

A Space-based Debris Cataloguing System for the New Space Era

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Abstract

Over the past decades, space activities have increased significantly, giving rise to a growing threat: space debris. Today, over 28,160 objects are tracked by the U.S. Space Surveillance Network, primarily those larger than 10 cm in low-Earth orbit (LEO). However, 100,000s of debris below this size remain largely untracked, despite being a major cause of mission-ending damage. Most Space Situational Awareness (SSA) systems can catalogue objects down to 10 cm, but conjunction assessments and collision avoidance manoeuvres only address less than 1% of the impact risk. Meanwhile, spacecraft remain vulnerable to catastrophic, undetected collisions with debris between 0.1 and 10 cm. Hence, mitigating existing risks is a critical priority for the space sector. The growing importance of SSA highlights the need to track centimetre-sized debris.

This paper presents a Phase 0 feasibility study of the Threat and Hazard Evaluation for Intelligent Awareness (THEIA) mission, a space-based system designed to address this observation gap. THEIA employs a dual-payload constellation of 12-unit CubeSats, with radar satellites performing initial orbit determination and optical satellites enabling precise orbit determination. The baseline configuration, consisting of 15 radar satellites and 108 optical satellites in complementary orbital planes, achieves approximately 26% catalogue completeness of 5–10 cm debris within five years. Although below the 80% target, the study demonstrates the technical feasibility of centimetre-class debris tracking within CubeSat constraints and confirms the potential for scalable small-satellite architectures.

The financial analysis, based on a discounted cash flow model, indicates strong economic viability with a positive net present value exceeding €1 billion under hybrid funding assumptions. However, limitations remain in radar payload performance, constellation coverage, and dynamical modelling, which considered only simplified perturbations. Future work should include higher-fidelity modelling, collision risk assessment for observer satellites, shielding and avoidance strategies, and the evaluation of larger platforms to increase radar performance and catalogue completeness.

Overall, THEIA demonstrates that centimetre-class debris cataloguing is both technically and economically feasible, providing a foundation for safer and more sustainable space operations.

Acronyms

AOCS	Attitude and Orbit Control System
BOL	Beginning of Life
CAD	Computer-Aided Design
CAN	Controller Area Network
CAPEX	Capital Expenditures
CMOS	Complementary Metal-Oxide-Semiconductor
COTS	Commercial Off-The-Shelf
ConOps	Concept of Operations
DCF	Discounted Cash Flow
DSM	Design Structure Matrix
DTM	Drag Temperature Model
ECSS	European Cooperation for Space Standardization
EOGS	Earth Observation Ground Station
EOL	End of Life
EOP	End of Operations
EPS	Electrical Power System
ESA	European Space Agency
FOV	Field of View
GNSS	Global Navigation Satellite System
I²C	Inter-Integrated Circuit
INCOS	International Council on Systems Engineering
IOD	Initial Orbit Determination
LEO	Low Earth Orbit
MDL	Modular Decomposition Level
NASA	National Aeronautics and Space Administration
NPV	Net Present Value
OPEX	Operational Expenditures
OPM	Object-Process Methodology
PCDM	Power Conditioning and Distribution Module
PNT	Positioning, Navigation and Timing
POD	Precise Orbit Determination
SAR	Synthetic Aperture Radar
SBSA	Space-Based Space Awareness
SNR	Signal-to-Noise Ratio
SPI	Serial Peripheral Interface
SSA	Space Situational Awareness
SSO	Sun-Synchronous Orbit
STK	Systems Tool Kit
THEIA	Threat and Hazard Evaluation for Intelligent Awareness
TT&C	Telemetry, Tracking, & Command
WACC	Weighted Average Cost of Capital

1. Introduction

1.1 Background & Motivation

Over the past decades, space activities have increased significantly, giving rise to a growing threat: space debris. Today, over 28,160 objects are tracked by the U.S. Space Surveillance Network, primarily those larger than 10 cm in Low Earth Orbit (LEO). However, 100,000s of debris below this size remain largely untracked, despite being a major cause of mission-ending damage.

Most Space Situation Awareness (SSA) systems can catalogue objects down to 10 cm, but conjunction assessments and collision avoidance manoeuvres only address less than 1% of the impact risk. Meanwhile, spacecraft remain vulnerable to catastrophic, undetected collisions with debris between 0.1 and 10 cm.

Mitigating this risk is a critical priority for the space sector. Closing the observation gap for centimetre-sized debris would enhance spacecraft safety, improve conjunction assessments, and strengthen the sustainability of space operations.

This paper presents a feasibility study for the Threat and Hazard Evaluation for Intelligent Awareness (THEIA) mission, which targets debris in the 5–10 cm range and aims to achieve 80% catalogue completeness within this size regime.

1.2 Aim of the Study

The THEIA mission aims to close the critical observation gap for 5–10 cm debris in LEO, achieving an 80% catalogue completeness within less than five years. To accomplish this, THEIA will deploy a constellation of 12U CubeSats comprising two satellite types: one equipped with optical sensors and the other with Radar. This dual-payload architecture enhances SSA by reducing positional uncertainties, improving risk assessments, and refining collision avoidance decision-making.

While tracking centimetre-sized debris will inevitably increase conjunction warnings and potential manoeuvres, THEIA will counter this by improving conjunction accuracy. More precise orbit determination will minimise false alerts, reduce unnecessary manoeuvres, and support cost-efficient satellite operations, providing spacecraft operators with more reliable risk evaluations.

1.3 Top-level Mission Requirements

The mission's aim was translated into a set of top-level requirements that define the system capabilities needed to meet stakeholder needs and ensure the mission fulfils its intended purpose.

- **S-FUN-001:** The mission shall deploy a constellation of satellites equipped with a sensor capable of tracking debris larger than 5 cm.
- **S-FUN-002:** The constellation shall catalogue debris located at the 600-800 km altitude range.
- **S-FUN-003:** The constellation shall catalogue debris located between the 60-105 °deg inclination range.
- **S-FUN-004:** The system shall record the observation in a database.
- **S-FUN-005:** The constellation shall generate and maintain a space debris catalogue to enable accurate orbital characterisation.
- **S-OPE-006:** The constellation shall downlink observational data necessary for building and maintaining a space debris catalogue.
- **S-PHY-007:** The constellation shall downlink observational data for catalogue generation at least twice per day.
- **S-FUN-008:** The constellation shall provide Level 0 debris observation data for building and maintaining a space debris catalogue.
- **S-CON-009:** The satellites shall perform initial orbit determination (IOD) and conduct revisits to refine object trajectories through precise orbit determination (POD) to build the space debris catalogue.

