging of targets or debris clouds with very distinct geometries. One satellite (T_x) is transmitting an EM wave (red), received by all other satellites (R_x) to provide a multistatic description of relevant parts of the debris cloud, using forward scattering (blue) and back scattering at a variety of angles (green). Satellites can switch between receive/transmit modes and some will have additional processing capabilities. Some will be used as additional imaging nodes, in the sequence and geometry most relevant to the current objective. Generic CubeSat design adapted from [6]. Whole figure adapted from [7]).

2.2 Dynamic Constellations

Analyses of actual collisional events (when backed with sufficient data) and collision avoidance maneuvers (e.g. 2010 Envisat satellite and upper stage rocket) show that, for objects with known and stable orbits, it is better to know risks at least half an orbit in advance. With average object velocities of 7 – 9 km/s, it means advance sweeping of orbits by the satellite constellation is preferable (Fig. 3, left). This "A-Train" approach can provide images up to several orbits ahead, as the volumetric image (hashed sphere) covers a range of altitudes above and below the intended orbit of the asset to protect.

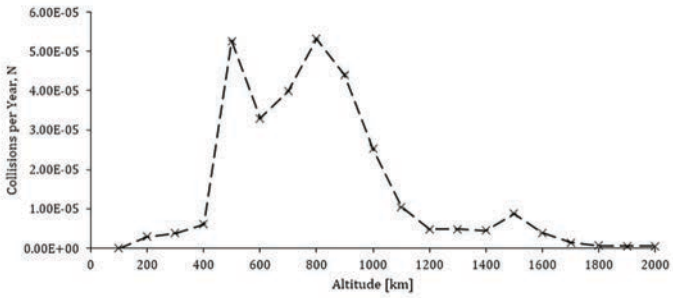

Fig.2 Collision risks peak at certain altitudes (analysis of the DISCOS and MASTER datasets by J. Hussein, U. Bath). These regions will be targeted for volumetric analyses with satellite constellations.

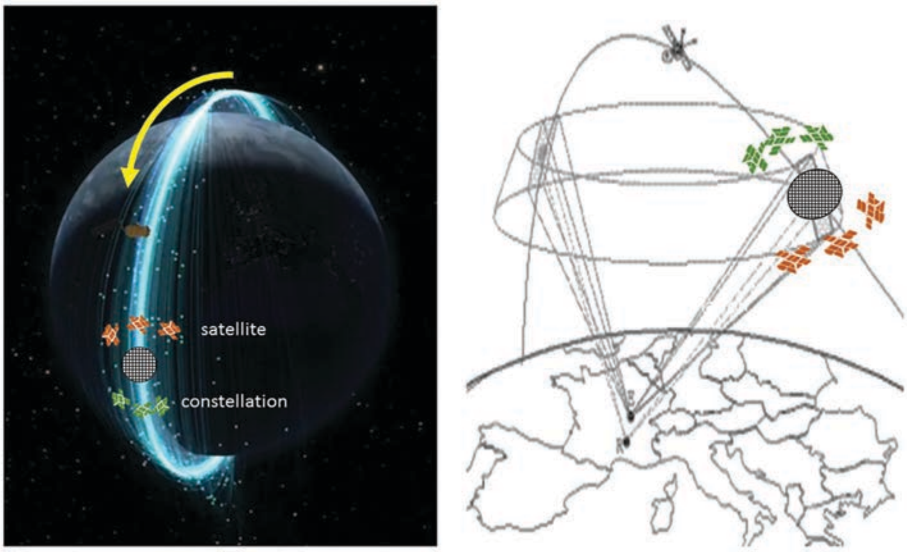

Fig.3 Left: "A-train"-style configuration: the constellation of satellites is sweeping up to several orbits ahead of the asset to protect, imaging a volume at different orbital altitudes and different lateral ranges. Background image: ESA (2013). Right: ground-based radars are powerful and can be used as "sources of opportunity", providing additional illumination of space targets. Background sketch adapted from [15].

How dynamic can the constellation be? This will depend on the altitudes (before and after reconfiguration), the sizes of the satellite nodes, and the types of propulsion. Preliminary calculations considered a range of traditional (chemical), electric, cold gas and steam propulsion, and simple Hohmann orbit transfers for CubeSat-like platforms. Depending on how the mission is implemented, and the possible mix of propulsion modes as more nodes are added to the constellations, these provide an envelope of possible configurations (and show which propulsion modes are best adapted for which portions of the constellation). Post-mission, safe de-orbiting of these satellites also needs to be accounted for in the propulsion budget, to avoid potentially creating more debris.

