DANTE: A Spaceborne Radar Constellation for Debris Detection and Tracking

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Abstract— **The growth of active objects as well as space debris in Low Earth Orbit (LEO) is increasing collision risk and challenging the sustainability of space operations, while current ground-based radars remain limited in sensitivity, coverage and update rates especially for small objects. This paper presents DANTE (Detection ANd Tracking of space dEbris), a spaceborne radar constellation concept designed to enhance debris detection, tracking and orbit refinement directly from LEO. DANTE employs multiple low-cost satellites equipped with X-band phased-array radars operating in two modes: a Tracking Mode for trajectory refinement of known objects and a Beam-Park/Electronic Fence Mode for debris discovery. Performance analyses indicate sub-meter resolution in tracking mode and effective detection of small debris in discovery mode. The mission study shows that a scalable multi-ring constellation can achieve global debris coverage. DANTE offers a viable path to improving space situational awareness in congested orbital environments leveraging on smallsat SAR heritage and a design-to-cost approach.**

Keywords— ***Space debris, Space Situational Awareness (SSA), Spaceborne radar, LEO congestion, Debris detection and tracking, Radar constellation, X-band phased-array radar, Coherent tracking, Electronic fence, Small satellite systems***

I. INTRODUCTION

Low Earth Orbit (LEO) has become increasingly congested due to the rapid growth of space activities such as the deployment of large commercial constellations and the cumulative effects of space objects fragmentation events. Over 20,000 trackable objects larger than approximately 10 cm are currently catalogued while the population of smaller debris is estimated to exceed millions of fragments capable of causing damage at orbital velocities exceeding 7–10 km/s [1]. The continued growth of these populations significantly increases the probability of collisions, raising concerns about mission safety, operational costs and the long-term sustainability of the near-Earth space environment.

Several studies have shown that collision risk in LEO is no longer dominated solely by operational satellites but increasingly by debris-debris and debris-satellite interactions. This is particularly relevant within densely populated orbital shells between 500 km and 1,100 km altitude [2]. Accurate knowledge of debris orbits is central to collision avoidance and space situational awareness (SSA). At present, SSA capabilities rely primarily on ground-based radar and optical sensors operated by national space surveillance networks but also commercial suppliers. While advanced ground radars can statistically observe debris down to millimeter scale, routine tracking and catalog maintenance remain limited to objects on the order of several centimeters or larger [3]. Moreover, ground-based systems suffer from intrinsic limitations, including geographic coverage gaps, susceptibility to ionospheric/atmospheric effects and limited revisit frequency for individual objects [4].

Public orbital debris data are usually provided as Two-Line Element (TLE) sets but their accuracy limits how well potential collisions can be predicted [5]. Studies show that for objects in LEO, position errors from TLE-based orbit propagation typically grow significantly on a daily basis, depending on how often the TLEs are updated and how well atmospheric drag is modeled [6][7].More advanced orbit determination methods, such as fitting multiple observations or using laser ranging, can improve accuracy, but these techniques are not available for most debris objects [8].

To address these limitations, space-based sensing architectures have gained increasing attention as a complement to ground-based assets. Operating above the atmosphere, spaceborne sensors offer persistent coverage, reduced propagation errors, and the ability to observe debris independently of ground station geometry In particular, space-based radar systems have been identified as a promising approach for detecting and characterizing debris populations that remain below the routine sensitivity threshold of terrestrial radars [9][10]. Early concept studies have demonstrated that in-orbit radar measurements could significantly improve knowledge of debris spatial density and orbital element distributions, especially for small-size debris in critical altitude bands [10].

This paper introduces DANTE (Detection ANd Tracking of space dEbris), a spaceborne radar constellation concept designed to enhance debris detection and trajectory refinement in LEO. DANTE aims to close persistent observation gaps in current SSA systems and provide timely, high-fidelity orbital information in increasingly congested orbital environments. The paper is organized as follows. Section II outlines the current space debris environment and the limitations of existing monitoring approaches. Section III introduces the DANTE system concept and mission design. Section IV describes the radar payload, operating modes, and performance; and Section V concludes the paper with a summary of results and future perspectives.

