

Space-Based Sensor Fusion for Refined Space Debris Cataloguing

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Abstract

Monitoring centimetre-class orbital debris is critical for spacecraft safety and the long-term sustainability of Low Earth Orbit (LEO), as fragments below current ground-based tracking thresholds can still cause mission-ending damage. This study presents the payload-level design of a dual-sensor architecture for space-based space situational awareness (SBSSA), comprising an active radar for Initial Orbit Determination (IOD) and a visible-band optical sensor for Precise Orbit Determination (POD).

For each payload, a metrics-driven trade space is developed that maps design variables to catalogue-relevant figures of merit. The optical analysis prioritises time-on-detector (dwell), angular accuracy, field of view (FOV), and illumination geometry; the radar analysis focuses on volumetric coverage, range and range-rate precision, dwell, and off-nadir viewing. Operational constraints from power, pointing, and communications are incorporated. Observation concepts are defined accordingly: the optical payload is considered in sun-synchronous orbit with anti-sun pointing to ensure favourable illumination and background conditions, while the radar payload employs off-nadir scanning to enlarge coverage within the 600–800 km debris band. Minimum detectability conditions are set to reflect catalogue integration requirements.

Representative Pareto-optimal designs are identified for both payloads and assessed against higher-level indicators, including catalogue maintenance potential, observation scheduling feasibility, and downlink load. The outcome yields concrete recommendations on optical aperture, detector format, FOV, and integration times, together with radar effective range, FOV geometry, and measurement precision. The translation from payload parameters to constellation-level implications—revisit frequency, handover latency, and the minimum number of spacecraft needed to sustain POD cadence—is quantified.

A simplified joint simulation of the two payloads is included only to check consistency between subsystem design and system-level behaviour. While individual payload requirements are met, temporal handover between radar detections and optical follow-ups emerges as a limiting factor, motivating refinement of orbital geometry, sensor co-location, and scheduling strategies prior to constellation optimisation.

Acronyms

CCD	Charged Coupled Device
CMOS	Complementary Metal-Oxide-Semiconductor
DSM	Design Structure Matrix
DTM	Drag Temperature Model
ECI	Earth-Centered Inertial
EKF	Extended Kalman Filtering
EOL	End of Life
FOV	Field of View
FWHM	Full Width at Half Maximum
IOD	Initial Orbit Determination
LEO	Low Earth Orbit
POD	Precise Orbit Determination
PSF	Point Spread Function
SAR	Synthetic Aperture Radar
SBSA	Space-Based Space Awareness
SNR	Signal-to-Noise Ratio
SSA	Space Situational Awareness
SSO	Sun-Synchronous Orbit
STK	Systems Tool Kit
THEIA	Threat and Hazard Evaluation for Intelligent Awareness
TLE	Two-Line Element

1. Introduction

The small orbital debris population that remains below current tracking thresholds poses a significant risk to low Earth orbit (LEO) operations [1]. Sub-catalogue debris can cause catastrophic collisions with LEO satellites or mission-ending damage. Reliable cataloguing of these objects is essential for collision avoidance, mission planning, and long-term orbital safety. Current catalogues rely mainly on ground-based radar and optical sensors; for these systems, many small objects are below the detection threshold, and observations are further limited by weather and geography, leading to coverage gaps—particularly for small objects [2]. These limitations motivate a space-based solution to detect and catalogue small debris and maintain a more complete, up-to-date catalogue.

Two sensing technologies, active radar and passive optical, are considered as complementary elements of a space-based sensor network capable of addressing this challenge. Active radar provides the full observable set (range, range-rate, and angles) in a single pass, making Initial Orbit Determination (IOD) more effective. However, radar's usable range is constrained by power and aperture limitations, which constrain the volume of space surveyed per unit time. In contrast, passive optical sensors offer very

long detection ranges across large volumes but primarily deliver angle-only measurements; accurate orbit estimation therefore requires longer time in the field of view (FOV). When prior orbital knowledge is available, optical sensors can efficiently update object states because the required time in FOV is reduced.

These characteristics motivate a division of roles in cataloguing operations: radar systems for IOD, while passive optical sensors for continuous, resource-efficient catalogue maintenance. This synergy leverages the strengths of both modalities—radar provides reliable initial states and optical delivers high-cadence updates that keep catalogue uncertainties bounded.

The present work forms part of the wider Threat and Hazard Evaluation for Intelligent Awareness (THEIA) [3] mission, project aimed at closing the observational gap for small orbital debris in the 5-10 cm range. While the overall mission encompasses systems, electrical, communications, mechanical and mission designs, this article provides a focused analysis of the radar and optical payloads, contributing to the definition of sensor architectures capable of supporting THEIA's global objective of building and maintaining a comprehensive debris catalogue.

This paper outlines the general orbit-determination requirements needed to create and update a catalogue from a space-based platform. The focus is placed on CubeSat-class satellites to demonstrate the feasibility of distributed sensing using small spacecraft. Two sensor models from prior literature, one for radar and one for optical, are adapted and assessed against key figures of merit: (i) time in field of view, and (ii) sensor accuracy. Pareto fronts are presented to expose the trade space, and representative payload designs are selected for each sensor. A notional orbital-constellation design is then simulated to assess the catalogue capabilities of the combined architecture.

The aim of this study is to characterise the relationship between payload design parameters and mission-level performance with respect to identified figures of merit. The associated limitations and constraints are also delineated, clarifying the bounds of the design space and the implications for a practical and scalable constellation.