2.3 Radars – Powers and Ranges

Using a constellation of satellites adds constraints to the types of radars used, as their form factor needs to be compatible with the size of satellites (nano-satellites, in this case) and their operating power needs to match the power available at each node in the constellation, or even beamed from a larger node to a smaller node (e.g. with laser or microwave, although this option is still highly hypothetical). Existing radars are regularly supplemented with new designs, sometimes tailored to nano-satellites [14].

The generally smaller ranges and powers available directly in space make it more attractive to also consider powerful ground-based radars as "sources of opportunity". For example, the NORAD radar (USA) transmits at 6MW, the GRAVES radar (France) at 2MW and Fylingdales (UK) at 0.6MW. GRAVES operates at a frequency of 143 MHz, with an altitude range between 400 and 1,000 km [15]. The return scattering from space to Earth is affected again by the atmosphere, ionosphere and geometric spreading. Capturing their echoes on targets directly from space would allow larger detection ranges (in orbit), higher resolutions and, making use of multistatic geometries, more information about the actual targets. Moreover, because these radars are already operating continuously, they would not impact on the power budget of the space mission. The slight drawback that they are used to "fence" the space around a particular country or region means they cannot be used on a regular basis, but they can ideally supplement the smaller-scale radar imaging of the constellation (Fig. 3).

2.4 Scaled Demonstrator

The next stage is to put our volumetric imaging design [5] into practice and to identify the best multistatic imaging geometries from the high number of possibilities (incidence angles varying between 0° and 90°, scattering angles between -90° and +90°, bistatic angles between 0° and 180°). The underlying scientific concepts made use of scaled experiments followed by measurements at sea [16], simplifying the multitude of multistatic configurations to only a handful. The second issue is how best to highlight the returns of interest and build the array of transmitters and receivers whilst keeping the signal processing manageable and timely, and this can again use subsea experience [17, 18].

The scaled demonstrator is currently using 5 radar transceiver modules (RFbeam K-LC6-V2, transmitting at 24 GHz with a 250-MHz wide sweep FM input and a very small form factor of 66 × 25 × 6 mm). The transmit power is small (10 dB m), and the antenna gain equals 3 dB. A variety of test objects are used, with radar cross-sections of 1 cm^2 (small for the scaling down of this experiment), and velocities in the range of 14 m/s (again, in the interest of scaling, but also to simplify the first approaches at processing the data). Calibrations with full and hollow spheres have constrained the beam patterns, asymmetrical and wide in the X-Y plane (and narrow in the Y-Z plane). The transmitter is driven by a voltage controlled oscillator (VCO), which can be tuned from 24 GHz to 24.25 GHz. The same oscillator is used to IQ demodulate the return signal. The frequency chirp caused by object motion is used to infer ranges. Our approach relies on the general chirplet transform [19]. Generating multiple chirplet transforms over the parameter space allows the correct values to be estimated as those which best concentrate energy (related to the maximization of Renyi entropy). Best fits match actual parameters of target ranges and velocities, measured independently for single or multiple targets, moving toward or away from the imaging radars (Fig. 4).