II. SPACE DEBRIS ENVIRONMENT AND MONITORING LIMITATIONS

Observational data indicate that the majority of space debris objects are concentrated in Low Earth Orbit (LEO), particularly at altitudes between approximately 500 km and

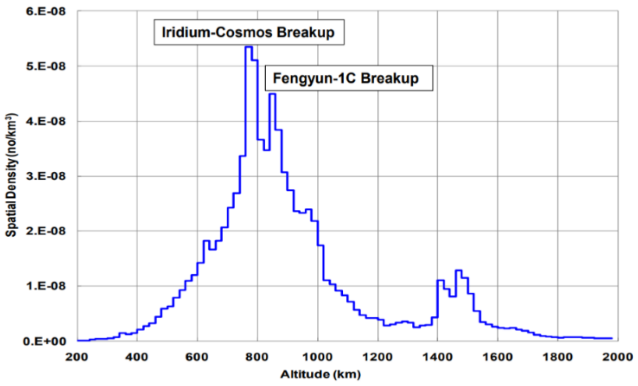


Fig. 1. Satellite distribution in Low Earth Orbit [14].

1,100 km (see Fig.1). Within this region, distinct inclination clusters are observed around 53°, 80°, 90°, and 98–100°, reflecting both historical launch practices and the orbital choices of modern satellite systems [11][12]. These altitude–inclination bands coincide with heavily used orbital shells for large commercial constellations and Earth observation missions, resulting in a high spatial density of objects and, consequently, an elevated probability of collision events. Databases such as ESA's DISCOSweb [13] provide a comprehensive catalogue of trackable space objects, including active payloads, defunct satellites, rocket bodies, and fragmentation debris, amounting to more than 40,000 recorded entries. Despite their breadth, these catalogues remain inherently incomplete. Routine tracking is generally limited to objects larger than a few centimeters, leaving a substantial population of smaller yet potentially hazardous debris undetected. In addition, update rates for debris Two-Line Elements (TLEs) typically range from one to four days in addition to several hours of latency. Over these timescales, orbital perturbations - most notably atmospheric drag - can introduce kilometer-scale position uncertainties, which degrade conjunction assessment accuracy and limit the effectiveness of collision avoidance strategies.

Ground-based radars form the backbone of current space surveillance networks, yet they suffer from several structural limitations:

- Detection sensitivity: objects smaller than approximately 5–10 cm are difficult to detect reliably depending on altitude and radar power.
- Coverage gaps: large portions of the Earth's surface, particularly oceans and the southern hemisphere, remain poorly covered while accessible sensors are geographically clustered.
- Atmospheric effects: ionospheric disturbances and weather can degrade signal quality and detection reliability.
- Scale and cost: high-performance radar installations require large infrastructures and substantial operational budgets.

As a result, current systems provide an incomplete and often outdated picture of the debris environment, particularly in the most congested orbital shells.

III. DANTE RADAR SYSTEM CONCEPT AND MISSION DESIGN

DANTE is conceived as a constellation of small satellites operating in Low Earth Orbit (LEO), each equipped with a compact X-band radar and oriented to observe debris objects upwards, i.e., at higher altitudes relative to the sensing satellite. This observation geometry is particularly effective for monitoring the most densely populated debris regions in LEO, while simultaneously minimizing interference and clutter originating from the Earth's surface. The overall constellation architecture and observation geometry are illustrated in Fig. 2, which highlights the multi-ring deployment concept and the relative geometry between the spaceborne radars and the debris population.

The system architecture is driven by three main design principles:

- Scalability, enabling progressive performance improvement through incremental growth of the constellation;
- Affordability, achieved through a design-to-cost philosophy and the use of heritage technologies derived from micro-SAR radar systems;
- Global coverage, obtained through orbital geometry and constellation configuration rather than reliance on geographically clustered ground-based infrastructure.

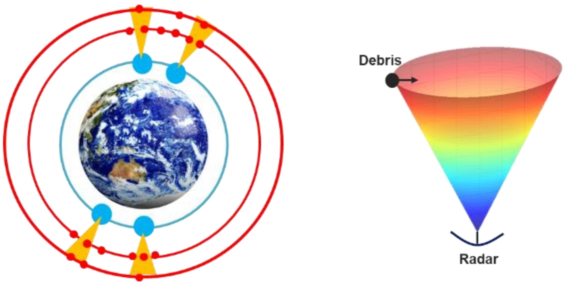
Each DANTE satellite operates in a near-polar (≈ 90° inclination) circular orbit, with initial altitudes starting at approximately 500 km.

