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Imaging large fields of small targets with shaped EM fields, adaptive beam steering and dynamic constellation antennas

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ABSTRACT

Space debris is an increasing problem, with ca. 18,000 objects large enough to be tracked from the ground and conservative estimates of 670,000 small (1 – 10 cm) debris. Collisions have become a key issue in operation and decommissioning of spacecraft, adding costs and risks to space missions in all orbits, with the added threat of collisional cascading if some debris fields become dense enough. Their accurate mapping in 3-D, and their evolution with time, therefore become paramount, but in-flight approaches are constrained by limited fields of view and limited spatial resolutions. The shapes of debris are of interest as it might affect long-term movements, and the larger ones will be of interest for retrieval missions and in the emerging field of debris exploitation. Leveraging on developments in acoustic imaging of complex subsea targets (e.g. Guigné, 1986; Blondel and Caiti, 2006; Guigné and Blondel, 2017), we propose an approach based on a collection of transducers acting as both EM transmitters and EM receivers, imaging debris fields in 4 dimensions (space and time) and using techniques such as beam steering and waveform inversion to retrieve as much information as possible on their shape and size distributions. Accurately located nanosatellites (as a constellation or in very small swarms) are positioned dynamically to image a particular volume in space. Individual sources are repeatedly actuated, with the other nanosatellites in the swarm acting as receivers. This gives access to a potentially large series of multistatic scattering measurements of any target. These are processed in real-time within each node, reducing the overall computation burden. The first result is a volumetric image of debris within the field of view aggregated from all nodes. Beam steering focuses on diffractions, creating virtual pencil beams from which high-resolution imagery can be formed, yielding information on sizes of individual targets and on shapes (via multi-angle diffraction patterns). This requires accurate positioning of the individual transducer nodes (nanosatellites), achievable using global positioning networks and EM time-of-flight checks between nodes. By varying the relative positions of nodes in the swarm, it is also possible to adapt the focusing to regions of particular interest. By using several nodes as transmitters, positive/destructive interference between sources can also be used to induce high signals in places of interest and null signals in other places (for example to avoid interference with or detection by instruments within the field of view). This enabling technology is adaptive, as the number of individual nodes can be adapted to suit operational requirements, from small groups to larger constellations of nanosatellites. 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 allow growing constellations or re-deploying subsets as mission profiles evolve. Beyond Earth orbit, this approach can also be used to map planetary environments and assist future asteroid mining operations.

KEYWORDS: space debris – satellite constellation – adaptive imaging – multistatic – dynamic focusing

RATIONALE

Space Debris

Access to space is increasing, along with the number and type of stakeholders, from national or international space agencies to corporations, universities and other entities. This results in an increasing density of assets in the most desirable orbits, for example Low Earth Orbit (LEO) and Geostationary Orbit (GEO). As orbits overlap or drift, this has resulted already in close to a dozen high-speed collisions between artificial satellites, most of which were only noticed afterwards, often because of performance loss or degradation. For example, the 2009 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 (for example the US in 1985).

The simple launch of assets in space is not without challenges either, creating debris ranging in size from spent propulsion stages to flakes of paint or bolts. Activities in space can also create additional debris, from lost tool boxes to smaller objects. Some of these objects will drift and be destroyed during atmospheric re-entry, but others can stay in orbit for years or decades. 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, and radar sensitivity drops below critical sizes or at higher altitudes[1]. Smaller debris (1 – 10 cm) are estimated conservatively 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. There are new initiatives to better monitor space debris, although preliminary analyses showed they would still be limited by physical limitations associated to ground-based surveys[2].

These ever increasing numbers and densities will ultimately lead to what is known as the “Kessler effect”[1], with collisional cascading becoming frequent enough that access to space becomes problematic (Figure 1). This was flagged up already in 1978, but no concerted effort has been made so far to remove space debris. Analyses of removal effectiveness and interplay between spatial stakeholders[3,4] show persuasively that there is less incentive for any entity to start removing debris as long as the removal costs remain high. Technology innovative solutions are now being proposed to remove debris, and some are tested in Low Earth Orbit with varying success. But they rely on accurate information about where space debris are, and what sizes/types of objects need to be considered.

