SUTED - A DETAILED STUDY FOR THE APPLICATION OF THE FLYEYE TELESCOPE TO THE SURVEY OF THE MEO ORBITAL REGION

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ABSTRACT

SUTED study, SUrvey TElescope for the Debris detection, promoted by the Italian Space Agency and lead by OHB Italia with the participation of SpaceDyS, has been successfully completed in February 2021, demonstrating the possibility to build up a catalogue of dangerous MEO objects using a ground network of 4 Flyeye telescopes, equipped with an ad hoc real time shutter for space debris observations. They make it possible to discover and catalogue (COLD START) within 2 months 100% of GNSS-like (Global Navigation Satellites) debris with a size bigger than 35 cm.

A whole set of realistic simulations were performed based on the ESA MASTER8 Population Model. The observational strategy was defined based on the orbital characteristics of the target objects (MEO), the sensors (Flyeye telescopes) and the network. The simulations have concerned a whole set of optical observations, subsequently processed by SpaceDyS for performing orbit determination and catalogue build up, using ad hoc developed advanced orbit correlation algorithms.

1 SUTED STUDY OVERVIEW

SUTED study (SUrvery TElescope for the Debris detection) focuses on the analysis and demonstration of the capability of a network of Flyeye telescopes to detect and catalogue MEO space debris. In order to validate the proposed system, realistic simulations have been performed: the term “realistic” is used here to state that all the driving difficulties of the task are addressed, so that the final results are reliably significant to evaluate the efficiency of the system in accomplishing the task in terms of object population coverage, catalogue build up and catalogue maintenance.

The output of such simulations obviously depends on all the imposed assumptions, (e.g., target objects characteristics, observational site selection and network architecture, observational strategy, physical observational conditions, meteorological constraints, etc.).

In this view, in order to properly evaluate the driving elements involving the entire system, the simulations are based on full cycle simulations, i.e. starting from the generation of the simulated optical measurements, passing through the data processing and ending with the catalogue of orbits.

The SUTED study logic is depicted in Figure 1. The following main activities have been performed:

- Selection of a **Space Debris Population Model** to be used as ground truth for the simulations. A representative sample has been extracted from the up-to-date ESA MASTER8.
- **Network architecture definition** (number of observatory sites, locations, number of involved instruments, etc.).
- **Observational strategy definition** on the basis of the sensor setup.
- **Detectability assessment**, determined by a combination of interplaying factors, such as light, Earth shadow and clouds, object dimensions, etc.
- **Generation of the optical measurements**, by using a Simulator SW tool, running all the orbits contained in the population record and check the observability and detectability conditions for each station of the network.
- **Correlation and Orbit determination**, by using the SpaceDyS SW libraries. This will include the computation of preliminary orbits starting from the simulated tracklets, the full differential correction and the subsequent refinement of the orbits with additional observations. The resulting catalogue will

