Feasibility study on the recycling of a close to end-of-life optical Earth-observing satellite constellation for orbital debris detection

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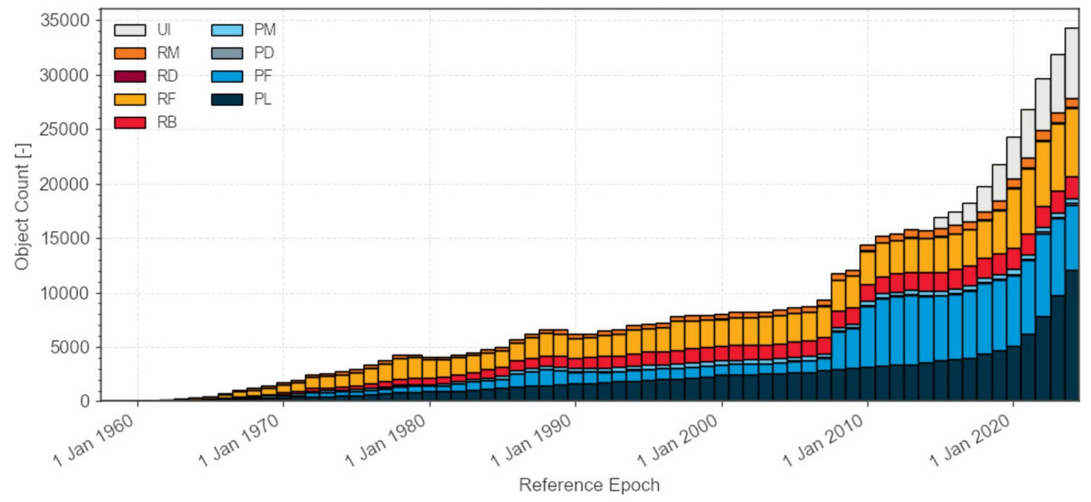
Introduction

The growing amount of space debris is a phenomenon that dates back to the first man-made object launched into space: the Soviet spacecraft Sputnik-1. Due to the exploration of space only being a recent technological advancement with scientists and engineers operating under the assumption that space was "self-cleansing" (Schefter, 1982), the 60s and 70s were plagued with space missions that gave no regard to their sustainability.

By the late 1970s, data analysis and population simulations of existing debris catalogues helped bring to light the worsening situation. One particular threat was the cascading effect of debris colliding with each other and creating more debris: this was coined the "Kessler Syndrome" after NASA astrophysicist Donald J. Kessler.

Despite knowledge of this phenomenon and its repercussions, the ever-growing numbers of yearly space launches alongside various events such as in-space collisions and anti-satellite tests have all contributed to the population of objects larger than 10 com being at around 30 000.



▲ **Figure 1: Evolution of space debris (from ESA)**

However, a 1cm large piece of debris would be enough to cause serious damage and potentially disable a spacecraft; current estimations place the population of debris of this size at around 1 100 000. These pieces of debris pose a real threat to active satellites. As an example, the ISS has had to perform on average 1.3 collision avoidance manoeuvres a year since its launch; this statistic is predicted to increase with time.

In order to perform the collision avoidance manoeuvres, satellite organizations require accurate debris orbit predictions. However, ground-based observations have limitations:

- The atmosphere prevents the observation of objects smaller than around 2 cm.
- Accurate prediction techniques require long observation periods and accurate object identification to reduce errors.

This work aims to address the second point, by studying the feasibility of recycling a soon-to-be-disposed Earth observing constellation, rescoping it for debris observation. This study will focus on comparing the recycled constellation's observation access time to that of current ground-based observation capabilities. The difference in observation access times will determine the "value for money" of this recycling, which can be divided into two points:

- Observation access times of a piece of debris will be longer, leading to better orbit predictions with fewer errors
- There will be no need to launch new payload to achieve these new observation access times which will help contribute to the hope of a space circular economy

Systems selection

In order to compare the observation access time of debris between a recycled constellation and a ground station, they need to be defined. The constellation, Cosmo-SkyMed, has been chosen based on the following:

- It must be in LEO.
- It must possess optical observation capabilities with a reasonable resolution.

The ground stations have been chosen from ESA's Space Surveillance and Tracking segment; one optical and one radar: OGS & TIRA.