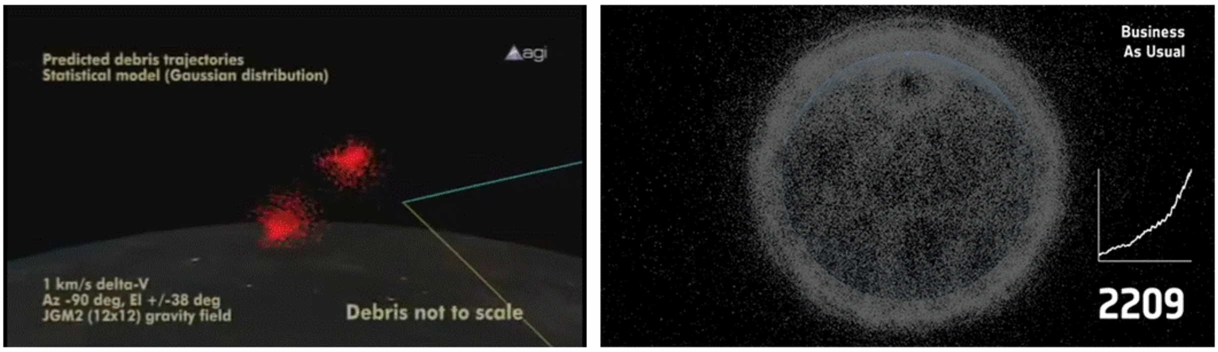

Figure 1. Left: the large quantity of debris generated by satellite collisions (in this case, the 2009 Kosmos-Iridium collision) will travel at high speeds along different vectors. Right: in a “business as usual” scenario where space debris are not removed, the density of objects increases rapidly and makes access to space increasingly risky and expensive. Image credits: (left) https://www.youtube.com/watch?v=4qSrdtFzeOE; (right) http://www.esa.int/Our_Activities/Operations/Space_Debris/Analysis_and_prediction.

Databases such as DISCOS (*Database and Information System Characterising Objects in Space*, https://discosweb.esoc.esa.int/web/guest) contain information about the largest objects, and models such as MASTER (*Meteoroid and Space Debris Terrestrial Environment Reference*, https://sdup.esoc.esa.int/web/csdtf) provide extremely useful information. But they are restricted to objects large enough to have been catalogued.

Recently created objects, or objects not entered into the catalogue, will be missed, with potentially dramatic consequences. Objects already mapped, or soon to be mapped, are usually identified from their radar cross-section; if their backscatter is not large enough, they might be missed or misidentified. Imaging them from different angles should therefore provide more information about their exact natures. Already in 1978, it was pointed out[1] that radar sensitivity drops importantly as objects get beyond a critical size and/or higher altitudes. Ideally, radar imaging should therefore be conducted from closer, i.e. orbits similar or neighboring the debris. Finally, if debris clouds are dense enough, it is difficult to estimate the numbers, locations and types of objects within the cloud if looking along a single line-of-sight, as commonly used in backscatter radar applications.

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.

Parallels with Underwater Acoustics

The challenges and solutions of remote sensing rely on the applications of wave propagation and scattering, and there are therefore interesting analogies to make between the neighboring fields of electromagnetic (EM) scattering and acoustic scattering. The distinction between extended targets (appearing as a rather continuous surface) and point targets (appearing as individual scatterers) is geometrically delimited by the characteristics of the imaging device (beamwidth and signal duration). Electromagnetic waves interacting with an extended target will be influenced[4] by the orientation relative to the imaging line-of-sight, the micro-scale roughness of its surface at scales similar to the imaging wavelength, and its actual composition, leading to different extents of surface vs. volume scattering (Figure 2). Point targets will be detectable if they scatter enough energy back to the imaging radar and if their response is sufficiently distinct from the background. The same physical processes are at play in underwater acoustics[5], and they can be used in similar ways.