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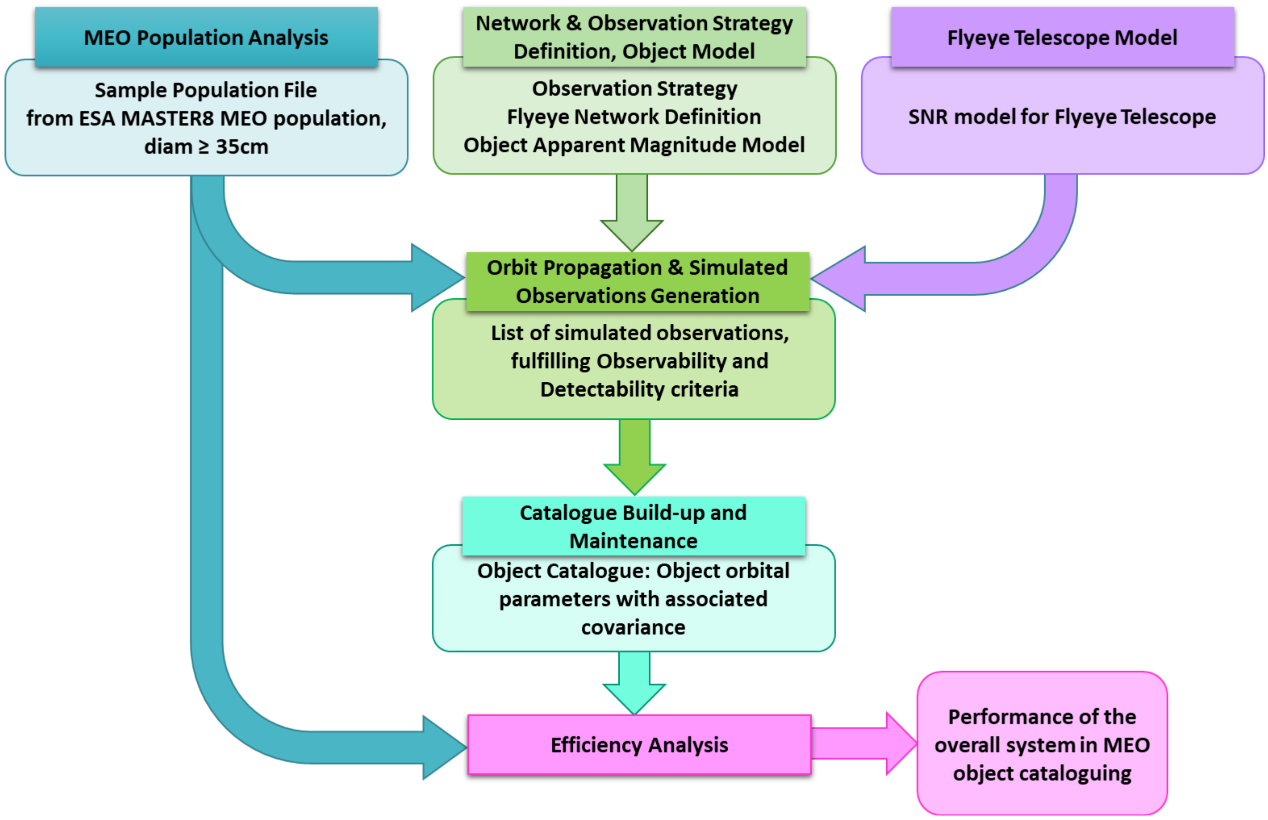

Figure 1: SUTED study logic

include both orbital parameters and covariance.

- **Overall performance analysis**, assessing the completeness level of the population and the orbital accuracy against the simulation assumptions.

All the studies, simulation and validation tasks, refer to the Flyeye telescope as an innovative optical ground-based observational instrument and its related performances.

2 FUNDAMENTAL STUDY ELEMENTS

In the following, a brief description of the fundamental aspects addressed in the SUTED study is provided.

2.1 POPULATION SAMPLE

The European Space Operations Centre (ESOC) provided a reference population of man-made objects down to object sizes of 1 cm, supposed to orbit around the Earth at epoch 2023-11-01. The population was generated according to the MASTER-8 model, which is currently the de-facto standard in the space debris community. The MASTER-8 population was converted to a de-sampled one, which amounts to 820613 objects. This was the baseline population, the reference population from which we extracted the sample to be used in the simulations.

Since this study concentrates on MEOs, the de-sampled baseline population was filtered, considering only MEO resident and MEO transient objects. Moreover, only objects above a suitably chosen size were selected. For MEO resident class, only objects greater than 35 cm were retained.

The filtered population contains a total of 594 MEO resident objects with diameter above 35 cm. We distinguish between GNSS-like orbits and other MEO resident objects, according to the definitions reported in Table 1. The MEO transient objects amount to 8983. Our choice was to include in the final population sample the entire set of 594 MEO resident objects greater than 35 cm and to extract randomly a sample containing 1% of the MEO transient objects. The result is summarized in Table 2.

Table 1: Definitions of the MEO subclasses.

MEO resident objects		
Acronym	**Name**	**Definition**
GNSS	GNSS-like orbits	(Global Navigation Satellite System) Number of revolutions per day in [1.5; 2.5] and eccentricity smaller or equal to 0.2.
NNSS	Not GNSS-like orbits	Orbits in the MEO class, which are not in the GNSS class.

Table 2: Number of objects per orbital regime, contained in the population sample.