1.1 Orbit Determination

A space debris catalogue maintains each object's state and covariance at an epoch time, it estimates future states through propagation, and associates new observations to

a debris. To achieve this, detected observations must undergo the Orbit Determination procedure. Observations must support both initial orbit determination (IOD)—a coarse state solution without prior information—and precise orbit determination (POD), which refines an existing state estimate for catalogue maintenance.

Optical systems define angles-only data [4], which yields a precise attributable $[\alpha, \delta, \dot{\alpha}, \dot{\delta}]$ that lacks the range and range-rate, $[\rho, \dot{\rho}]$, to define a six-dimensional state vector through direct measurements [5]. Traditional IOD algorithms, such as Gauss's algorithm, exploit the elliptic properties of an orbit to approximate $[\rho, \dot{\rho}]$ mathematically [6]. This method, however, fails if the target remains in the field of view for a short period of time. Otherwise known as a short arc observation, this condition forces use of techniques such as the admissible region or uncorrelated track association [5]. These techniques complicate the orbit determination process for long-term debris cataloguing.

Pulsed radar systems, however, directly measure $[\rho, \dot{\rho}]$. Moreover, $[\alpha, \delta, \dot{\alpha}, \dot{\delta}]$ are obtainable through direct measurements or finite difference techniques. Thus a target is fully observable independent of the arc length. Relative to optical systems, Radar angular measurements are imprecise, constrained to high power, large in size, and hold reduced range coverage.

Recovering the full six-dimensional state, in a single pass, imposes stricter demands on time in field of view and angular accuracy during IOD, or else requires multi-pass linkage methods. By contrast, active radar can measure angles, range, and often range-rate in one pass, simplifying IOD.

2. Requirement Analysis

The study investigates radar and optical payloads sized for two constellations—one radar and one optical—each composed of 12U CubeSats, with the aim of achieving a cost-effective solution. The system shall be capable of cataloguing orbital debris with diameters as small as 5 cm in the LEO region between 600 and 800 km altitude. This threshold is chosen because tracking debris down to 5 cm significantly reduces the operational risk in LEO by approximately an order of magnitude [7]. This section derives the payload requirements from orbit-determination performance and the overall cataloguing process.

2.1 Optical System

The optical system needs to be optimized for precise orbit determination (POD), meaning refining the object's state using previous knowledge of the orbit. The observations must provide sufficient data for this process to be effective. The two main parameters affecting the success of the orbit determination process in angles-only optical observations are the time in the field of view (FOV) and the accuracy of the observation [8]. With prior orbital knowledge, convergence is achievable with at least 10 s of continuous observation in the FOV and 2 arcsec measurement accuracy [9]; these thresholds are also adopted in comparable space-based sensor studies [10]. From the need to ensure successful orbit determination, a series of payload requirements can be derived. The observation strategy is assumed to be sidereal tracking, in which the spacecraft maintains a fixed attitude with respect to the Earth-Centered Inertial (ECI) frame, resulting in stars appearing as dots. The payload requirements derived for POD are therefore as follows:

- The field of view shall be at least $5^\circ \times 5^\circ$ to ensure a sufficient chance of achieving 10 seconds in the FOV and to provide the observed volume necessary to maintain an adequate detection rate [11].
- The observation subsystem shall generate a minimum of four distinct data points per orbital pass to support successful POD and reduce the likelihood of false-positive detections during a single pass of debris through the FOV [12].
- The angular error shall not exceed 2 arcseconds.

Furthermore, additional requirements that are not directly related to the orbit determination process can also be defined:

- The payload shall observe 5 cm debris at ranges up to 1000 km to ensure a sufficient detection rate and observed volume.
- The telescope shall have an f-number between f/1 and f/45 to ensure ease of manufacturing.
- The focal length shall not exceed 35 cm to fit in a 12U form factor.
- The minimum detection threshold is an SNR of 5 [11].

2.2 Radar System

The Space-Based Radar system must conduct Initial Orbit Determination (IOD) of Debris. The parameter that ensure IOD success is observation precision, while the parameters that maximise debris observations is volumetric coverage.

For IOD success the Radar system must complete the following:

- Define the debris' state within a single pass. This avoids track-let association and traditional IOD algorithms [8] which both of these perform poorly under short-arc conditions.
- Define the debris' 3σ state covariance. To ensure follow-up observation, all possible positions of the debris should be known at the time of follow up observation. This means the state should be propagated alongside the covariance matrix [6].
- The probability of detection shall be prioritised over probability of false alarm. False positives are rejected by the two-stage observation redundancy. A false negative, however, prevents POD and a new entry into the catalogue.

At the sensor level the IOD requirements are:

- The radar shall define all 6 components directly, to define TLE without classical Initial Orbit determination techniques [6].
- The Radar shall achieve a minimum Probability of Detection of 99% at a maximum Probability of False alarm of ≤ 0.001 .
- The SNR shall be greater or equal to 7 dB. Figure 1 demonstrates the SNR required to achieve the required probability of detection and false alarm.
- The radar bore-sight direction shall be off-zenith. This eliminates Doppler ambiguity, and therefore false detections [13].
- The radar shall detect a Radar Cross Section of greater than $0.00785m^2$. This derives from the 5 cm debris detection requirement [14].