This orbital choice is motivated by several considerations. First, a polar orbit lies between the main debris inclination clusters, enabling effective observation of both mid- and high-inclination debris populations. Second, a perfectly polar orbit experiences negligible nodal precession, which allows the system to exploit the natural J2-driven precession of debris orbits. As a result, debris objects with different right ascension of the ascending node (RAAN) progressively drift into intersections with the sensing satellite's orbital plane. This mechanism ensures that debris in the most populated altitude bands can be observed within approximately one year, independently of their initial RAAN.

To extend coverage to higher debris altitudes while respecting the maximum radar detection range, the architecture foresees the deployment of multiple orbital "rings" at different altitudes, for example at 500 km, 650 km, and 750 km, with each ring hosting a subset of the constellation.

The coverage performance of the DANTE system is primarily determined by the relative orbital geometry between the sensing satellites and the debris population, as well as by radar field of view, detection range and the total number of satellites. Assuming circular orbits for both debris and sensing platforms, detections occur predominantly at the intersections of the two orbital planes. Differences in mean motion between debris and shield satellites ensure that, over time, all true anomalies of a given debris orbit are sampled.

A near-polar inclination is key to achieving global coverage. While the shield satellites remain fixed in RAAN, debris objects at different altitudes and inclinations undergo continuous nodal precession. Debris orbits that are initially poorly aligned progressively drift to intersect the shield plane near the equator, where relative geometry is favorable for



(a) (b)

Fig. 2. (a) Schematic representation of the DANTE constellation architecture based on multiple orbital rings. Blue dots denote spaceborne radar platforms for debris detection and tracking while red dots represent debris objects. (b) Illustration of the radar field of view and relative debris motion.

observation. Mission analyses confirm that this effect enables observation of all debris in the most populated altitude and inclination bands within approximately one year.

Coverage simulations assume a radar beamwidth of 5° and an opposite, upward-looking nadir-pointing geometry. Under these assumptions, the time required to observe a complete debris population depends on both the number of satellites deployed along a single orbital ring and the orbit altitude. Higher altitudes benefit from a larger instantaneous field of view, which reduces the time required to achieve full-sky coverage. Lower altitudes, while hosting denser debris populations, require longer accumulation times to reach equivalent completeness. Parametric analyses show that increasing the number of satellites distributed along the same orbital ring significantly reduces the time required for full-sky debris observation. A configuration with approximately 200 satellites uniformly spaced along a single ring achieves full debris sky coverage in roughly 15 days. However, such a configuration implies a large constellation size. A more pragmatic solution limits the total number of satellites to approximately 100 and distributes them across multiple orbital rings. In a representative configuration, 33 satellites are allocated to each of three altitude rings. In this case, full-sky coverage is achieved in approximately 90 days per ring. By combining observations from multiple rings at different altitudes, the system can effectively monitor debris populations across the most congested regions of LEO while remaining within the radar's maximum detection range of approximately 100 km.

Overall, the coverage analysis demonstrates that the DANTE architecture is inherently scalable. Faster revisit times and more frequent catalogue updates can be achieved by increasing constellation size, while smaller configurations still provide meaningful global coverage on longer timescales. This flexibility allows the system design to be adapted to mission objectives, cost constraints, and evolving space situational awareness requirements.

TABLE I. DANTE OBSERVATION MODES

Mode	Description	Use Case
Tracking	Follows individual debris	High-res tracking & ISAR imaging
Beam-Park	Fixed stare, logs passing objects	Population statistics, quick detection
Electronic Fence	Detects debris crossing a virtual plane	Real-time warning for collision zones
Mixed	Switches between modes for flexibility	Balanced tracking and searching

IV. RADAR PAYLOAD DESIGN, OPERATING MODES AND PERFORMANCE

The DANTE payload is a very compact X-band phased-array radar optimized for mid-range operations, with a maximum detection range of approximately 100–120 km. Key design parameters include:

- Operating frequency: 9.6 GHz
- Transmit power: ~800 W (29 dBW)
- Antenna gain: ~36 dBi
- Bandwidth: 400 MHz
- Noise figure: ~3 dB

The electronic subsystem is very compact and has an envelope of 6 dm^3 and a mass of less than 6 kg.