MEO		MEO transient			TOTAL
GNSS	NNSS	LEOT	HEO	GEOT	
317	**277**	**68**	**15**	**6**	**683**
594		**89**			**683**

2.2 OBSERVATION CONCEPTS

Optical observations have the advantage of exploiting the abundant radiation provided for free from the Sun. On the other hand, have constraints resulting from the physics of the observation process. Because the source of light illuminating the satellite/debris is the Sun, an essential requirement is that the object is outside the shadow cone of the Earth. Moreover, the optical ground sensor cannot operate unless the ground station is inside the same shadow cone. Last but not least, there are meteorological constraints: a simple cloud cover is sufficient to prevent any optical observation.

Once these fundamental observation conditions are satisfied, the possibility to actually detect a particular object depends on the signal to noise (S/N) ratio of the source acquired by the sensor.

All these considerations lead to the identification of two different concepts, namely the Observability and Detectability conditions.

Observability: an object passing over a station is observable at a specific time if the sun light reflected by the target object could be readable by the selected ground station telescope. It is mostly related to geometrical constraints (e.g. elevation angle, sun below horizon, etc.)

Detectability: Once the Observability conditions are satisfied, the factors allowing to detect a particular object must be analysed (S/N condition). The possibility to detect the object trail is fundamentally dependent on the object apparent magnitude and angular speed, and on the sensitivity of the applied optical sensor.

2.3 FLYEYE TELESCOPE: A UNIQUE TECHNOLOGY

The telescope is based on a patented technology, named Flyeye, which grants high accuracy in an extremely wide Field of View (FoV=44 sq. degrees) and the astronomic resolution tailored for typical European observational sites (1.5 arcsec/pixel).

In the SUTED study, an analytical S/N model based on current Flyeye telescope characteristics is used for observations detectability assessment.

Table 3:Flyeye telescope features

Flyeye Telescope Main Features	
Class Aperture Diameter	1 m
Entrance Pupil Shape	Circular
Optical Efficiency	>0.8
Field of View	6,7deg x 6,7 deg
Pixel Scale	1.5”x1.5”
Pixel Size	15 µm
Axes maximum speed	7deg/s
Axes maximum acceleration	12deg/s^2

2.4 FLYEYE NETWORK DEFINITION AND OBSERVATION STRATEGY IDENTIFICATION

The Flyeye network has been defined considering both meteorological correlation and seasonal effects.

Since the telescope must be in full darkness during observations, a nearly equatorial station can operate in theory only about 10 hours per day (namely). Higher latitude stations can operate on the average for a similar time but with huge seasonal changes. This implies that, to have a quite constant total amount of available observing hours, the observing stations have to be in both hemispheres and at similar latitudes. Moreover, the number of stations must be sufficient to recover the meteorological effect, and stations must not be too close to avoid having the same meteorological situation.

The selected network includes 4 Flyeye stations, two in the northern and two in the southern hemisphere.

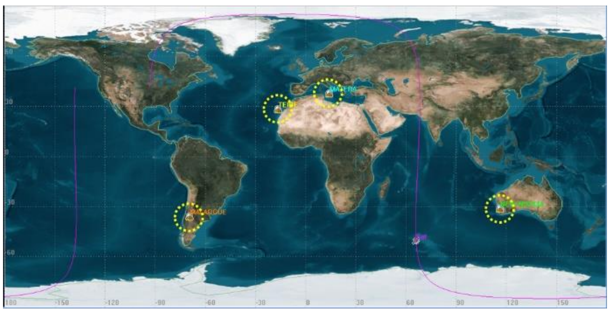

Figure 2: Flyeye Network

Another crucial aspect of study is the definition of the observation strategy, focusing the observations in the sky areas where the target objects are more easily observable and detectable. It has to be remarked that, being the MEO orbital belt quite large, including objects near to both LEO and GEO belts, the object orbital characteristics are quite various and different from each other. Therefore, it is not possible to define a unique observation strategy optimal for all these kinds of orbits. The adopted observation strategy is optimized for the observation of Resident MEO object in the GNSS-like subclass.

A strip of sky (Fence) is identified, which is cyclically observed by the telescope to intercept all the debris going through it. The selected fence combines a strip around the equatorial plane (where all the objects must pass through) and a part bending along the edge of the Earth shadow cone (where the phase angle is the most favorable). This strategy is named **Mixed Strategy**.