Name	φ (°)	λ (°)	h (m)
OGS	28.30096	-16.51182	2396
TIRA	50.6166	7.1296	264

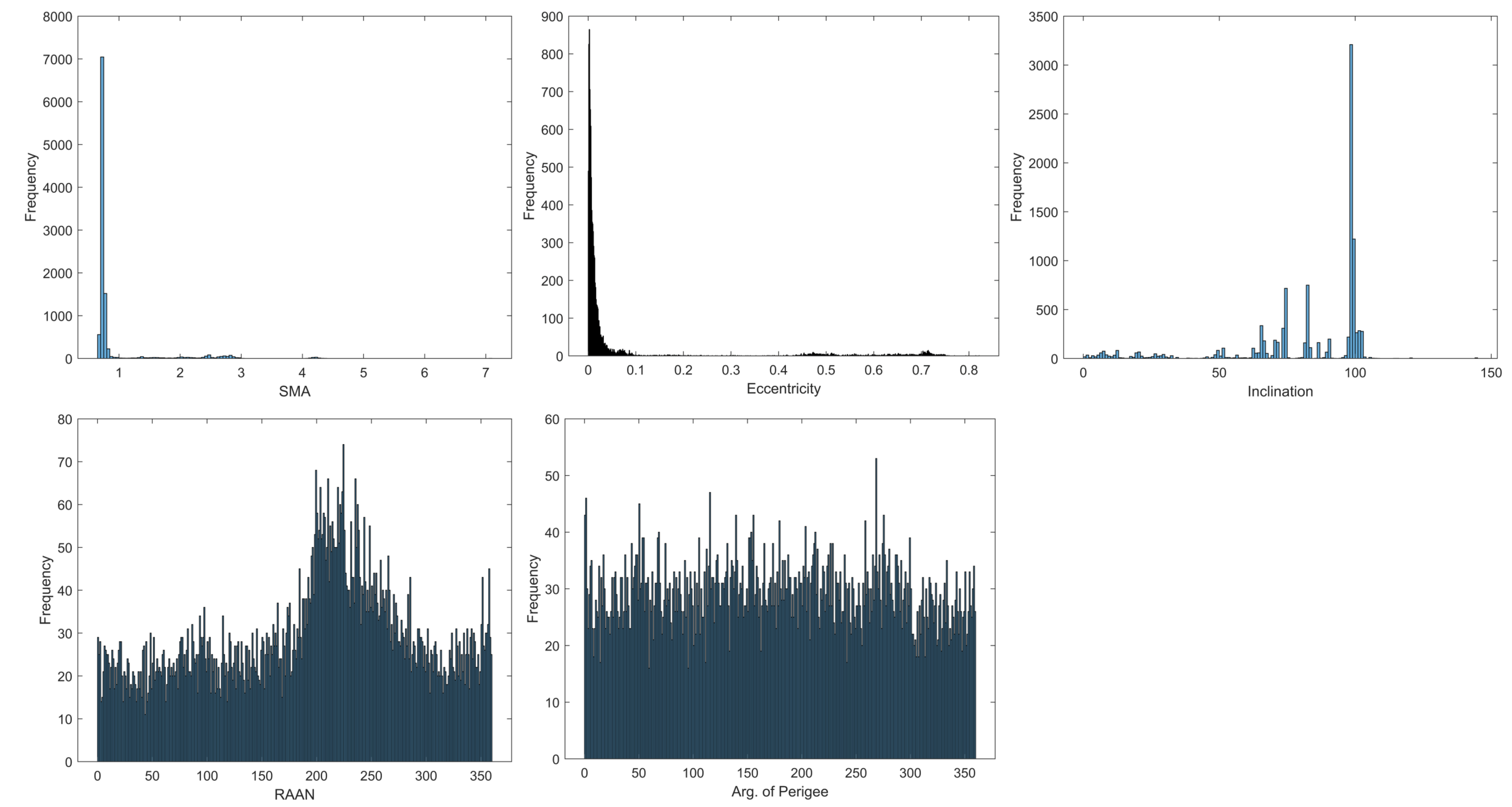
▲ **Table 1: Coordinates of the chosen ground stations**

Name	Altitude (km)	Ecc.	Inc. (°)	RAAN (°)	AoP (°)
Cosmo-SkyMed 1	619.6	≈ 0.0001	97.86	29	84
Cosmo-SkyMed 2	619.6	≈ 0.0001	97.86	29	89
Cosmo-SkyMed 3	619.6	≈ 0.0001	97.86	44	90
Cosmo-SkyMed 4	619.6	≈ 0.0001	97.86	29	90

▲ **Table 2: Characteristics of the satellites of the chosen constellation.**

Method

To simulate the recycled constellation's observation access time of debris, this debris needs to be defined. To do that, debris data from the space-track 3LE catalogue was analysed. The distribution of orbital elements of all tracked debris is detailed below.