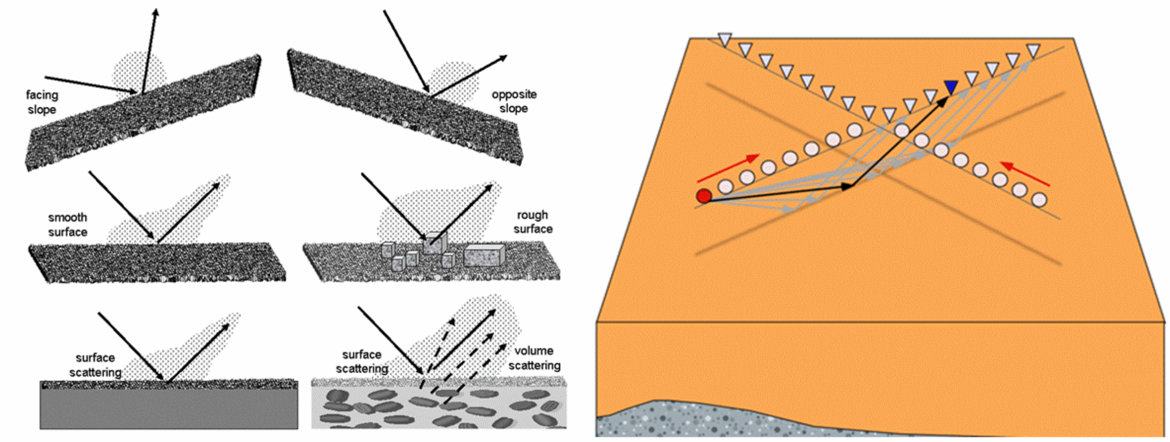

Figure 2. Target scattering will be strongly influenced by its orientation relative to the imaging beam, its roughness at scales comparable with the imaging wavelength, and its actual composition, more favorable to surface or to volume scattering (left: from [6]). It makes therefore sense to image targets from different angles, measure their scattering using a variety of geometries, and investigate both scattering and diffraction; this is the approach used in high-resolution seabed investigations, using the JYG-cross (right: from [7]).

Sonar imaging uses high frequencies, with broad or narrow beams, to measure the backscattering from extended targets, e.g. the seabed or a shoal of fish, of from point targets, e.g. rocks or mine-like objects against cluttered backgrounds[6]. Targets facing away from the sonar will deflect sound waves away from the backscatter direction, and multistatic sonars are used to get more accurate detection and monitoring of the target properties, be they roughness or volume scattering[8]. Measuring the scattering where it is larger, or provides the most information, results in "multistatic" geometries, in which the transmitter(s) and receiver(s) are physically decoupled. The key to successful surveying lies in identifying the best transducer configurations, adapted to the types of targets, and this can be done with simulations or, better, with scaled laboratory experiments[9]. Conversely, sub-seabed imaging needs to use lower frequencies, as they are less attenuated by the seabed. Diffraction by point targets and seabed discontinuities large enough to be detected by backscattered waves will yield distinctive returns, but once again, use of multistatic geometries is essential to differentiate between close targets and to make the most of the scattered signal. Figure 2 (right) shows the patented JYG-cross geometry[10,11], in which sound waves are directed toward targets and discontinuities of interest, and their scattering is recorded at a multiplicity of receivers along and away from the line of sight. Refined over several decades of use in a variety of marine environments, this approach to sub-seabed investigation[7,11] mixes low- and high-frequency signals, using techniques such as beamforming, beam steering and synthetic-aperture rendering to detect very small objects in large volumes (typically several orders of magnitude larger. Could this combination of approaches be of use to the detection and identification of space debris?

MULTISTATIC IMAGING OF DEBRIS FIELDS

Dynamic Constellations

Bistatic radars have already been used in space, flying along pre-determined orbits, and from Earth, from fixed locations[12]. Multistatic radars are also increasingly coming to the fore. Earlier, we had identified the need to image potential debris from as close as possible, i.e. in space and from neighboring orbits. We propose therefore[13] to use a collection of transducers acting as both EM transmitters and EM receivers (Figure 3), imaging debris fields in 4 dimensions (space and time). For cost reasons, and for easier and faster deployment, this will rely on nanosatellites. 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).