1.4 Context of the Development

This study was conducted as part of the Group Design Project of the MSc in Astronautics and Space Engineering at Cranfield University (UK). The project brought together a multidisciplinary team of students, working under academic supervision, to perform a Phase 0 feasibility study.

The design process was strongly influenced by industrial engagement. Key customer preferences were incorporated to reinforce the applicability of the mission to real operational needs. Specifically, the requirement to use a Cube-Sat platform in the 6U–12U range was adopted, resulting in THEIA's 12U architecture. In addition, the preference for locating debris within a 590–750 km Sun-Synchronous Orbit (SSO) aligned closely with the mission's target orbital regime. These alignments with stakeholder priorities ensured that the proposed solution remains technically feasible, responsive to market demand, and relevant to the evolving needs of the space sector.

2. Methodology

The methodology adopted for this study follows a structured systems engineering process, ensuring traceability from stakeholder needs to technical solutions.

2.1 Systems Engineering Approach

The development of THEIA was conducted combining top-down requirements flow-down with iterative design loops [1, 2]. This ensured a structured framework for system definition, functional decomposition and architecture development.

2.1.1 Stakeholder analysis

The identification of stakeholders involved in the space debris problem is essential for developing an effective and operationally relevant solution. Stakeholders were classified according to their contribution to the problem, potential benefits from its resolution, and possible roles in supporting or collaborating with the initiative. Table 1 presents the qualitative trade-off performed. Almost all identified stakeholders were retained in the analysis, except for insurance companies, which, despite their financial influence, provide limited operational value and were excluded as primary stakeholders.

Table 1: Qualitative Trade-Off of Stakeholders. H = High, M = Medium, L = Low (qualitative assessment scale)

Type	Estimated Influence	Estimated Importance	Final Project Impact	Risk Level	Budget	Barrier to entry
Defence	H	M	H	H	Billion €	H: National-level access required
Satellite Operators (commercial)	H	H	H	M	Million € - Billion €	M: Financial and tech difficulties
Insurance	M	L	L	L	Million €	M: Highly specialised market
Space Agencies	H	H	H	M	Billion €	M: Government control required
Government	H	H	H	M	Billion €	M: Bureaucratic challenges
Launch Providers	M	M	M	M	Million € - Billion €	M: Infrastructure investments
Human Spaceflight Organisations	H	H	H	H	Billion €	H: crew safety requirements

2.1.2 ConOps

The Concept of Operations (ConOps) defines the intended use of the system and its interactions with stakeholders. It provides a high-level operational perspective that links stakeholder needs with system functions. The overall scheme of operations is presented in Figure 2.

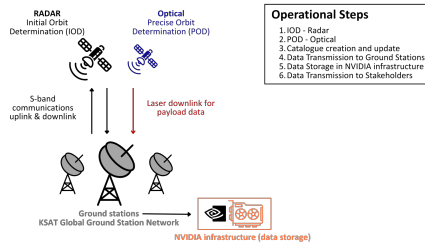


Fig. 2: ConOps Scheme

Figure 1 illustrates the ConOps sequence diagram, showing the interactions between systems, stakeholders, and mission segments, and highlighting the sequential task flow.

Finally, the mission timeline is summarised in Figure 3. During the first five years, a constellation composed of 15 radar satellites and 108 optical satellites is deployed to generate the catalogue (see Section 2.1.3). The subsequent five years focus on catalogue updates and on-demand services, supported by a second identical constellation. End-of-life (EOL) of both constellations is achieved in five years, in compliance with ESA's Zero Debris Approach. Launches are implemented in batches, with radar satellites deployed using Electron and optical satellites through a combination of Electron and Falcon 9 rideshare missions. Communications and subsystem operations follow defined duty cycles and margins, including S-band links, payload data dumps, reaction wheel desaturation, battery charging cycles, and state-of-health verification.

The operational concept also accounts for subsystem-level constraints and recurring activities. A two-year period is reserved for end-of-operations (EOP), ensuring controlled deorbiting and passivation. Communications are scheduled with a minimum of 10 S-band contacts per day for housekeeping data, complemented by at least 2 daily payload data dumps from the optical satellites. Reaction wheel desaturation is performed approximately every 58 orbits to maintain attitude control stability. From an electrical perspective, a full state-of-health assessment is carried out within the first week after deployment, power availability is sized for a worst-case scenario of 33 minutes of eclipse per orbit, and batteries are fully recharged after each eclipse, with a maximum charging time of 60 minutes.

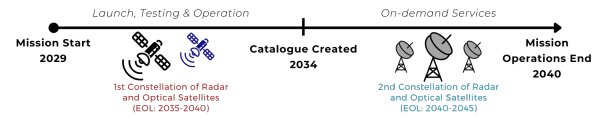


Fig. 3: Mission Timeline Summary. EOL= End of life.

2.1.3 Use Cases

Three representative use cases were defined for the mission:

- **Catalogue Creation:** Create and update a catalogue that is 80% complete for objects within the 5-10 size range. Stakeholders: Space Agencies, Governments and Defence.
- **On-Demand Position Services:** Providing on-demand position data of specific debris, allowing stakeholders to make data-driven decisions for avoidance manoeuvres. Stakeholders: Satellite Operators, Human Spaceflight Organisations, Launch Providers, Space Agencies.
- **Orbital Spot Data Services:** Providing orbital spot data, allowing risk assessment for mission planning. Stakeholders: Satellite Operators, Human Spaceflight Organisations, Launch Providers, Defence, Space Agencies.