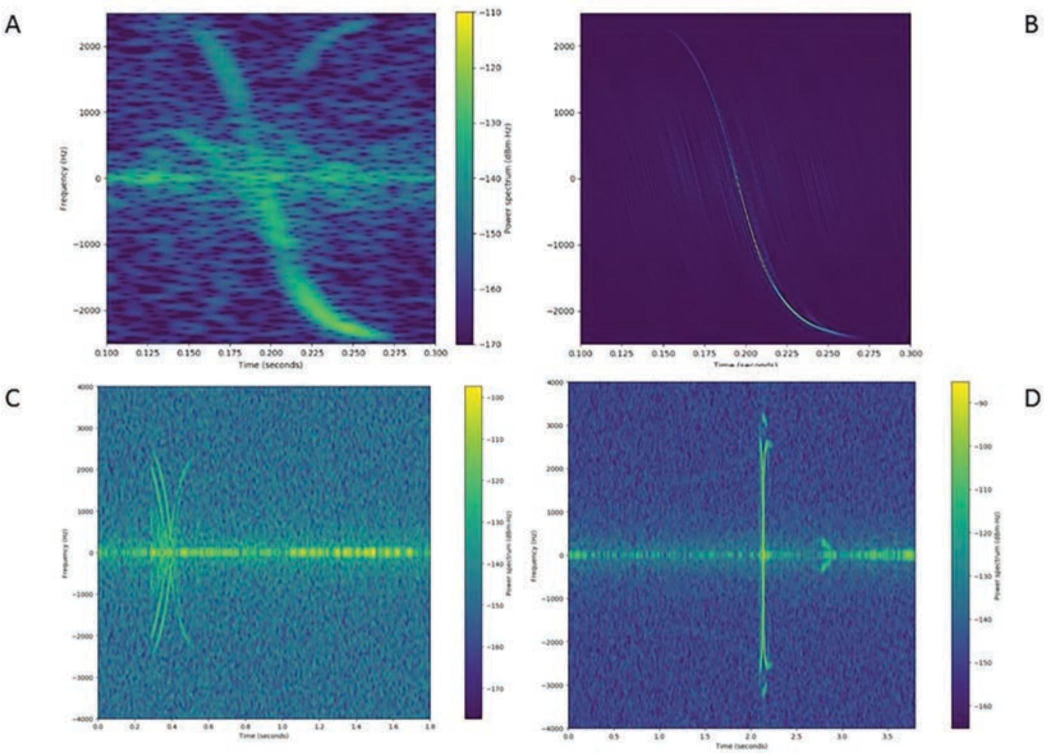

Fig.3 Measurements of different targets: (A) Short-Time Fourier Transform (STFT) plot of a single target at close range; (B) application of ridge detection and chirplet transform, showing improvement to target measurements; (C) STFT plot of a cluster of targets incoming along the same vector, before chirplet transform; (D) STFT plot of targets at cross trajectories (incoming and crossing), before chirplet transform and further improvements (by A. Perez de Bartolome and C. Mallet, U. Bath)

In their current stage, these experiments are now investigating different multistatic geometries, and how the final scaling parameters can fully represent the field conditions. Additional steps in signal processing are also used to increase the quality of scattering returns and the identification of targets (Fig. 4-B).

3 WAY FORWARD – CONCLUSIONS

Space debris are an increasing problem and, in the absence of large-scale clean-up, there are strong risks of a Kessler effect with collisional cascading and reduced access to specific orbits, in particular Low Earth. Recent developments in debris removal technologies need to be supported by adequate mapping of where space debris are, how dense particular clouds are, and estimates of the types and physical characteristics of individual targets (e.g. tumbling rates, materials, sizes). Earth-based detection is limited by the ranges and the electromagnetic responses of some targets, leading to large under-estimates of the numbers and positions of smaller targets.

Drawing on recent advances in underwater acoustics, we have designed an innovative approach using multistatic radar imaging from a dynamic constellation of satellites [5]. This enabling technology is adaptive, as the number of individual nodes can be adapted to suit operational requirements, from small groups to larger constellations. It is also dynamic as the virtual antenna they create can be changed very fast, either by repositioning them or only activating particular transmitters/receivers, making for responsive space missions. On-board data processing allows fast, distributed processing, making individual nodes more affordable, and the modular aspect allows growing constellations or re-deploying subsets as mission profiles evolve. Use of established techniques like beam steering, waveform inversion and synthetic aperture allow access to information about large volumes, like debris clouds, and details of the smaller targets.

Backed by the on-going experiments, the field demonstration of the benefits from physically decoupled transmitters and receivers can be achieved with a low-cost, low-profile constellation of nanosatellites in Earth orbit. Tentatively named MANTIS (for "Multi-Aspect Network for Target Imaging in Space"), this approach provides a generic mission concept, which can be refined depending on the exact operational objectives and the partners involved.

This approach is not limited to space debris, and once operational, it can be adapted to monitoring of asteroid fields, planetary rings (e.g. future missions to Saturn) and to assist in future asteroid mining operations [20]. In the same way that multistatic imaging of targets at sea (and below the seabed) has developed disruptive technologies [17, 18], the extension of scaled demonstrations of multistatic radar imaging of rapidly moving targets to space will provide a low-cost, modular approach to detecting and monitoring space debris on the path of important assets.

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