▲ **Figures 2-6: The first five orbital elements' distribution within the orbits of all tracked debris**

The debris field used for analysis was then defined as a group of individual points in the area where debris is most present in space. Its definition is displayed in table 3 and is illustrated in figure 7.

Element	Field Bounds	Step
a	7250 km ± 50 km	2 km
e	0.0095	n/a
i	98° - 100°	1 °
Ω	TBD ± 15°	0.5°
ω	TBD ± 15°	0.5°

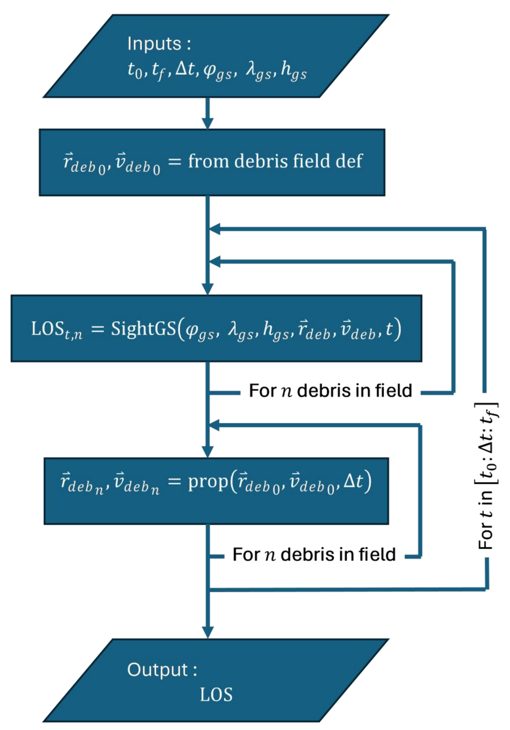
▲ **Table 3: Characteristics of the defined debris field.**

▲ **Figure 7: Visualisation of the defined debris field.**

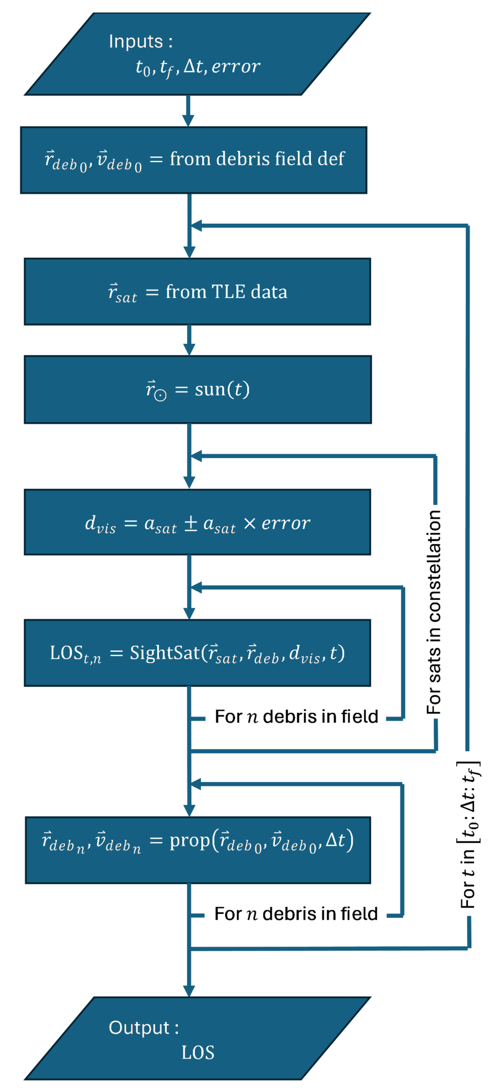
The comparison process is based on two algorithms. Algorithm 1 calculates the observation access time of a debris field from a constellation. It does this by checking for a line-of-sight between each individual point in the field and each satellite in the constellation. This line-of-sight must be the length of the satellite's focal length. As this is only a preliminary feasibility study, this length has been chosen to be the satellite's nominal altitude with a 20% leeway. The line-of-sight computation also only returns positive if the debris is sunlit, and outside of a 35° satellite-to-Sun exclusion zone.