Furthermore, there requirements imposed that are independent of initial orbit determination are:

- The radar antenna shall be no larger than 5×0.2 meters in size. This is derived from the 12U constraint [3]

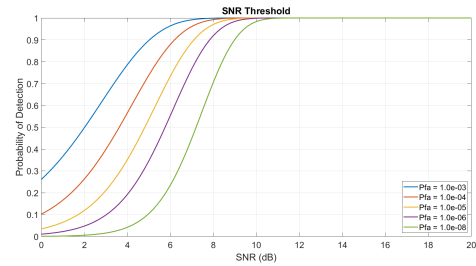


Fig. 1: SNR definition

- The transmitted frequency must lie within 5-5.03 GHz, 45.5-47 GHz or 66 - 71 Hz. This is ITU defined 'Radio-Navigation' [15].
- The peak RF power must be no greater than 22.5 Watts [3]

3. Methodology

3.1 Optical Payload

A methodology is proposed to characterise payload performance and to guide payload selection for the application at hand. Candidate payloads are first screened against the mission requirements; performance is then evaluated using a payload model adapted from [11] to the specific objectives of the study. The trade-space of all feasible designs is constructed and assessed using two figures of merit that drive angles-only precise orbit determination: (i) time in the field of view (FOV) and (ii) angular measurement accuracy.

3.2 Sensor

Choosing the right visible-light sensor is crucial to the payload's effectiveness. The main drivers for this application are: (i) an active area large enough to achieve the required FOV while keeping the angular resolution within requirements; (ii) noise performance and quantum efficiency sufficient to maintain the signal-to-noise ratio above the specified threshold across all observing conditions; and (iii) a readout time—the interval to transfer image data and halt acquisition—short enough to allow multiple sequential exposures during a single debris pass. The Andor Balor sCMOS [16] sensor from Oxford Instruments was selected to satisfy these requirements, choosing CMOS over a CCD due to its faster readout, which enables a greater number of detections within each pass.

Table 1: Andor Balor sCMOS key parameters [16]

Parameter	Symbol	Value	Units
Pixel size	p	$12 \mu\text{m}$	μm
Horizontal pixels	N_H	4128	px
Vertical pixels	N_V	4104	px
Sensor size (horizontal)	b_1	0.0495	m
Sensor size (vertical)	b_2	0.0492	m
Dark current	I_{dark}	0.5	$\text{e}^- \text{px}^{-1} \text{s}^{-1}$
Quantum efficiency	Q	0.61	(fraction)
Readout noise (rms)	σ_{read}	4.3	e^-_{rms}
Readout time	t_{read}	0.0185	s

3.3 Optical payload model

The payload model is based on a pinhole camera model [11] to show how 3D observational event can be imaged in a 2D focal plane.

3.3.1 Field of View

The rectangular FOV has aperture angles Φ_1 and Φ_2 described by Equation 1 [17]:

$$\begin{aligned}\Phi_1 &= 2 \arctan\left(\frac{b_1}{2f}\right) \\ \Phi_2 &= 2 \arctan\left(\frac{b_2}{2f}\right)\end{aligned}\quad (1)$$

Where b_1 and b_2 are the sensors sizes and f is the focal length of the telescope.

3.3.2 Streak

A CMOS image sensor converts incident photons into digital signals via pixel-level photodiodes and in-pixel amplification. When the shutter opens, incoming light is integrated at each pixel over a defined exposure (integration) time, accumulating charge proportional to irradiance. After the shutter closes, the stored charges are converted to voltages and read out.

Assuming the debris can be treated as a point light source as it passes through the field of view, then while the shutter is open it will illuminate a sequence of pixels, forming a streak. This occurs due to the fast relative kinematics characteristic of LEO-LEO observations. From the imaging geometry, the streak length L_{st} (in pixels) can be expressed as in Equation 2 [11]

$$L_{\text{st}} = \frac{f v_{t,a} \tau}{\cos(\theta_{\text{obj}}) d p}, \quad (2)$$

where f is the focal length, τ is the exposure time, $v_{t,a}$

is the relative tangential velocity between the spacecraft and the debris, d is the distance to the object, and p is the sensor pixel pitch. The angle θ_{obj} is defined between the line of sight to the debris (from the camera center) and the focal-plane normal. This angle lies approximately in $[0, \Phi/2]$, where Φ is the full field of view. Assuming a uniform distribution in this interval, the average value $\theta_{\text{obj}} \approx \Phi/4$ is used.

3.3.3 Signal

The example piece of debris can be modelled as a flat plate of with a side of length r . Assuming diffuse reflection [11] show that the total signal S expressed in number of generated electrons from a LEO debris can be express by:

$$S = \frac{H}{8 h \nu} (\rho r^2 (0.4)) \frac{D^2 \tau}{d^2} Q, \quad (3)$$

where $H = 1361 \text{ W m}^{-2}$ is the solar constant, $h = 6.626 \times 10^{-34} \text{ J s}$ is Planck's constant, and $\nu = 600 \text{ THz}$ is the optical frequency of interest. The parameter $\rho = 0.3$ denotes the reflectivity of the debris [18]. The optical system is described by the aperture diameter D and the exposure time τ , and the observation geometry is determined by the distance d between the debris and the spacecraft. Finally, Q represents the quantum efficiency of the sensor.

3.3.4 Noise

A realistic output signal shall account for noise contributions. In CMOS sensors such as the one selected for this study, four main sources of noise are typically present [11].

Shot Noise: (σ_{shot}) is noise due the natural fluctuations in the number of photons that arrive to the sensor.

Sky Background noise: (σ_{sky}) is from photons coming from the minimal light in the sky.

Dark Noise: (σ_{dark}) is due to a phenomenon called dark current where some electrons are randomly generated even when no signal is received.

Read Noise: (σ_{read}) is an inherent noise of the camera and it is generated when the pixels are read and the signal amplified.