The antenna subsystem is based on a planar active phased-array architecture. The array consists of 20 tiles arranged in a 5 × 4 configuration in azimuth and elevation, respectively, forming an overall aperture of approximately 1.25 m × 1.00 m. This configuration enables electronic beam steering while remaining compatible with small-satellite power, mass and volume constraints.

The radar operates in three primary modes to address complementary space situational awareness needs (see Table 1):

- Tracking Mode: this dedicated to trajectory refinement of known debris objects. In this mode, the radar beam is steered to follow a predicted debris path, enabling coherent integration and high signal-to-noise ratio. The resulting measurements support sub-meter-level resolution and accurate orbit updates.
- Beam-Park, aimed at debris discovery and population monitoring. The radar beam is fixed or scans predefined regions, detecting debris as it crosses the field of view. While resolution is lower than in tracking mode, this mode enables efficient detection of previously uncatalogued objects and supports statistical characterization of the debris environment.
- Electronic Fence mode enables continuous monitoring of predefined orbital regions and supports rapid detection and alerting for debris crossing critical altitude shells, complementing tracking operations.
- Mixed Mode: Operational flexibility allows switching between tracking and discovery functions to adapt to mission priorities and debris density.

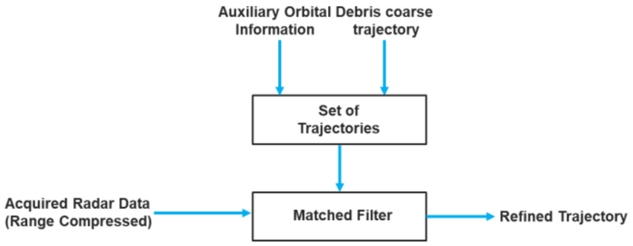


Fig. 3. DANTE Tracking Mode processing strategy. The system exploits a priori orbital knowledge to enable efficient coherent processing and high-precision trajectory refinement.

In tracking mode, the DANTE system exploits a priori orbital knowledge to enable efficient coherent processing and high-precision trajectory refinement. Coarse orbital information, derived from existing catalog data or previous detections, is used to generate a set of candidate debris trajectories consistent with the expected motion within the radar field of view. Range-compressed radar data acquired by the spaceborne sensor are then processed on the ground using a matched-filtering approach, where each hypothesized trajectory is tested against the measured signal. Since the debris radar return is a function of the assumed trajectory, only the correct trajectory hypothesis allows coherent phase alignment over time, resulting in a strong peak response. The refined trajectory is therefore identified as the one that maximizes the matched-filter signal-to-noise ratio. This approach allows DANTE to compensate for limited instantaneous sensitivity by exploiting coherent integration over the debris dwell time, while keeping onboard processing requirements minimal. The ground-based tracking-mode processing scheme, and its exploitation of a priori orbital knowledge to maximize coherent integration, are summarized in Fig. 3.

An example of the signal-to-noise ratio (SNR) variation as a function of debris inclination and debris diameter in DANTE tracking mode is shown in Fig. 4. In this scenario, the radar satellite operates in a near-polar orbit (90° inclination) at an altitude of 500 km. The reduction in SNR observed for increasing inclination differences is primarily driven by geometrical effects. As the inclination mismatch between the radar and the debris increases, the debris trajectory crosses the radar beam differently reducing the time the object remains within the antenna field of view. This shorter dwell time limits the achievable coherent integration leading to a decrease in SNR. Table 2 reports a summary of the DANTE radar performance. The performance figures reported in Table 2 reflect a trade-off between detection capability, system simplicity and suitability for small satellite platforms. Detection and trajectory refinement down to centimeter-class objects at short ranges and meter-class objects at distances up to 100–120 km demonstrate that meaningful debris tracking can be achieved with compact X-band radars operating from LEO. Constraints on beamwidth and steering angles are intentionally selected to preserve antenna efficiency and gain rather than maximizing instantaneous field of view for a single spacecraft.