Algorithm 2 calculates the observation access time of a debris field from a ground station. It does this using the same method described previously. For radar observations, all constraints are removed, as focal length and sunlight are no longer a factor. For optical observations, the debris must be sunlit, and the ground station must not.

Note: the SightGS and SightSat functions in the algorithm are the line-of-sight computations. The prop function is for object propagation.



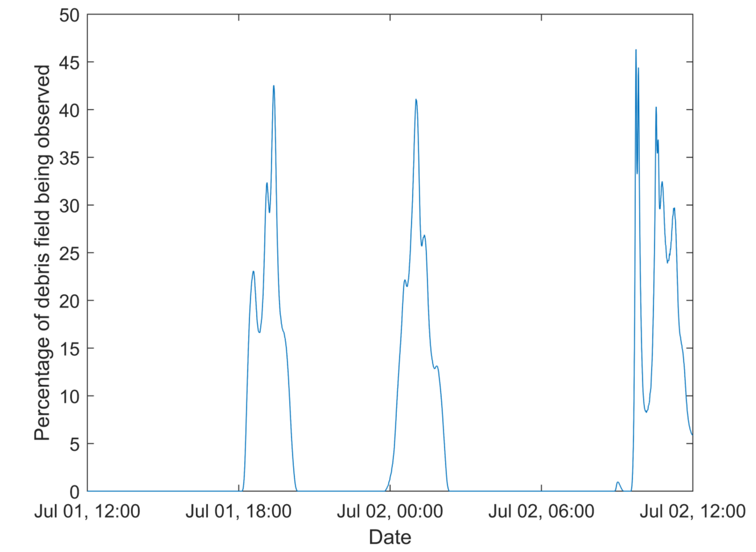
▲ **Algorithm 2**



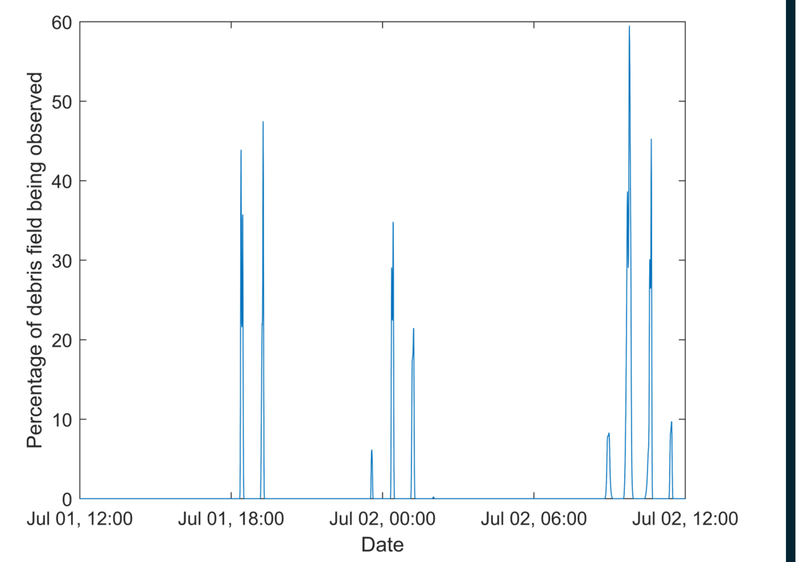
▲ **Algorithm 1**

Results

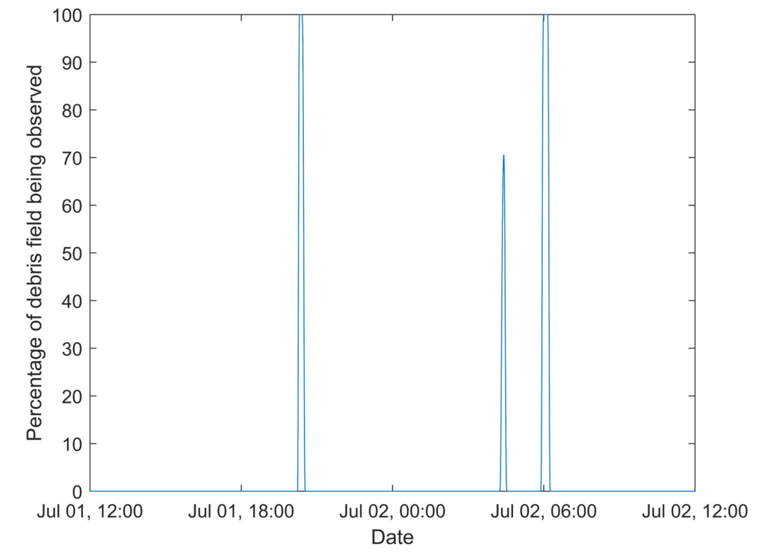
The results for this comparison are displayed below. These come in the form of plots showing how much of the debris field is being observed over a 24-hour period.