2.1.4 System Architecture

The system architecture was developed following a V-Model lifecycle, which provides a sequential and symmetric framework in which system definition and decomposition on the left side of the “V” are directly mirrored by integration, verification, and validation activities on the right. This approach also incorporates risk management and ensures traceability across requirements [3–5]. In this study, systems architecture is defined as the embodiment of both form (physical structure) and function (operational behaviour), enabling a structured and logical decomposition of the system into key segments [6].

The design process follows a structured flow from mission requirements to subsystem realisation through functional allocation and interface definition [7]. The final mission architecture was resolved into 3 primary segments:

- **Space Segment:** Two independent constellations are employed to optimise performance. The radar constellation performs initial orbit determination (IOD) to detect the maximum number of debris objects, while the optical constellation observes the detected debris to classify and catalogue it through precise orbit determination (POD).

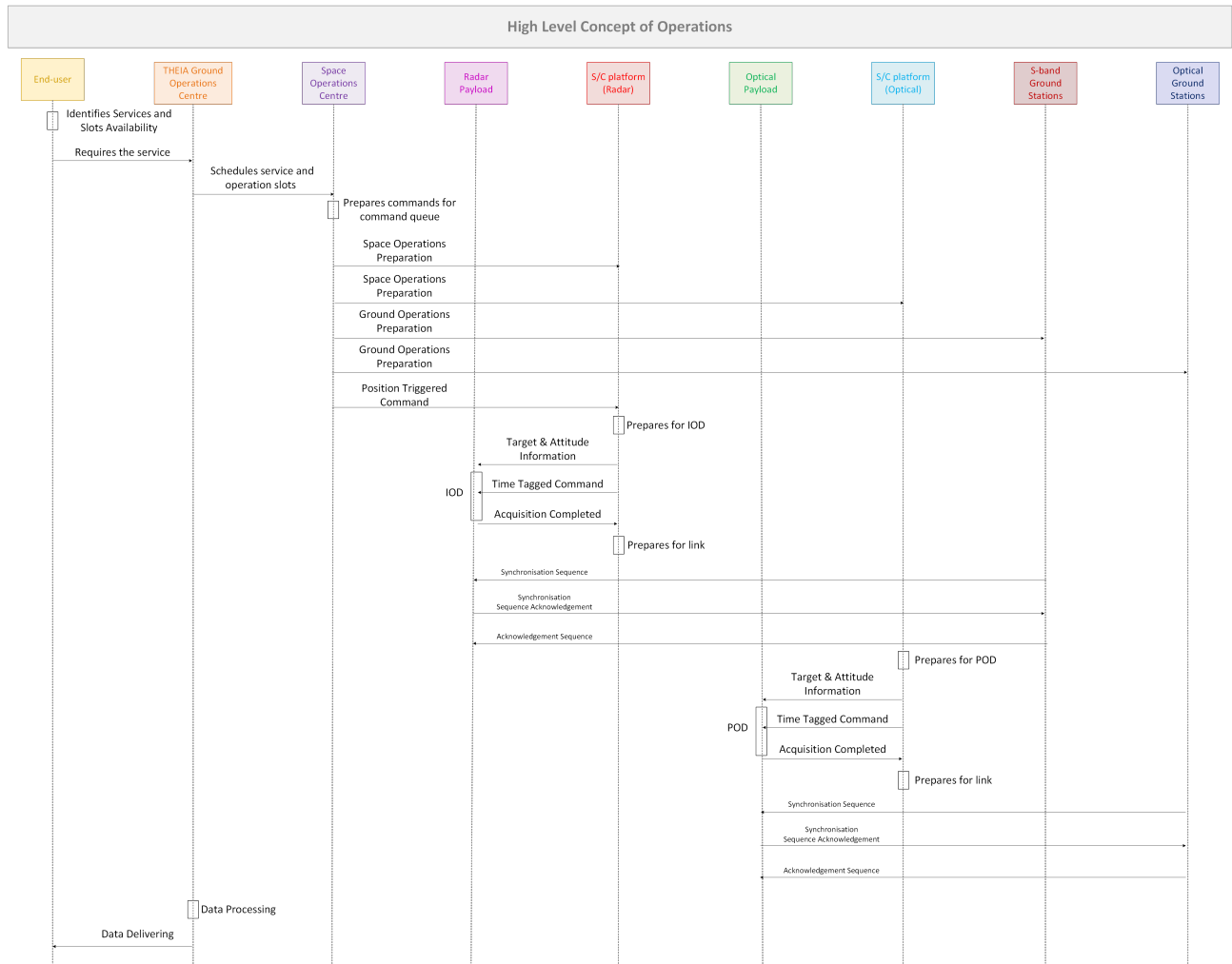


Fig. 1: ConOps Sequence Diagram

- **Ground Segment:** Comprising mission control facilities, S-band and commercial optical ground stations, and the data processing centre.
- **Launch Segment:** Encompassing launcher selection and deployment strategy to insert the constellations into their operational orbits.

Figure 4 presents a unified Object-Process Methodology (OPM) model that represents the system's structure and behaviour in a single, coherent diagram, illustrating relationships and interactions across all segments.

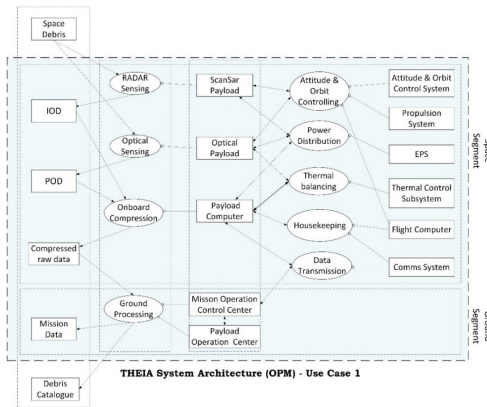


Fig. 4: THEIA System Architecture

Interface definition followed a two-step approach. First, decomposition levels were established to create a clear hierarchical breakdown of subsystems and components (Figure 7).