The total noise can be approximated as a sum of independent Gaussian noises [19] [11], as shown in Equation 4.

$$N = \sqrt{\sigma_{\text{shot}}^2 + \sigma_{\text{sky}}^2 + \sigma_{\text{read}}^2 + \sigma_{\text{dark}}^2} \quad (4)$$

Other variances can be calculated as follows:

$$\sigma_{shot}^2 = S \quad (5)$$

$$\sigma_{sky}^2 = K \cdot n_{ip} \cdot \tau \quad (6)$$

$$\sigma_{dark}^2 = I_{dark} \cdot n_{ip} \cdot \tau \quad (7)$$

$$\sigma_R^2 = R_N^2 \cdot n_{ip} \quad (8)$$

In these cases, n_{ip} is the number of illuminated pixels, I_{dark} is the dark current of the chosen sensor, R_N is the read noise of the sensor and $K = 0.01 \frac{\text{electrons}}{\text{pixel} \cdot \text{s}}$ is the dark sky count [19].

The number of illuminated pixels can be calculated with Equation 9 by multiplying the streak length by the streak width W_{streak} .

$$n_{ip} = L_{streak} W_{streak} \quad (9)$$

Before the width of streak can be defined some consideration about the resolution of the sensor need to be made.

3.3.5 sub-Pixel Centroiding Considerations

In telescopes with a large field of view (FOV), the angular resolution per pixel is typically much coarser than the required one. A common solution to this problem is the use of sub-pixel resolution techniques, widely applied in star trackers [20]. These methods enable the recovery of an object's position with a precision finer than the pixel scale by estimating the centroid of the image formed on the detector.

Sub-pixel resolution relies on the assumption that the image of a point source spans at least two detector pixels [20]. If the signal is confined to a single pixel, all information about the object's intra-pixel position is lost. In diffraction-limited systems, the point spread function (PSF) of a distant point source can be approximated by a two-dimensional Gaussian distribution:

$$I(x, y) = I_0 \exp\left(-\frac{(x - x_0)^2 + (y - y_0)^2}{2\sigma^2}\right) \quad (10)$$

where (x_0, y_0) denotes the centroid position and σ is the standard deviation in pixel units. The full width at half maximum (FWHM) of the Gaussian is related to σ as [21]:

$$\text{FWHM} = 2\sqrt{2 \ln 2} \sigma \quad (11)$$

A FWHM of at least 2 pixels is typically required to ensure that the signal spans multiple pixels, allowing for accurate

Gaussian fitting and sub-pixel centroiding [20] [21]. However, large FOV optical systems are often undersampled, meaning that $\text{FWHM} < 2$ pixels.

To address this, a minimum signal width of two pixels is imposed by defining:

$$W_{\text{pix}} = \max\left(2, \frac{2.44, \lambda, F}{p}\right) \quad (12)$$

where λ is the wavelength, $F = f/D$ is the focal ratio, and p is the detector pixel pitch. The second term represent the diffraction limited FWHM in pixels of the telescope. When the optical PSF does not meet the 2-pixel criterion, this can be achieved through intentional defocusing [22], which spreads the light over a larger number of pixels. While this reduces the signal-to-noise ratio (SNR), it enables the use of sub-pixel resolution techniques by ensuring the PSF is sufficiently sampled.

For space debris observations, objects typically appear as streaks rather than point sources due to their motion during exposure. Nonetheless, the same principle applies: the streak can be modelled as a convolution of the Gaussian PSF with a line segment [23]. Fitting this model to the observed intensity profile allows for sub-pixel localization of the streak endpoints, thereby meeting angular resolution requirements even in the presence of undersampling. Therefore, we define the streak width to be at least two pixels, assuming defocusing is applied when necessary to satisfy this condition.

3.3.6 SNR

Finally, it is possible to calculate the signal to noise ratio using:

$$\text{SNR} = \frac{S}{N} \quad (13)$$

3.4 Parametric study

A parametric study was conducted using the camera model. The goal was to find which telescope parameters meet the requirements. Furthermore the study aims at finding an exposure time that, while being possibly not optimal for every observational scenario, meets the detection requirements for all the observational scenarios. A flow chart of the study is shown in Figure 2.

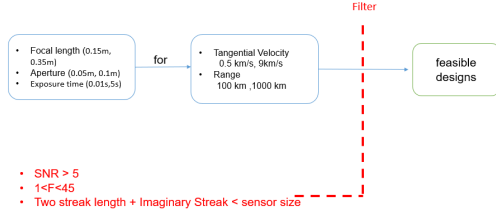


Fig. 2: Flow chart of parametric study

The value ranges chosen are also shown in Figure 2. The focal length and aperture ranges were constrained by the requirements. A maximum relative tangential velocity of 9 km/s and a maximum range of 1000 km were chosen. The resolution of 100 for each variable sweep was chosen. The debris size was kept at 5 cm as this is the worst case scenario in terms of signal received.

3.4.1 Process

The following steps were conducted for each combination of focal length, aperture and exposure time, which in this analysis constitutes a possible design. First the F number constraint was applied and the designs that did not meet the requirement were discarded. For each combination of relative tangential velocity and range the camera model was used to estimate SNR and streak length. Then the design was considered feasible if, for all the observational scenarios, it met the following requirements:

- $SNR > 5$
- Two streak length + imaginary streak length < sensor size

This final filter originates from the requirement of at least 4 data points per debris pass. While the shutter is open, information about the debris's location and the corresponding time stamp is lost, because the debris may be accelerating relative to the satellite. Therefore, the only useful data points are the start and end of each streak, and at least two streaks are required to satisfy the requirement. Here, we define an "imaginary streak" as the trace that would be recorded during the shutter's readout time when the shutter is closed. This ensures that, over one pass of debris through the field of view (FOV), at least four data points are retrievable.