Accurate positioning of each satellite in the constellation is important, and this can be achieved using global positioning networks, either for each satellite individually or, if limited by processing/hardware, by absolute positioning of key "nodes" in the satellite constellation and relative positioning of the other satellites respective to these nodes. The distinction between "nodes" and lighter satellites, with less processing power or less hardware, is not an obstacle to dynamic reconfiguration of these constellations, as laboratory experiments with up to 1,000 robots[14] show it is possible to optimize the positioning of individual elements in noisy environments despite sparse situational awareness. For both absolute and relative positioning, EM time-of-flight checks between nodes can also be used to refine positional information.

Distributed Processing

Measurements acquired by each satellite are processed in real-time within each node, reducing the overall computation burden. The first result[13] is a volumetric image of debris within the field of view aggregated from all nodes (Figure 4, left). By varying the relative positions of nodes in the swarm, or which nodes are transmitting and which nodes are receiving, it is also possible to adapt the focusing to 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).

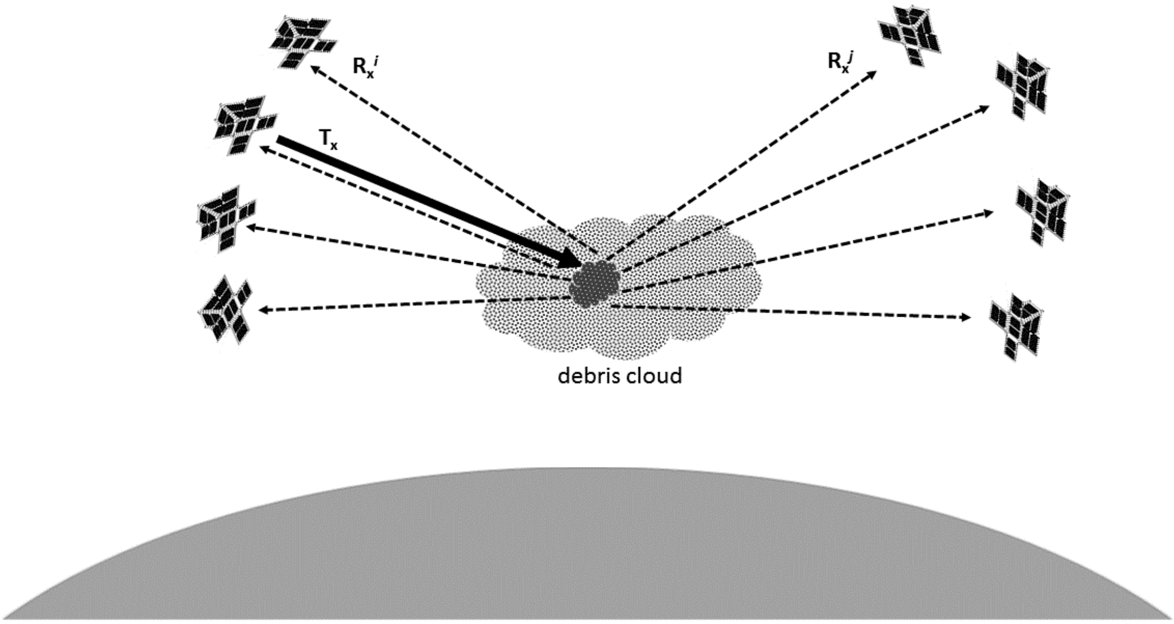

Figure 3. One of the many constellation geometries used to detect/image debris clouds. One satellite (T_x) is transmitting an EM wave, received by all other satellites (R_x) to provide a multistatic description of relevant parts of the debris cloud. Satellites can switch between receive/transmit modes and some will have additional processing capabilities. Generic CubeSat design adapted from http://aprs.org/psat/cube-hinge2.GIF.