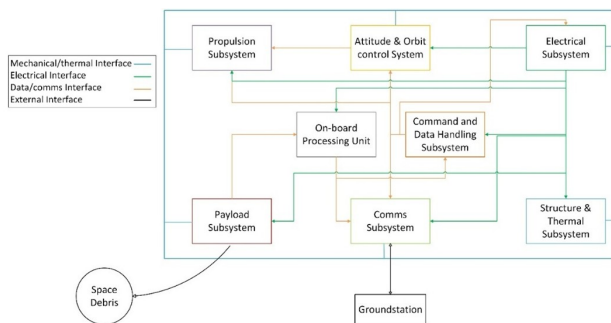


Fig. 5: Space Segment Interfaces

Second, space segment interfaces were defined, including internal subsystem interactions and external connections, as shown in Figure 5.

Name								
		Payload Subsystem	Onboard Processing	Propulsion Subsystem	ADCS Subsystem	Command & Data Handling	Structure & Thermal Subsystem	Communication Subsystem
Name	Seq	1	2	3	4	5	6	7
Payload Subsystem	1	•	•			•		•
Onboard Processing	2	•	•			•	•	•
Propulsion Subsystem	3			•	•	•		•
ADCS Subsystem	4			•	•	•		•
Command & Data Handling	5				•	•	•	•
Structure & Thermal Subsystem	6	•	•	•	•	•	•	•
Communication Subsystem	7	•	•	•	•	•	•	•
Electrical Subsystem	8	•	•	•	•	•	•	•

Fig. 6: Space Segment DSM

To further analyse interdependencies and modularity, a Design Structure Matrix (DSM) was employed to map interactions between system components (Figure 6). Three metrics [8] were used to evaluate modularity, with the results summarised in Table 2. These metrics indicate that the system exhibits moderate granularity with high inter-component connectivity, reflecting a balance between modularity and functional integration.

Table 2: Modularity results of the 2 systems under study

Decomposition Level	$M_{G\&G}$	$M_{G\&G,inter}$	MDL
Level 2	0.3078	0.9048	29.40

The modularity metrics in Table 2 indicate that the system exhibits a balanced architecture, with moderate granularity and strong inter-component connectivity. Specifically, the $M_{G\&G}$ value of 0.308 reflects that intra-module connectivity is higher than inter-module connectivity, confirming that components are reasonably clustered into functional modules, but some interactions occur across modules to support system integration. The $M_{G\&G,inter}$ value of 0.905 highlights that inter-module coupling is relatively low compared to the ideal modular case, suggesting that modules are largely self-contained and interact efficiently with other modules only when necessary. Finally, the MDL value of 29.40 quantifies the overall coupling complexity from an information-theoretic perspective; this moderate value indicates that the system decomposition captures the essential interactions without introducing excessive architectural complexity. Collectively, these metrics confirm that the architecture provides effective subsystem independence while maintaining the connectivity required to meet mission performance objectives.

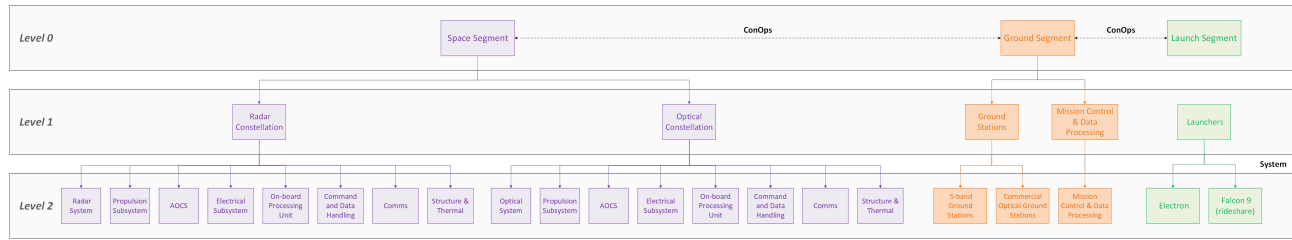


Fig. 7: THEIA Decomposition Levels

2.2 Mission Design

2.2.1 Orbit and Constellation

The constellation architecture was developed through an iterative build-up process. The radar constellation was designed to maximise detection coverage and perform IOD, while the optical constellation was optimised for POD, refining debris trajectories and maintaining catalogue accuracy. It should be noted that the radar constellation design is based on the earlier radar configuration and was not updated to match the improved design presented in Section 2.5.1. A MATLAB simulation propagated both satellites and debris, accounting for J2 perturbations, eclipse periods, and payload field-of-view constraints.

The radar constellation consists of 15 satellites distributed across five orbital planes at altitudes between 590 km and 750 km with an inclination of 80° , providing coverage of 85% of the debris population within 350 days. The optical constellation comprises 108 satellites in two sun-synchronous planes (742.04 km and 657.96 km), achieving a revisit time of 7.2–9.5 hours and maintaining observation of 76.2% of debris. When integrated, only 34.05% of the radar-detected debris is revisited within the 20-minute POD window, resulting in an effective catalogue coverage of 25.9% over five years. The configuration of both constellations is illustrated in Figure 8.

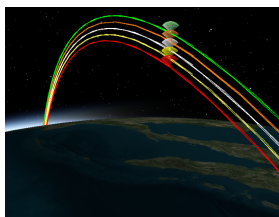
2.2.2 Launcher selection and deployment strategy

Launcher selection was performed through a trade-off analysis considering reliability, availability, cost, and payload capacity. Historical success, manufacturer heritage, projected launches through 2025–2027, and the number of satellites per launch were all considered. Candidate launch vehicles included Electron, Falcon 9 rideshare, Antares 230+, Ariane 62, Firefly Alpha, Minotaur I, IV, C, Proton M, Soyuz 2.1a, and Atlas V variants.

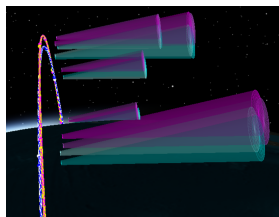
The constellation deployment begins in Q1 2029. Five radar satellites are deployed per Electron launch, while optical satellites are distributed between Electron and three Falcon 9 ride-share missions. Satellites are initially inserted into slightly elliptical phasing orbits. This approach allows satellites to execute optimised insertion manoeuvres and achieve even spacing within orbital planes over a two-year period.