3.5 Trade-space and figures of merit

All feasible designs are evaluated against two figures of merit that are directly related to the POD process. The

outcome is a trade-space of possible designs and a tool to inform payload selection for this application. The two figures of merit are: (i) time in the field of view, which should be maximized, and (ii) angular accuracy, which should be maximized (equivalently, the error minimized). From a sensor perspective, these map to two key parameters: field of view (FOV) and centroiding accuracy.

In sidereal tracking, the time an object remains within the FOV depends on the specific observing scenario, but it is always constrained by the FOV: a larger FOV allows longer continuous observations.

The angular coordinates accuracy of the debris in the focal plane (right ascension and declination) depend on several factors, including jitter, attitude/pointing knowledge, and timestamp accuracy. However, they are ultimately limited by the centroid accuracy, which is set by the sensor parameters.

This latter quantity can be estimated with Equation 14 [20]:

$$\sigma_{centroid} = C_{\sigma} \frac{\theta}{SNR}. \quad (14)$$

In Equation 14, $\sigma_{centroid}$ is the 1σ uncertainty on the centroid position, θ is the angular pixel size, and C_{σ} is a constant that depends on the point-spread function (typically $C_{\sigma} \approx 1$) [20].

3.6 Radar Payload

In this work a methodology is proposed to characterize payload performance and guide payload selection for IOD of debris. i) Candidate Radar Technologies are screened against mission-level requirements. ii) Performance of remaining technologies quantified through modification of an existing model []. A Volumetric Coverage - State Uncertainty trade-space is assessed. iv) Revisit time Uncertainty quantification through Kalman

3.6.1 Figures of Merit

- **Measurement Uncertainty:** Through Covariance propagation, the integration of velocity uncertainties grow the error ellipsoid [6]. If unfeasibly large, this prevents recovery observations from the optical system. The measurement uncertainty dictates the initial state covariance. Therefore, measurement uncertainty should be minimised to enable longer revisit times. Measurement uncertainty is defined by angle σ_a and

range σ_r .

$$\sigma_r = \frac{c}{2B\sqrt{2SNR}} \quad \sigma_a = \frac{\theta_{BW}}{k_m\sqrt{2SNR}}$$

c is the speed of light, B is bandwidth, θ_{BW} is the largest beamwidth direction, k_m is the monopulse pattern difference (typically 1.6 [24]), SNR is the Signal to Noise ratio

- **Volumetric Coverage:** Assuming a cone-like coverage pattern, it is decomposed into field-of-view (FOV), the angle between the centre-line and the side, and slant range. FOV defines the number of satellites required per plane; A large FOV observes a larger proportion of inclinations and RAAN. Slant range defines the number of satellite altitudes required.

Figure 3 illustrates that, at low slant ranges, FOV and slant range equally contribute to Volumetric coverage.

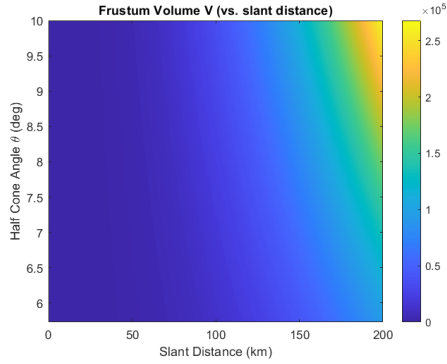


Fig. 3: Volumetric Coverage as a function of centre-line Range and half-cone field of view

3.6.2 Radar Technology Selection

The 5 cm resolution requirement forced selection of a Synthetic Aperture Radar (SAR) payload. SAR maximises SNR for a fixed slant range, therefore SAR minimise the measurement uncertainty. Equations 3.6.2 demonstrate the relationships clearly. For a mono-static configuration $SNR_{Monostatic} \propto \frac{1}{R^4}$, while $SNR_{SAR} \propto \frac{1}{R^3}$.

$$SNR_{Monostatic} = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^4 R^4 k T_n B L}$$

$$SNR_{SAR} = \frac{P_t G^2 \lambda^3 \sigma \delta_r}{2(4\pi)^3 R^3 k T_n F L V \cos(\phi)}$$

The terms are defined by Slonik in the Radar Handbook [13]. For this study, the parameters of interest are the

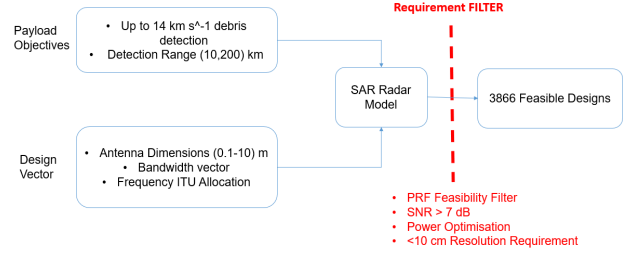


Fig. 4: High-level Methodology of Trade-space Generation

gain, G , slant range R , grazing angle, ϕ , RCS, σ , and wavelength, λ .

Scan-SAR and Strip-SAR were taken forward for quantitative study. The aim of the radar is to identify the maximum number of debris. Spotlight SAR relies on long, focused, integration times which minimises volumetric coverage.

3.7 Radar payload Model

The Synthetic Aperture Radar (SAR) Model is based on Golkar's Small Sat SAR parametric model [25]. Only alternations, additions and determination of fixed parameters are presented. The model was created in MATLAB, available through GitHub [26].

3.7.1 Design Variation Vectors

- **Antenna Dimensions:** Due to the 5 cm resolution requirement, the Azimuth dimension is fixed [17]. However, the width dimension can be varied to effect SNR. Through equation 3.7.1 and 3.6.2 $SNR \propto W^2$. The quadratic relationship between antenna width and SNR shows high sensitivity between the parameters and through equation 3.6.1 the measurement uncertainty.

$$G = \frac{4\pi L W}{\lambda^2}$$

[25]

- **Range:** Equation 3.6.1 and 3.6.2 illustrate $\sigma \propto R^{3/2}$, while the conical volume, V , is proportional to the slant range squared. The high sensitivity to both figures of merit makes key design variable.