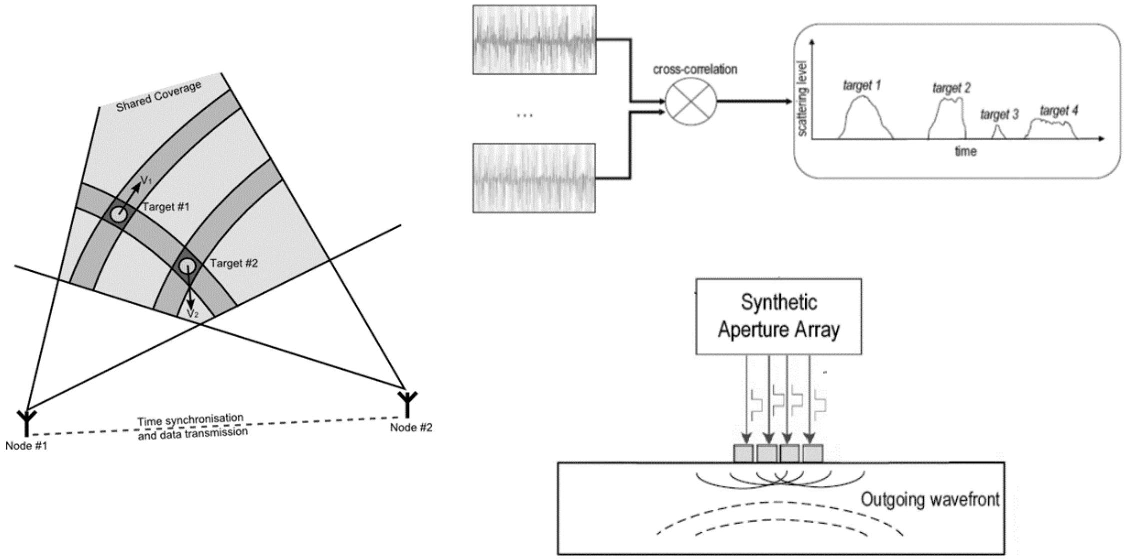

Figure 4. Left: use of multistatic geometries enables accurate location of individual volumes, shown here for 2 transducers (from https://en.wikipedia.org/wiki/Multistatic_radar#/media/File:Multistatic_resolution.png, Creative Commons Attribution 3.0 Unported license). Right: on-board processing allows the separation of individual targets and accurate positioning of individual transducers can be used for synthetic aperture processing (both sketches by the authors, UK Patent Application #1705641.7, 2017).

As the transmitter(s) and receivers within the constellation are accurately positioned with respect to each other, it is possible to use additional techniques[13], e.g. cross-correlation between suitably time-delayed signals to distinguish close targets (Figure 4, top right). In specific configurations, either by design or by dynamic adjustment of individual positions, it is also possible to create virtual antennas[13], adding synthetic-aperture for high-resolution imaging of individual targets.

The accurate positioning, relative or absolute, of all satellites in the constellation, can be used to synchronize their respective clocks, for example to the key "node(s)". The dual use of most (or all) satellites as transmitters and receivers can then be built upon to transmit synchronized signals and, through constructive/destructive interference[13], induce higher signals in places of interest (for example to image difficult targets) or to create local nulls in specific regions of space (for example to avoid interfering with another satellite's instruments, or to avoid detection of debris imaging activities by third-parties).

By modulating signals and frequencies[13], it is also possible to vary the exact ranges of the near-field and far-field, to favor the detection of larger regions with debris or to focus in smaller volumes associated with targets of interest. As target scattering will vary between near-field and far-field, iterative focusing makes it possible to garner more information, aiding in their identification or in the measurement of specific properties such as their relative velocities and multi-frequency responses.

As a last consideration, one might query whether the introduction of this type of constellation actually contribute to the problem by later adding defunct nanosatellites to the general space debris. This is a valid question[15], but this can be mitigated at the design stage (e.g. by adhering to NASA guidelines for debris reduction) and at decommissioning stage, for example through rapid de-orbiting[16]. The constant communication between nodes in the constellation would rapidly identify those most at risk, and appropriate mitigation strategies can then be put in place

CONCLUSION

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 Orbits and Geostationary Orbits. 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, this article aims to show how multistatic geometries, with physically decoupled transmitters and receivers, can be achieved with a low-cost, low-profile constellation of nanosatellites in Earth orbit. 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.

This approach is not limited to space debris, and once operational, it can also be adapted to monitoring of asteroid fields, planetary rings (e.g. for future exploration missions to Saturn) and to assist in future asteroid mining operations[17].

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