2.2.3 AOCS design

The AOCS maintains satellite stability and pointing accuracy, which is critical for effective debris observation and follow-up measurements. Eleven operational modes ensure stability and dynamic management (see Table 3), covering all mission phases and enabling reliable sensor operation.



(a) Radar Constellation



(b) Optical Constellation

Fig. 8: Radar and Optical Satellite Constellations

Table 3: Modes and phases of the mission

	1. Post-Launch Detumble	2. Safety / Standby	3. Nominal Pointing (Survey)	4. Target-Acq & Lock (Follow-up)	5. Reorientation (Slow)	6. Alignment for Transmission	7. Orbit Maintenance / Correction	8. Measurement Dumping	9. Sensor Calibration	10. Collision Avoidance / Emergency	11. End-of-Life
Launch & Separation	Primary	Fallback	N/A	N/A	N/A	N/A	N/A	On-demand	N/A	Fallback	N/A
Early Operations (LRGP)	N/A	Standby	N/A	N/A	On-demand	N/A	On-demand	On-demand	Standby	Fallback	N/A
Communicat- ing	N/A	Standby	Standby	Standby	On-demand	N/A	On-demand	On-demand	Primary	Fallback	N/A
Nominal Survey (Radar)	N/A	Standby	Primary	N/A	N/A	Standby	On-demand	On-demand	On-demand	Fallback	N/A
Follow-up Observations (Optical)	N/A	Standby	N/A	Primary	On-demand	Standby	On-demand	On-demand	On-demand	Fallback	N/A
Communicat- ion / Downlink	N/A	Standby	N/A	N/A	On-demand	Primary	On-demand	On-demand	On-demand	Fallback	N/A
Maintenance / Correction	N/A	Standby	N/A	N/A	On-demand	N/A	Primary	On-demand	On-demand	Fallback	N/A
End-of-Life / Decommis- sioning	N/A	Standby	N/A	N/A	On-demand	N/A	On-demand	N/A	N/A	Fallback	Primary
Collision Avoidance / Emergency	N/A	Standby	Fallback	Fallback	On-demand	Fallback	Fallback	On-demand	N/A	Primary	Fallback

N/A always for cube satellites

defines which subsystems are active during specific mission phases, and duty cycles are tuned to ensure that energy drawn from the battery during eclipses is fully recovered in subsequent sunlit periods. Both satellite variants achieve the payload uptime target of 65% per orbit under nominal operations. For the radar variant, this is only attainable by limiting peak power use in favour of extended operational duration, remaining within the narrow margins imposed by the 12U CubeSat form factor.

Verification was performed using a Simulink model of the solar array, regulator, battery, and time-switched loads, which simulated transitions between sunlight, eclipse, and mode changes. Results confirm that the system can maintain safe operation throughout the planned service life.

The EPS data interface separates control and payload domains in a hybrid topology. A CAN bus provides reliable command and telemetry links between the EPS, flight computer, payload computer, and optical terminal. The payload data chain is implemented as a dedicated Ethernet network capable of sustaining throughput greater than 1 Gb/s between the payload processor, storage buffer, and optical downlink. Additional subsystems interface via RS-485, I²C, or SPI, as supported natively by their COTS components, removing the need for custom interfaces.

In summary, the COTS-based EPS and associated data interfaces satisfy the requirements of a 12U platform while imposing operational constraints on other subsystems. The optical variant is comfortably supported within available margins, whereas the radar variant is severely power-limited due to surface area and internal volume restrictions. These limitations reduce available energy for continuous operation and short-duration peaks, which directly impacts radar payload performance. Duty-cycle management ensures feasibility, but further studies should assess larger platforms, improve EPS simulation fidelity, and update power budgets as subsystem definitions mature.

Table 4 presents the spacecraft orbit-average power for all operational modes.

Table 4: Spacecraft orbit average power for all modes

Mode	Optical		Radar	
	Day OAP (W)	Eclipse OAP (W)	Day OAP (W)	Eclipse OAP (W)
Safe Mode	33,68	28,35	33,68	28,35
Manoeuvre Mode	73,29	51,73	73,29	51,73
Detumble Mode	61,23	51,6	61,23	51,6
Nominal Mode (Eclipse Transmit)	51,45	37,32	84,79	37,32
Nominal Mode (Day Transmit)	56,37	23,9	89,7	23,9

2.2.4 End-of-life

The EOL strategy complies with the five-year rule for LEO missions. Atmospheric drag decay was estimated using MATLAB and STK simulations, validated against the 1976 Standard Atmosphere and the Drag Temperature Model 2020 (DTM-2020). Satellites are manoeuvred to a disposal orbit of 350 km, ensuring natural re-entry within five years.

2.3 Electrical & Communications Subsystems

2.3.1 Electric Power Systems (EPS)

The EPS design process commenced with a trade-space analysis of key components, followed by an orbit-averaged power assessment to evaluate candidate solutions against mission demands. This analysis established power limits that constrain other subsystems, particularly the radar payload and high-rate communications. Based on these constraints, two triple-deployable articulated solar arrays were selected, capable of generating 135 W at beginning-of-life (BOL) and approximately 122 W at EOL.

Battery sizing was driven by a conservative depth-of-discharge limit of 22%, resulting in a capacity of 100 Wh. The system adopts a PC/104 form factor, common in CubeSat platforms, allowing stacking pass-through connectors that simplify integration and reduce external harnessing. A Power Conditioning and Distribution Module (PCDM) with integrated maximum power point tracking, regulated 12/5/3.3 V rails, and a 100 Wh battery was selected, supporting up to 50 W continuous load or 160 W short-duration peaks. Collectively, these components define the practical power envelope for both satellite variants.

Power allocation is organised into five operational modes: Safe, Detumble, Manoeuvre, Nominal (Eclipse Transmit), and Nominal (Day Transmit). Each mode de-

2.3.2 Flight Computer and Communications Subsystems

The flight computer serves as the central controller for each satellite and provides precise navigation, positioning, and timing (PNT) capabilities. Processing requirements were estimated following [9], including lines of code per process (e.g., AOCS control, telecommand processing) and process execution rates. Process execution is mode-dependent, enabling estimation of a minimum processor clock speed of 246.6 MHz. Accurate PNT data is required to support payload observation reliability, necessitating integration of a GNSS receiver and an atomic clock to provide long-term timing stability. Payload data storage requirements exceed gigabit-scale buffers; terabit-scale dedicated storage is employed to accommodate data between downlinks. Figure 9 illustrates the flight computer subsystem configuration.