These limitations are effectively mitigated at the system level through the deployment of a distributed, multi-ring constellation composed of more than 100 low-cost satellites. While individual satellites have modest coverage, the cumulative effect of many platforms significantly increases revisit frequency, spatial coverage and catalog refresh rates. As a result, overall system performance is driven by constellation scalability rather than single-sensor capability, making the architecture well suited for continuous debris monitoring in increasingly congested orbital environments.

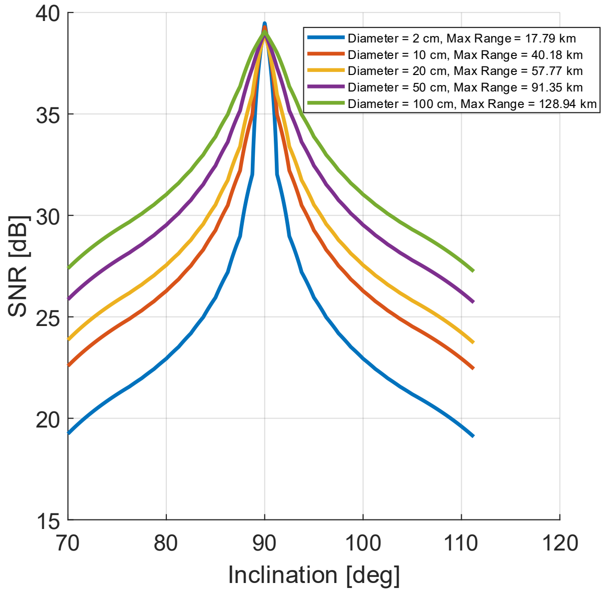


Fig. 4. DANTE SNR versus debris orbital inclination and diameter (tracking mode). The radar is assumed to be position at an orbit of 90 degrees inclination.

Fig. 5. DANTE Performance Summary.

Requirement	**Value**	**Comments**
Satellite Altitude	500-1000 km	
Object Detection Performance Trajectory Refinement	2 cm @ 15 km 1 m @ 120 km	Object diameter
Object Detection Performance Discovery	2 cm @ 10 km 1 m @ 90 km	Object diameter
Number of Satellites	>100 on multiple rings	Low-cost solution may allow for multiple sats
Steering Angles	Max steering Az: 3° Max steering El: 3°	Tradeoff possible between agility and detection performance
Beamwidth	Beamwidth: 2° (az), 2° (el)	

V. CONCLUSIONS

This paper has presented DANTE (Detection ANd Tracking of space dEbris), a spaceborne radar constellation concept aimed at improving debris detection, tracking and trajectory refinement in Low Earth Orbit. The proposed architecture addresses key limitations of current ground-based space surveillance systems namely (i) restricted coverage, (ii) sensitivity gaps for small objects (iii) and limited update rates. This is achieved by placing sensing capabilities directly into orbit.

DANTE is based on a constellation of small satellites equipped with compact X-band phased-array radars and deployed on multiple near-polar orbital rings. This configuration enables global coverage of the most populated debris altitude and inclination bands through natural orbital precession effects. Coverage analyses demonstrate that, even with modest individual sensor capabilities, the distributed constellation approach enables repeated observations of debris objects over time This allows robust trajectory refinement and timely catalog updates. System scalability allows performance to be adapted to mission needs by adjusting the number of satellites and orbital rings, while maintaining compatibility with small satellite cost, mass and power constraints.

The radar payload design adopts a design-to-cost philosophy. This approach combines moderate steering angles and narrow beamwidths with coherent processing techniques to maximize detection performance. In tracking mode, DANTE exploits a priori orbital information to perform ground-based coherent integration and matched-filter processing enabling high-precision trajectory refinement. Performance analyses show that centimeter-class debris can be tracked at short ranges and meter-class debris at distances exceeding 100 km. Overall, the DANTE concept demonstrates that effective debris monitoring is feasible by exploiting the cumulative performance of many low cost platforms operating cooperatively. DANTE provides a viable and flexible approach to enhancing space situational awareness and supporting the long-term sustainability of increasingly congested orbital environments by combining space-based radar sensing, coherent ground processing and scalable constellation deployment.

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