3 ORBIT PROPAGATION AND SIMULATION OF OBSERVATIONS

Each object of the population sample has been propagated using a commercial propagator integrated with specifically developed SW modules.

The simulated scenario implemented all the observational constraints (physical, geometrical, sunlight, etc.), the network and the observational strategy (mixed strategy) to define a list of possible optical observations during accessibility periods referred to each observatory and object. Therefore, each generated observation fulfils the observability condition. To each observation is then associated the object apparent visual magnitude (considering phase angle, object albedo, air mass correction factor) and the related S/N, allowing to check the compliance to the detectability condition.

Finally, the list of simulated observations, fulfilling both observability and detectability conditions, is stored in a file following the agreed format to be used by the Orbit Determination algorithm.

The simulated station meteorological conditions are taken into account in a dedicated filter applied before the Orbit Determination activities.

3.1 ORBIT DETERMINATION AND EFFICIENCY VALIDATION

The entire process of construction of a catalogue from scratch (COLD START) and of its maintenance using only survey observations (no use of additional follow-up strategies) was simulated. In the process, only observations are used. No a priori knowledge of the orbits is assumed. The orbital data of the population sample used to generate the observations are exploited only for the analysis of the results.

The starting point of the orbit determination algorithms are the *attributables*. The observation of a trail appearing in the image resulting from a single exposition is stored in the form of two detections, defining the position of the start and end of the trail. The measurements of the positions on the celestial sphere are given using right ascension α and declination δ in the topocentric equatorial frame, centred at the observer. A couple of detections, $\{(t_i,\ \alpha_i,\ \delta_i),\ \mathrm{i}=1{,}2\}$, defining the beginning and the end of a trail, is a tracklet. From a tracklet it is possible to get information on the proper motion of the object. The entire information comprising the mean angular position and velocity associated to the trail is stored in an attributable $\mathrm{A}=(\bar{t},\alpha,\delta,\dot{\alpha},\ \dot{\delta})$, referred to the mean epoch $\bar{t}$ of the tracklet. The information contained in an attributable is not enough to compute a full six parameters orbit. Information on the range and range rate, i.e. the distance of the object from the observer and the radial velocity, are missing.

Advanced methods for initial orbit determination (IOD), based on the usage of the first integrals of the two-body problem, were applied to find 2-tracklets correlations [2, 3]. The obtained orbits are always solutions of a least squares problem and as such their covariance is always provided.

The attribution of additional tracklets to a known orbit is performed comparing any new tracklet with the prediction computed using the orbit. The comparison takes into account the predicted uncertainty. The attribution of new tracklets is considered successful only if it is possible to obtain an orbital fit with the entire set of tracklets (differential corrections convergence) and the obtained solution is good according to predefined metrics (for example the RMS of the residuals is under a fixed threshold and does not degrade with the addition of new tracklets).

The data are processed day by day (simulation of a data centre behaviour). At each step (IOD or attribution) a procedure of *correlation management* is performed to remove duplicates and merge, if possible, correlations having some tracklets in common. The general iteration scheme is represented in Figure 3.

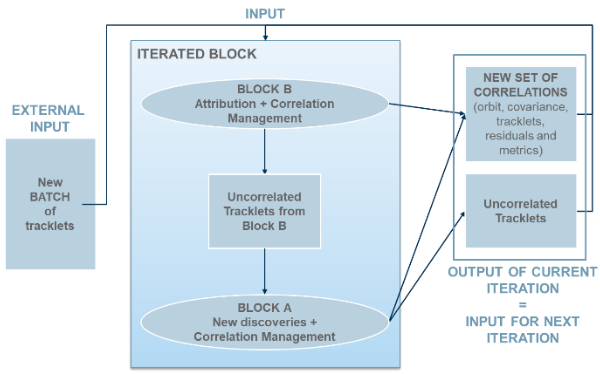

Figure 3: General iteration scheme.

A lower limit of three tracklets is imposed in order to accept a correlation as a new discovery and insert it in the provisional catalogue. An object is inserted in the catalogue if its accuracy 48 hours after the end of the simulation is within a fixed envelope defined in the RTW local orbital frame. The RTW frame is centred in the object and its axes are defined by the radial, transversal and out-of-plane directions. The envelope for MEO objects in RTW is defined by the thresholds (600 m, 3000 m, 1500 m), according to [4]. This is the envelope adopted for the simulations of this study.