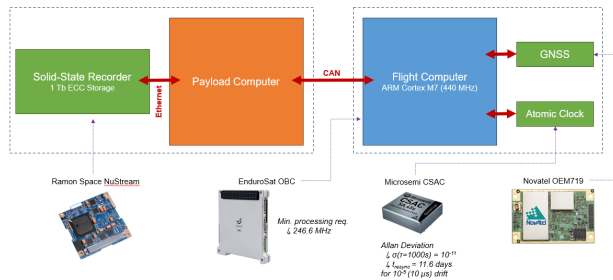


Fig. 9: Flight computer subsystem and associated data storage components

Satellite communication is divided into two subsystems: a TT&C system for command and telemetry, and a high-data-rate payload downlink. The TT&C subsystem complies with ECSS standards [1], operating in the S-band. Estimated data rates, following [9], yield a worst-case uplink of 1 Mbps during memory reload and 10 kbps downlink during nominal operations.

The payload generates approximately 2.2 Tb of data per day, necessitating high-rate downlink capabilities beyond the S-band. Constellation-wide crosslinks are required for clock synchronisation. Considering an average pass length of 8 minutes, the minimum required data rate is 2.8 Gbps. A trade-off between Ka-band RF and free-space optical communications favoured optical links for small-satellite implementation. Figure 10 presents the selected communications subsystem configuration.

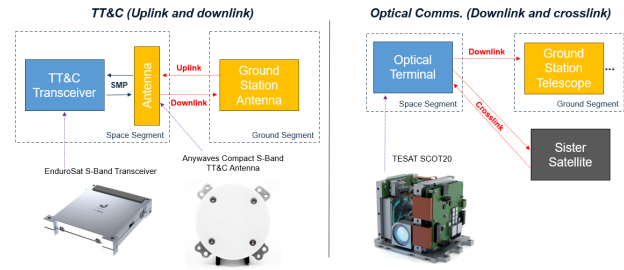


Fig. 10: Communications subsystem overview, including TT&C and high-rate optical payload downlink

Verification was performed using the KSATLite ground station network. Link budgets confirm successful TT&C uplink and downlink, and optical payload downlink performance (crosslink not included), with a link margin greater than 3 dB defining success. Further validation was conducted using STK and MATLAB. STK identified numerous viable daily links, while MATLAB simulations of waveforms using CCSDS standards highlighted potential suboptimal modulation and coding choices for the TT&C subsystem.

2.4 Mechanical & Propulsion

2.4.1 Propulsion

The propulsion system employs Busek BIT-1 RF ion thrusters with the following characteristics: thrust of 105 μN , specific impulse of 2250 s, maximum power of 10 W, and mass of 53 g.

Thruster selection was constrained by the 46 W continuous power budget allocated from the EPS, which eliminated most high-thrust electric propulsion options. Mission requirements also limited transfer time between phasing and operational orbit to meet the five-year mission lifetime (S-OPE-013). A MATLAB-based trade study was conducted to optimise thruster selection for maximum thrust-to-power ratio. The BIT-1 was selected, with four thrusters operating simultaneously, providing sufficient thrust for the transfer while staying within power constraints. The CubeSat accommodates up to eight thrusters, enabling redundancy for emergency manoeuvres and EOL operations. With an operational lifetime exceeding two years, the chosen configuration ensures completion of orbit transfer within acceptable timeframes while preserving redundant thrusters for subsequent manoeuvres.

2.4.2 CAD Model

The final mechanical configuration integrates all subsystems while ensuring structural integrity, mass optimisation, and compliance with deployment and operational requirements. Component placement respects subsystem constraints including power, thermal, and communications considerations. Figure 11 illustrates the CAD model of both the Optical and Radar CubeSats. The 3D model enables derivation of the inertia matrix, center of mass, and specific surface area relevant to drag calculations. It also provides a basis for thermal analysis in future studies.

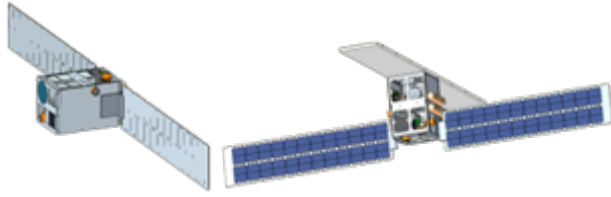


Fig. 11: Complete deployed 3D CAD model: Optical CubeSat (left) and Radar CubeSat (right)

2.5 Payload

2.5.1 Initial Orbit Determination (IOD) Payload

Accurate orbit determination requires defining a debris object's position and velocity at a specific epoch [10]. High relative velocities between observer and debris result in short observation windows (short arcs), typically less than 2° , which render traditional geometry-based IOD methods, such as Gauss or Herrick-Gibbs, ill-conditioned [10]. As a result, only active sensors capable of directly measuring range, range-rate, azimuth, and elevation, with derivation of angular rates through numerical differentiation, are suitable for initial orbit determination.

The CubeSat form factor (12U) and the requirement for sub-5 cm resolution constrained the active sensor to a 50 W power budget and a maximum antenna size of 5×0.2 m. These limitations reduce the signal-to-noise ratio (SNR) and directly influence measurement uncertainty.

A parametric trade study was conducted using the Radar Equation and the Synthetic Aperture Radar (SAR) Equation [11]. Fixed parameters included transmitted power and maximum antenna dimensions, while antenna size (0.3–5 m) and line-of-sight range (10–200 km) were varied. Additional parameters were adopted from the POD presented in Section 2.5.2. Four sensor technologies were considered: monostatic, bistatic, Strip SAR, and Scan SAR. Figures of merit were field-of-view (FOV) and maximum range, with the highest values indicating optimal coverage and detection performance.