3.7.2 Sub-Swath Definition

For ScanSar, the number of sub-swaths increases the effective field of view, therefore volumetric coverage, at

the penalty of integration time and slant range per swath, therefore SNR and measurement uncertainty. The method was as follows:

- Design vectors of number of sub-swaths and slant range were chosen.
- The SAR antenna area was defined while across track, frequency were held constant.
- Minimum antenna dimension requirement eliminated unfeasible antenna sizes.
- The required Antenna area and Slant Range was used to assess the SNR, and measurement uncertainty.
- The associated slant range was used to define Field of View.
- The 7dB SNR requirement was used to highlight valid Range and subswath combinations.

3.7.3 Central Carrier Frequency Definition

Defined in section 2.2, ITU constraints place 3 available frequency, f , bands. Through equation 3.6.1 and equation 3.6.2 $\sigma \propto \frac{1}{f^{5/2}}$ while $FOV \propto \frac{1}{f}$, therefore maximising uncertainty penalises the field of view therefore the volumetric coverage and ultimately the number of debris identified per second. Frequency was determined through fixing slant

range and antenna dimension parameters while assessing the relationship between RF power and transmit frequency. RF power was the only remaining free variable within the SNR equation.

3.7.4 SAR Graze angle Definition

For a zenith pointing, radar systems detections have identical Doppler signatures either side of the centre-line. This requires an angled viewing geometry, therefore a grazing angle must be defined [13]. The grazing angle max-

imises the swath width, therefore field of view, at the cost of increasing slant range, therefore measurement uncertainty. A minimum grazing angle of 20 degrees was taken [17]. This ensured feasible measurement uncertainty therefore optical revisit times.

3.8 Filtering and Propagation

The propagated state covariance can be further reduced through filtering [6]. This is required due to the poor angular measurement uncertainty of Radar systems [13].

An extended Kalman filter was used for its simplicity and good non-linear handling for high sample rates [6]. Shown through the previous section, this suits the high PRF design of the chosen SAR system.

3.8.1 Extended Kalman Filtering

Prior to the filter, a sampled debris orbit was taken i) angle-rate uncertainties, with respect to the observer, were approximated through equation 15 [27]. ii) sample debris detections gated by chosen radar range and FOV parameters. iii) LVLH to ECI conversion of remaining detections. iv) The PRI, Initial debris state, complete measurement uncertainty and time under FOV was used as initial parameters for an EKF. v) Rate of EKF convergence and debris state covariance was assessed at the end of the time in FOV. Assumptions include:

- Range-rate uncertainty of $5 \mu\text{m}$ [28].
- Ideal Clohessy Wiltshire dynamics in observation.
- Satellite and debris orbit are coplanar.
- Zero Process Noise - No perturbations expected.

Range-rate is assumed to be $5 \mu\text{m}$ as the range uncertainty were of similar magnitude to the wider literature [28].

$$\sigma_{\dot{a}} = \sqrt{2\sigma_a^2} \quad (15)$$

3.8.2 Monte Carlo Propagation

Once outside the Radar FOV, the Debris state and covariance was propagated through Monte Carlo Methods. The required optical maximum revisit time was defined when the debris 3σ was equal to the minimum swath within the optical FOV. This ensures a 99.7% likelihood of successful follow-up observation.

3.9 Mission Integration

To evaluate the performance of the dual-payload constellation, a simulation environment was developed in MATLAB and complemented with STK visualisation tools. A lightweight orbital propagator advanced the states of both satellites, with their associated payload models, and the synthetic debris objects. An event-drive access routine determined debris observability as a function of sensor constraints. Within this framework, the code counted if a debris object was observed by each system under imposed conditions (FOV, time and detectability thresholds). A simple dynamical model, which only considers the J2

perturbation of Earth's gravitational field was used, while additional effects such as atmospheric drag, solar radiation pressure, and third-body perturbations were neglected to reduce computational complexity.

Given the fundamentally different observation geometries, two dedicated constellations were adopted rather than a single mixed-plane architecture. The optical payload relies on angles-only measurements under favourable illumination, line-of sight, and dwell-time conditions, which are best satisfied in Sun-synchronous, anti-sun pointing scenarios. By contrast, the radar payload is range- and range-rate-capable but constrained by effective range and off-nadir geometry, favouring altitudes and phasing that maximise volumetric coverage over time. Separating the constellations allows each sensor type to operate at its optimal altitude, inclination and spacing.

Debris populations were generated synthetically, with random distributions in the 600–800 km altitude band and inclinations between 60° and 105°, consistent with the expected density peak identified in the MASTER environment. The RADAR satellites were tasked with Initial Orbit Determination (IOD), while optical satellites were configured to perform Precise Orbit Determination (POD) within a specified revisit window. Each debris object was required to remain within the payload's field of view (FOV) for a minimum dwell time to be considered detected.

A simplified version of the radar sensor model was implemented in this simulation. In particular, the inclination of the payload's FOV was not considered, and the sensor footprint was idealised as a symmetric cone defined only by its range and half-angle. This assumption reduced computational burden but may have led to an optimistic estimation of the effective detection performance.

Visibility constraints were incorporated for both payload types. For the optical constellation, eclipses, communication windows, and Sun–satellite geometry were modelled to ensure realistic illumination and line-of-sight conditions. For the radar constellation, off-nadir pointing was included according to the payload's effective range, and the natural drift in the Right Ascension of the Ascending Node (RAAN) was exploited to maximise coverage over time.