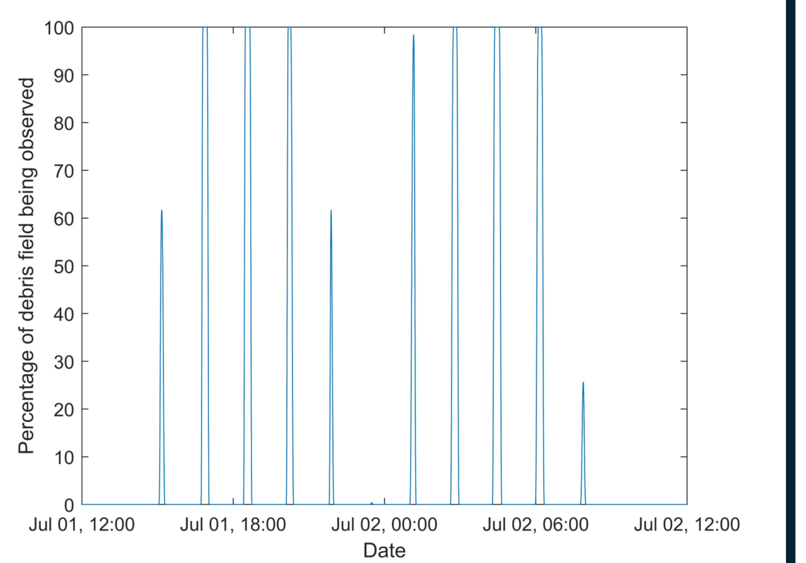
▲ **Figure 8: Percentage of Cosmo-SkyMed's observation access of the debris field (with a RAAN of 6°) over time.**



▲ **Figure 9: Percentage of Cosmo-SkyMed's observation access of the debris field (with a RAAN of 6° ±25°) over time.**



▲ **Figure 10: Percentage of OGS's observation access of the debris field over time.**



▲ **Figure 11: Percentage of TIRA's observation access of the debris field (with a RAAN of 6°) over time.**

	Const. RAAN 6°	Const. RAAN 6°±25°	OGS	TIRA
Total observation access time (mins)	451,5	198,5	57	178
Total number of useful passes	3	5-6	3	11
Avg. individual observation (mins)	113	38	18	16
Max. achieved field visibility	42%	54%	100%	100%
Visibility at half of total observation access time	18%	6%	70%	64%
Avg. time between observations (mins)	198	144	460	85
Time spent at over 90% field visibility (mins)	0	0	22,5	73

▲ **Table 4: Summary of results.**

Conclusions

There are several outcomes to this preliminary feasibility study. The recycling of an optical Earth-observing constellation in order to rescope it for debris observation is, at the moment, a trade-off between visibility and observation access time. This is due to the assumed limitations in focal length of Cosmo-SkyMed's hardware. This means recycling an optical Earth-observing constellation would have its advantages and its drawbacks.

However, the total amount of observation access time disregarding debris field visibility percentage is extremely high and heavily advantageous to reducing errors in debris orbit determination. Additionally, space technology is evolving very quickly, with satellite sensor resolutions getting smaller and smaller every year in order to more accurately observe Earth. This means recycling future close-to-end-of-life constellations would hopefully allow the observation of smaller and smaller pieces of debris.

However, in the time being, if solving the focal length limitation problem can be achieved, by either rescoping satellites with long-range radars or variable focal length optical cameras on board, the recycling of an Earth-observing constellation after its intended mission for debris observation would have the following benefits: not only would it lead to less errors in debris orbit determination and the ability to keep a better track on them, but it would also contribute to a circular space economy and prevent the need to launch new payload into space.