Table 5: Final Radar Design Parameters

Parameter	Value
Transmit Frequency	5 GHz
Antenna Area	0.334 m^2
FOV	5.87°
Maximum Range	68.24 km
Worst SNR	7.01 dB
Worst σ	23.66 m
Resolution	$5 \text{ cm } \mu\text{rad}$
Data Rate	19 Mbps
Mass	9.95 kg
Power	50 W

The trade study concluded with the selection of the Scan SAR configuration, which provides a full cone FOV of 5.87° , a maximum range of 68.24 km, and an average positional uncertainty of 23.66 m. The Pareto front, shown in Figure 12, represents the optimal trade-off between FOV, range, and positional uncertainty. Maximum range dictated the required orbital layers, FOV determined satellite phasing, and uncertainty defined the revisit times necessary to maintain catalogue accuracy. This design minimises the number of satellites required to meet the debris observation objectives; further implementation details are available in [12].

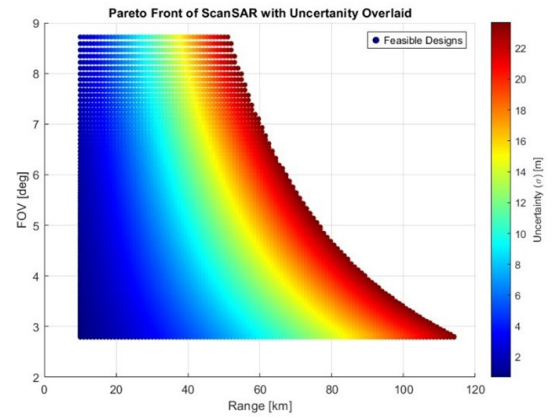


Fig. 12: Pareto front illustrating the trade-off between field-of-view, maximum detection range, and positional uncertainty for candidate IOD sensors

2.5.2 Precise Orbit Determination (POD) Payload

The precise orbit determination of debris objects relies on accurate optical measurements of their position over time. The payload must fit within a 12U CubeSat [13], detect debris as small as 5 cm, and provide sufficiently pre-

cise angular measurements for objects in the 600–800 km altitude range [14, 15]. Short observation windows and high relative velocities necessitate an optical subsystem capable of maintaining the debris within the field of view (FOV) for at least 10 seconds, while providing a minimum of four distinct measurements per orbital pass to satisfy POD requirements [13, 15].

The payload is constrained by a maximum telescope aperture of 10 cm and focal length of 35 cm [13]. To distinguish debris from stars and background objects, the system must generate streaks at least 10 pixels long and maintain a signal-to-noise ratio (SNR) greater than 5 [13, 16].

A parametric study was conducted to determine the optimal design, varying aperture, focal length, and exposure time for a CMOS-based camera while evaluating all observational scenarios. The figure of merit was the centroid error (σ_{centroid}), which quantifies the accuracy of object localization within a pixel [13]. Designs that did not meet the SNR, streak length, or POD observation criteria were discarded.

The final payload configuration achieves a focal length of 0.23 m, aperture of 0.1 m, 12.5° FOV, worst-case SNR of 21, worst-case centroid error of 0.52 arcseconds, and angular resolution of $52.2 \mu\text{rad}$. It operates at a data rate of 231 Mbps, with an exposure time of 1.16 s, consuming 2 W and weighing 5 kg (see Table 6). The trade space of feasible designs is shown in Figure 13. This configuration satisfies the POD requirements while minimizing the number of satellites required for catalogue maintenance [13–15].

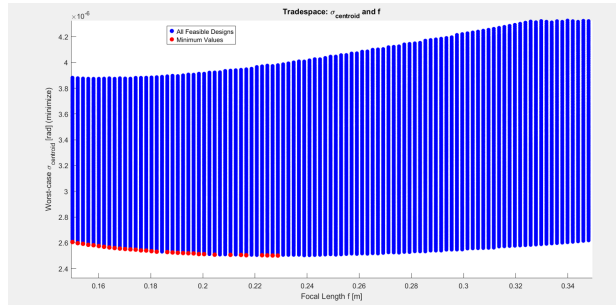


Fig. 13: Trade space of all the feasible designs

Table 6: Final Optical Design Parameters

Parameter	Value
Focal length	0.23 m
Aperture	0.1 m
FOV	12.5°
Worst SNR	21
Worst σ_{centroid}	0.52 arcsec
Resolution	$52.2 \mu\text{rad}$
Data Rate	231 Mbps
Exposure Time	1.16 s
Mass	5 kg
Power	2 W

3. Results & Discussion

The study evaluates the feasibility of a dual-payload CubeSat constellation for Space-Based Space Awareness (SBSA) targeting debris in the 1–10 cm size range. Due to payload resolution limits, effective observations are restricted to debris larger than 5 cm, meaning only the 5–10 cm size range can be reliably monitored.

3.1 Catalogue Performance

The proposed constellation design, comprising 15 Radar satellites and 108 optical satellites, achieves only 25.9% effective coverage of the targeted debris population over five years, falling short of the 80% catalogue creation goal. Simplified dynamical modelling, which accounts only for J2 perturbations, limits the fidelity of debris propagation. Future studies should include atmospheric drag, solar radiation pressure, and sensor pointing errors to improve accuracy.

Additionally, the high number of satellites required presents cost and operational challenges. The analysis also neglects collision risk for the observer satellites, which operate in the dense 600–800 km debris environment. Potential collisions could reduce constellation performance and generate additional debris, emphasizing the importance of incorporating shielding strategies, collision avoidance, and adherence to “no-debris generation” policies in subsequent iterations.

3.2 System Feasibility & Innovation

The system demonstrates technical feasibility under CubeSat constraints. Radar satellites perform initial orbit determination, while optical satellites enable precise orbit determination, supporting a phased observational strategy. However, the 12U form factor imposes significant limitations on radar payload performance, restricting effective

coverage and revisit frequency. Larger platforms could enhance power availability, payload capability, and overall constellation effectiveness.

The dual-payload architecture provides modularity and redundancy, with mission flexibility for future constellation upgrades. ScanSAR optical payloads and active radar payloads represent an innovative approach to space debris monitoring within small satellite platforms, demonstrating scalable SSA operations.