Finally, the number of satellites in each constellation was not predefined but derived through an incremental “build-up” roadmap. First, a single orbital plane with a minimum number of satellites was simulated to assess baseline detection performance. Additional satellites were

then iteratively introduced, either within the same plane or by adding new planes, until the detection and catalogue maintenance requirements were approached. The radar constellation was configured with the objective of detecting the maximum number of debris in the shortest possible time, while the optical constellation was designed to maximise the number of revisits within the shortest possible interval. This roadmap allowed identification of trade-offs between constellation size, coverage time, and catalogue completeness.

4. Results

4.1 Optical payload results

Figure 5 presents all feasible designs evaluated against their worst-case performance. The focal length is shown on the axis, since it is directly linked to the field of view through Equation 1.

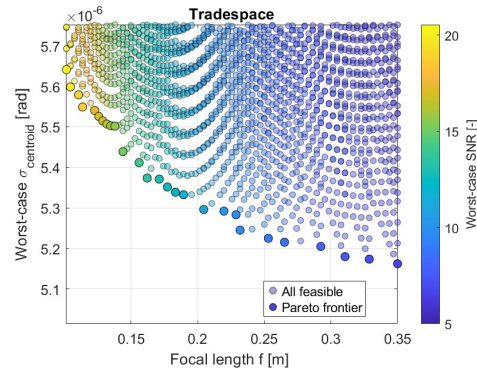


Fig. 5: Trade-space

There are two main trends that give rise to this Pareto front

1. **Field-of-View and Angular Resolution:** Reducing the focal length increases the FOV, which in turn worsens the angular resolution θ and thus increases the centroid error σ_{centroid} .
2. **Signal-to-Noise Ratio:** At the same time, a shorter focal length spreads the same total signal onto fewer pixels, raising the SNR and thereby reducing σ_{centroid} .

The two trends largely offset one another in terms of centroid accuracy; however, the dominant effect is the reduction in angular pixel size (i.e., the pixel's instantaneous field of view) as focal length increases. Consistent with this, the worst-case SNR declines at longer focal lengths:

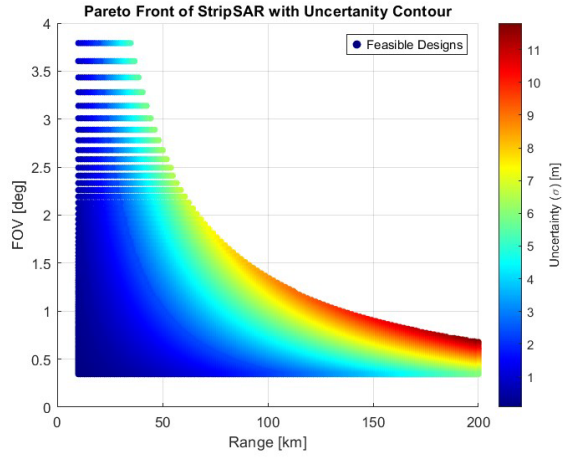


Fig. 6: StripSAR Tradespace: Defined by half-cone FOV and Slant Range

objects spend less time on each pixel, producing longer on-detector streaks, so the same signal is distributed over more pixels reducing SNR.

A focal length of 0.23 m was chosen for the mission simulation in section 4.4 as a good trade-off between FOV and centroid accuracy.

4.2 Radar Payload results

Figure 6 and 7 clearly show a Pareto frontier. The maximum volumetric is placed within the top right hand-side of the figure. While the minimum measurement uncertainty is placed within the lower left hand-side of the figure. Therefore these relationships are mutually exclusive. The StripSAR and ScanSAR design spaces are defined by different driving requirements:

- ScanSAR design space: Characterised by low uncertainties and low volumetric coverage, a stripSAR design enables a longer revisit time requirement over ScanSAR. The number of available solutions are limited through the PRF constrains. This leaves high SNR, therefore low measurement uncertainty, solutions to meet the requirements. This is expected; the small swath width (defined through FOV) enables longer integration times over the target.
- ScanSAR design space: Characterised by high volumetric coverage and high measurement uncertainty, a ScanSAR design can identify numerous targets at the penalty of a lower revisit time requirement for the

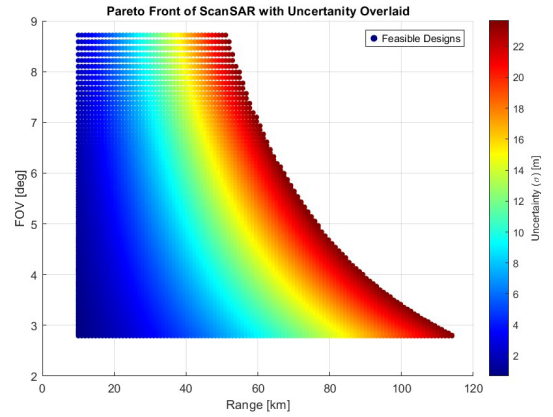


Fig. 7: ScanSAR Tradespace: Defined by half-cone FOV and Slant Range

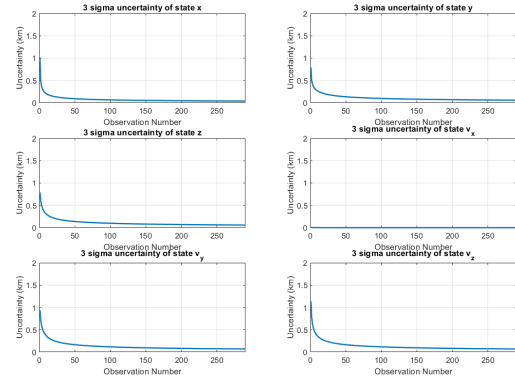


Fig. 8: Extended Kalman Filter: 3σ uncertainty reduction

Optical System. As a result, the ScanSAR design is ideal for numerous follow-up sensing platforms.