4 STUDY RESULTS

We stopped the simulation after the processing of 60 days of observations. Almost 92% of the entire population sample comprising both MEO resident and transient objects were catalogued. The situation is represented in Figure 4, in the size vs. perigee altitude plane:

- the green dots represent catalogued orbits.
- the blue dots are unconfirmed or degraded orbits, which means that the orbit is in the provisional catalogue or it has a reduced accuracy caused by a long gap in the observations.
- black dots are objects observed but still without a calculated orbit. All of them have perigee below 8000 km altitude.
- Red dots are objects not observed in the considered 2 months. They have small size and low perigee.

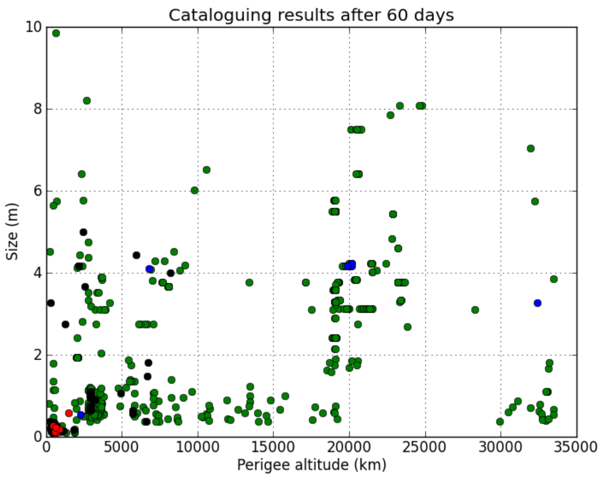

Figure 4: Results after 60 days.

In Table 4 and Table 5 a deeper analysis is performed for the MEO resident objects, which are the target of the study and represent the 87% of the considered population. The analysis is performed distinguishing between GNSS and NNSS orbital subclasses of the MEO class. It confirms the optimum performance of the cataloguing system, taking into account that the observation strategy is optimised for GNSS.

An interesting point is that in our simulations the orbital accuracy degradation (temporary envelope violation) is not a problem for the maintenance of the catalogue. In the presented simulation, the catalogued orbits are maintained successfully, meaning that the orbits are correctly updated through the attribution of new observations as soon as they are available, even when gaps of many days occur in the observations.

In conclusion, SUTED study has demonstrated that

- With a Network of 4 Very Large Field of View Flyeye telescopes (44 square degrees)
- Implementing an observation strategy optimized for MEO resident objects in GNSS-like orbit
- Considering a true MEO population sample extracted from the up-to-date ESA MASTER8 model, including objects with diameter ≥ 35cm
- Using the real SNR Flyeye telescope model for Object Detectability criteria verification
- Exploiting advanced Orbit Determination Algorithms for COLD START catalogue Build-up, simulating the realistic behaviour of a Debris Data Center,

100% of GNSS-like MEO objects are successfully discovered and catalogued within 2 months, and more than 96% of all MEO Resident objects are successfully discovered and catalogued within 2 months.

Table 4: Cataloguing efficiencies after 2 months of observations, for each subclass of MEO objects. The efficiency of orbit determination is computed as the ratio between the number of found orbits and the number of objects having at least three tracklets.

	GNSS	NNSS	Total MEO
Catalogue Obj.	100%	92.42%	96.46%
Eff. OD	100%	92.78%	96.63%

Table 5: Cataloguing results after 2 months, with respect to different object size thresholds. Results are provided for each subclass of MEO orbits, GNSS and NNSS.

	GNSS				NNSS			
Sizes (m)	**≥0.35**	**≥0.50**	**≥1**	**≥5**	**≥0.35**	**≥0.5**	**≥1**	**≥5**
No. Objects	317	315	308	58	277	247	120	8
Catalogued objects	317	315	308	58	256	227	111	7
Unconfirmed orbits	0	0	0	0	1	1	0	0
Without orbit (only 1-2 tracklets)	0 (0)	0 (0)	0 (0)	0 (0)	20 (0)	19 (0)	9 (0)	1 (0)
Not observed	0	0	0	0	0	0	0	0

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