3.3 Mission Economics & Business Strategy

This section evaluates the economic feasibility of the mission, presenting both the business model approach and the implementation of the cost model.

3.3.1 Business Model Approach

The proposed business model follows a phased deployment and monetisation strategy, structured around three progressive use cases outlined in Section 2.1.3. The approach draws on best practices in business model design [17–19] and the Business Model Canvas framework [20].

The core value proposition is to establish a reliable catalogue of 5–10 cm debris within five years, creating a foundation for subsequent service offerings.

Use Case 1 – Space Debris Catalogue Creation

- **Concept:** Establishes a high-fidelity catalogue of 5–10 cm debris, providing foundational data for system validation and further commercialisation.
- **Monetisation:** Funded by early-stage public investment and institutional contracts (e.g., ESA, NASA).
- **Stakeholder Engagement:** Collaboration with government agencies and policy-driven stakeholders to align with strategic space safety goals.
- **Value:** Enhances SSA and supports regulatory compliance by reducing untracked objects in LEO.

Use Case 2 – On-Demand Position Services:

- **Concept:** Builds on the catalogue to deliver precise, low-false-positive risk assessments for satellite operators.
- **Monetisation:** Tiered subscription services for collision avoidance decision support.
- **Stakeholder Engagement:** Service tiers tailored to satellite operators, insurers, and national space agencies.
- **Value:** Increases satellite lifespan, reduces manoeuvre costs, and enables more informed operational decisions.

Use Case 3 – Orbital Spot Data Services:

- **Concept:** identifies high-risk debris to enable proactive avoidance and mission replanning via timely alerts.
- **Monetisation:** Advanced subscription-based tiers and direct analytics contracts with commercial and institutional users.
- **Stakeholder Engagement:** Customised access levels and integration with existing SSA platforms.
- **Value:** Improves resilience of orbital infrastructure and enhances mission safety and planning efficiency.

This phased approach ensures scalability, linking early catalogue development to long-term commercial viability. Revenue generated from use cases 2 - On-Demand Position Services and 3 - Orbital Spot Data Services services is reinvested into system expansion, enabling the launch of a second constellation after five years.

3.4 Cost Model

The financial feasibility of the mission was evaluated using a Discounted Cash Flow (DCF) model, applying a 10% WACC-based discount rate to estimate the Net Present Value (NPV) of projected cash flows over a ten-year horizon. This top-down approach models a hybrid funding architecture, combining ESA contributions with debt financing to bridge initial negative cash flows, with repayment linked to revenue growth in operational years.

Capital expenditures (CAPEX) are dominated by satellite manufacturing and launch costs, as well as ground segment infrastructure (KSAT + EOGS) and data processing infrastructure (NVIDIA). Operational expenditures (OPEX) include mission operations, data transmission, and maintenance. ESA funding covers early-stage development, while debt financing bridges initial cash flow gaps and is repaid progressively from Year 5 onwards to maintain a positive DCF trajectory.

The financial model results in a Net Present Value (NPV) of 1,158.94 M€, demonstrating strong economic viability.

Figures 14 and 15 show the Cost Model Results:

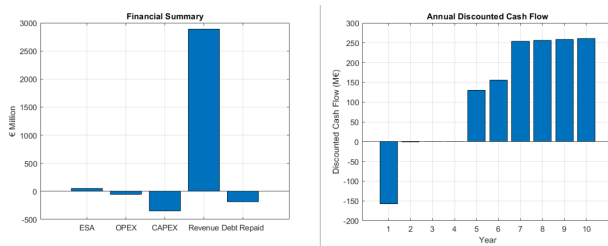


Fig. 14: Financial Summary & Discounted Cash Flow

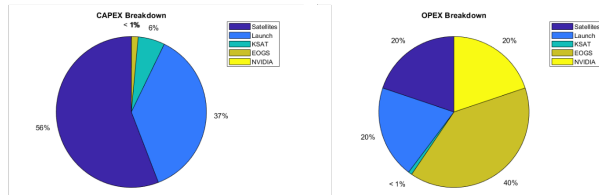


Fig. 15: CAPEX & OPEX Breakdown

Overall, the results indicate that the mission is economically sustainable, with projected revenues and funding mechanisms sufficient to support both initial constellation deployment and long-term system expansion.

4. Conclusions

This study investigated the feasibility of a dual-payload CubeSat constellation for space-based debris surveillance, targeting objects between 5 and 10 cm in size. The proposed system, comprising 15 radar satellites and 108 optical satellites, is capable of generating approximately 230 Tb of SSA data per day and requires an initial investment of roughly €50M. The radar satellites perform initial orbit determination, while the optical satellites carry out precise orbit determination to maintain the debris catalogue.

Although the constellation successfully satisfies end-of-life and catalogue maintenance requirements, it does not achieve the targeted 80% catalogue creation coverage, reaching only 25.9% within five years. The study also highlights that the analysis did not account for the collision risk of the SBSA satellites themselves. Potential impacts could compromise constellation performance and generate additional debris, undermining the mission's primary objective.

From a business perspective, the phased approach linking catalogue creation to on-demand services demonstrates economic feasibility. The financial model, based on a 10% WACC DCF analysis, indicates a positive Net Present Value of 1,158.94 M€, supporting the viability of the mission under the proposed funding and revenue strategy.

However, technical limitations, particularly in the radar subsystem, require further improvement to fully achieve the mission's objectives.

4.1 Future Work

Future studies should focus on refining the constellation configuration and incorporating higher-fidelity dynamical models, including atmospheric drag, solar radiation pressure, and sensor pointing errors, to better predict debris observation coverage. Optimisation algorithms could help reduce the required number of satellites while improving overall performance. Additionally, the collision risk of the surveillance satellites must be evaluated, with protective shielding, collision-avoidance manoeuvres, and adherence to "no-debris generation" policies considered as integral parts of the design.

Further work should also explore the potential benefits of larger satellite platforms to enhance radar performance and increase catalogue coverage. Conjunction assessments, mission lifetime analysis, and strategies to maximise catalogue completeness should be performed in parallel with business case refinement to ensure that the system remains both technically feasible and commercially sustainable.

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A space-based debris cataloguing system for the new space era

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