The chosen design was defined by the compatibility with the specific mission profile. The FOV and Range were chosen to minimise the number of Radar satellites. As a result, the Scan-SAR design was chosen with a range of 68.24 km, FOV of 5.87 degrees and Average uncertainty of 23.66 degrees [3]. The design had a PRF of 9750 Hz.

4.3 Revisit Time Definition

A PRF of 9750 Hz, or PRI of 102 s, enable 300 detections within the field of view of 5.87 degrees, under a maximum relative velocity of 9 km s^{-1} . At maximum slant range, this results in a required time in view of 0.125 s. Figure 8 demonstrates the converging relationship between

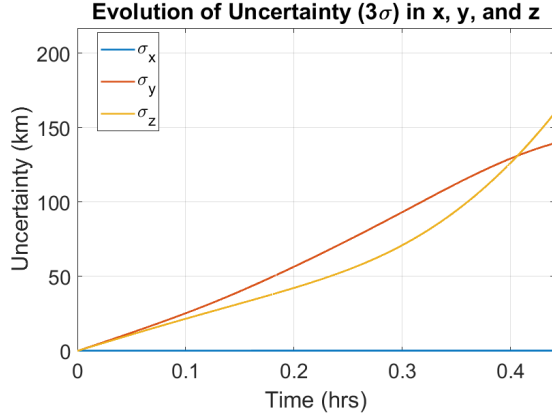


Fig. 9: Growth of Covariance Matrix under Monte Carlo Propagation

the debris' ECI Cartesian uncertainty and the number of detections via an EKF. The initial uncertainty is defined by the measurement uncertainty, while the number of detections is determined by the radar PRI and FOV. In figure 8 the FOV is fixed 5.87 degrees. Two conclusions can be drawn from figure 8:

- Low Radar PRI enable numerous detections within a single pass. Through an EKF, a low radar PRI results in a drastic reduction of final target state uncertainty. This enables longer propagation before the state 3σ is equal to minimum sensor swath width. As a result, radar PRI and required follow-up revisit time are proportional.
- There is an asymptotic relationship between post-EKF uncertainty and the number of detections. After 16.7% of maximum number of detection, the EKF holds diminishing returns.

The final state uncertainty defined the 3σ covariance matrix. The covariance matrix was sampled the propagated via Monte Carlo techniques [29]. The required follow-up revisit time was 20 minutes, this forced numerous optical satellites within the constellation. If the number of satellites were tightly constrained, one could use figure 9 to define post-EKF state uncertainty required, use figure 8 to define a minimum number of detections required and, therefore, the PRI required for a fixed FOV.

4.4 Mission integration

Both sensor parameters are used as inputs to the mission integration code, together with the 20-minute revisit

requirement between IOD and POD. The radar constellation, composed of 15 satellites distributed across five orbital planes at altitudes between 590 and 750 km and an inclination of 80 degrees, was configured to exploit the J2-induced drift in RAAN to maximise volumetric coverage. This design enables a full-sky scan in less than one year and results in an average detection rate of 85% over 350 days.

In contrast, the optical constellation consists of 108 satellites placed in in two Sun-Synchronous orbital planes (SSO). The adoption of SSO is driven by the characteristics of the optical payload, which requires consistent illumination conditions and favourable Sun-satellite geometry to ensure reliable observations. Within each plane, the optical satellites are deployed in pairs, allowing their fields of view to converge and thereby improving effective coverage and detection probability. Under this configuration, the optical constellation is capable of maintaining 76.2% of the catalogue, with revisit times ranging between 7.2 and 9.5 hours.

However, when both constellations were integrated into a sequential detection strategy, the results fell significantly short of expectations. Only 34.05% of the debris detected by radar was revisited by the optical payloads within the required 20-minute POD window. As a consequence, the overall effective catalogue coverage after five years was estimated at just 25.9%.

5. Future work

Future work, regarding the mission simulation, should incorporate the proper radar's FOV and a more complete dynamical models, including drag, solar radiation pressure, and third-body perturbations, to refine performance estimates. The consequences of deploying large constellations on the space environment must also be assessed, alongside the study of collision-avoidance manoeuvres necessary to ensure safe operations. The Radar assumed system model parameters should be tested; the radar cross section of debris geometry from different view angles and the SAR losses should be modelled. An investigation into multi-polarisation should be conducted to increase the radar capabilities and assess debris shape, material and orientation [30]. The optical payload model would also need to be validated, including the centroid accuracy estimation.

6. Conclusion

These results underline the limitations of the current constellation architecture and simulation assumptions. In

particular, the simplified dynamical environment and the lack of modelling of additional perturbations may underestimate potential opportunities for re-observation. Nevertheless, the negative outcome is valuable, as it identifies critical weaknesses in the baseline design and highlights the need for constellation reconfiguration, more accurate dynamical models, and possible payload co-location strategies in future iterations. Additional design iterations, together with a more realistic representation of satellite behaviour and detection performance, are required to properly evaluate the effectiveness of the proposed architecture.

In this study, we presented a preliminary analysis of the trade-offs of radar and optical payload configuration for a space based sensor network to catalogue small debris. We then simulated the presented strategy showing the limitation of the current configuration and the need of more iterations. While the current results should be viewed as preliminary, they provide useful insight on payload selection for the purposes of orbit determination.

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Space-based sensor fusion for refined space debris cataloguing

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