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Tracking the health of the space debris environment with THEMIS

Camilla Colombo[*†], Andrea Muciaccia*, Lorenzo Giudici*, Juan Luis Gonzalo*, Alessandro Masat*, Mirko Trisolini*, Borja Del Campo[+], Francesca Letizia[#], Stijn Lemmens[#]*

** Politecnico di Milano, Department of Aerospace Science and Technology, Via La Masa 34, 20156, Milan, Italy*

[+] DEIMOS, Airspeed 1, 151 Eighth Street, Harwell Campus, OX11 0RL

[#] European Space Agency, Space Debris Office, ESA/ESOC - European Space Operations Centre, Robert-Bosch-Str. 5, 64293 Darmstadt, Germany

camilla.colombo@polimi.it, andrea.muciaccia@polimi.it, lorenzo1.giudici@polimi.it, juanluis.gonzalo@polimi.it, mirko.trisolini@polimi.it, alessandro.masat@polimi.it, borja.delcampo@deimos-space.com, francesca.letizia@esa.int, stijn.lemmens@esa.int

[†] Corresponding Author

Abstract

In this paper the operational tool for the computation of the space debris index that will be released through a web-based front end by the end of 2023. The development of the software THEMIS is the results of an effort of Politecnico di Milano and Deimos UK within a project funded by the European Space Agency to track the health of the space environment the impact that current and planned missions have on it. The formulation for the assessment of the space debris index will be presented together with some examples of application to Low Earth Orbit missions.

1. Introduction

Space, as any other ecosystem, has a finite capacity. The continuous growth of space activities, due to our increasing reliance on services from Space, the privatisation of the space market and the lower cost of deploying smaller and distributed missions in orbit, is from one side improving human-life quality and, however, it is also contributing to overloading this delicate ecosystem.

International discussion is ongoing at the Inter Agency Debris Coordination Committee and at COPUOS on how to measure the overall capacity of the space environment and assess the impact that individual missions have on it. This quantification presents several challenges, as mission architecture can be diverse, from single monolithic spacecraft to large satellite constellations. Also, operational concepts for collision avoidance manoeuvres, post mission disposal design and the reliability of its implementation affect the environmental mission footprint. Long term simulations show that, with the deployment of large constellations and the steep increase in launch traffic of the last few years, space debris mitigation needs to adapt to this evolving environment.

The software THEMIS is developed by Politecnico di Milano and Deimos UK within a project funded by the European Space Agency to track the health of the space environment the impact that current and planned missions have on it. The space debris index of a single mission is evaluated by considering the risk of collisions and explosions of an analysed object and quantifying the effects in terms of cumulative probability of collision of the resulting simulated debris cloud on a set of targets representing the active spacecraft population. As the index is computed considering the debris flux coming from debris environmental tools and statistical estimation of explosion probability derived from historical data, the approach is able to update the assessment based on the evolution of space activities.

Moreover, the index can be computed on the whole population of objects in space to evaluate the overall space capacity. This can be projected into the future thanks to long-term simulations with ESA's DELTA software tool, that represent the evolution of the background population, and by aggregating and comparing the space debris index of several missions. The paper will present the operational tool for the computation of the space debris index that will be released through a web-based front end by the end of 2023. The paper is organised as follows: Section 2 presents the THEMIS space debris index in terms of its mathematical formulation, computational structure.

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2. THEMIS space debris index

To define the THEMIS software tool, it is first important to explain the mathematical formulation on which the backend of the software is based on. Then, the computational structure and design of the tool will be discussed with particular focus on the description and analysis of the effect maps that are used to evaluate the impact of a space mission on the active spacecraft population.

2.1 Index formulation

As described in [1] and [2], the space debris index in THEMIS follows the formulation of the Environmental Consequences of Orbital Breakups (ECOB) index [3] and is defined as a risk indicator. The formulation is composed by a probability term (p), which quantifies the collision probability due to the space debris background population and the explosion probability of the analysed object, and a severity term (e) associated to the effects of the fragmentation of the analysed object on the on the sustainability of the space environment. The index evaluation at a single time epoch is computed as

$$I = p_c \cdot e_c + p_e \cdot e_e \tag{1}$$

where p_c and p_e represent the collision and explosion probabilities, and e_c and e_e represent the collision and explosion effects, respectively. Following the approach in [4], the space debris index at a single time epoch is computed using Eq. (1) and the evaluation is performed for each time epoch in each phase of the mission (i.e. launch, orbit injection, cruise, end-of-life disposal). In the case the spacecraft is active, the computation of Eq. (1) is performed twice, with and without Collision Avoidance Manoeuvre (CAM) capabilities, so that, at a generic time epoch of the mission the index is

$$I = \beta \cdot I_{CAM} + (1-\beta) \cdot I_{no-CAM} \tag{2}$$

where I_{CAM} is the index at a single epoch when CAM capabilities are considered, I_{no-CAM} is the index at a single epoch when No-CAM capabilities are considered, and β is the CAM efficacy that can be set between 0 and 1 or can be computed using the ESA ARES tool based on the fractional risk reduction, which measures the efficacy of the avoidance strategy [5].
To assess the impact of the entire mission space environment, the value of the index is computed as:

$$I_t = \int_{t_0}^{t_{EOL}} I\,dt + \alpha \cdot \int_{t_{EOL}}^{t_{end}} I\,dt + (1-\alpha) \cdot \int_{t_{EOL}}^{t_f} I\,dt \tag{3}$$

where t_0 is the starting epoch, t_{EOL} is the epoch at which the operational phase ends. The first term of Eq. (3) refers to the operational phase of the object. The second and the third term refer to the Post-Mission Disposal (PMD) phase where it is contemplated that the End-Of-Life (EOL) disposal may fail [4]. The reliability of the PMD is included through the parameter α to be set between 0 and 1, tend is the epoch at which the disposal ends, and t_f is the epoch at which the object would naturally decay from its initial orbit. An upper limit for t_f can be used, for example 100 years [4].

2.1 THEMIS computational structure

Figure 1 shows the block diagram of the THEMIS computational core for the space debris index. Each component of the debris index in Eq. (1) is computed.
The explosion probability $p_e(t)$ Eq. (1) is derived from an estimation of statistical data extracted from ESA DISCOS database [6]. Object properties, their classification (into payload or rocket bodies) and their status (active/inactive) is used to extract a probability of explosion in terms of explosion probability density as function of year after launch. This is done for each class of objects, i.e. payload or rocket bodies, but could be also characterised for subclasses of objects of the same family, for example some particular class of rocket bodies.

The collision probability $p_c(t)$ in Eq. (1) is evaluated along the mission profile of the through kinetic gas theory [7][8] as explained in [1][2][9]. The debris flux used for the computation of the collision probability and the average impact speed are taken from ESA MASTER 8 [10]. The collision probability is computed against all the debris population if

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no CAM capability is implemented on-board the mission, or with only object larger than a set threshold if the spacecraft has CAM capabilities. The latter threshold is computed by considering ground tracking capabilities (e.g., about 10 cm for objects in LEO and 1 m for objects in GEO), and then considering the minimum size of a debris to trigger a catastrophic collision.

The fragmentation effects are stored in so-called effect maps. Indeed, an orbital grid approach is used for the computation of the probability term and the explosion terms [9][11]. In other words, a map is created for the orbital region of interest in the relevant orbital elements that characterise that region. This will be explained in the next Section.

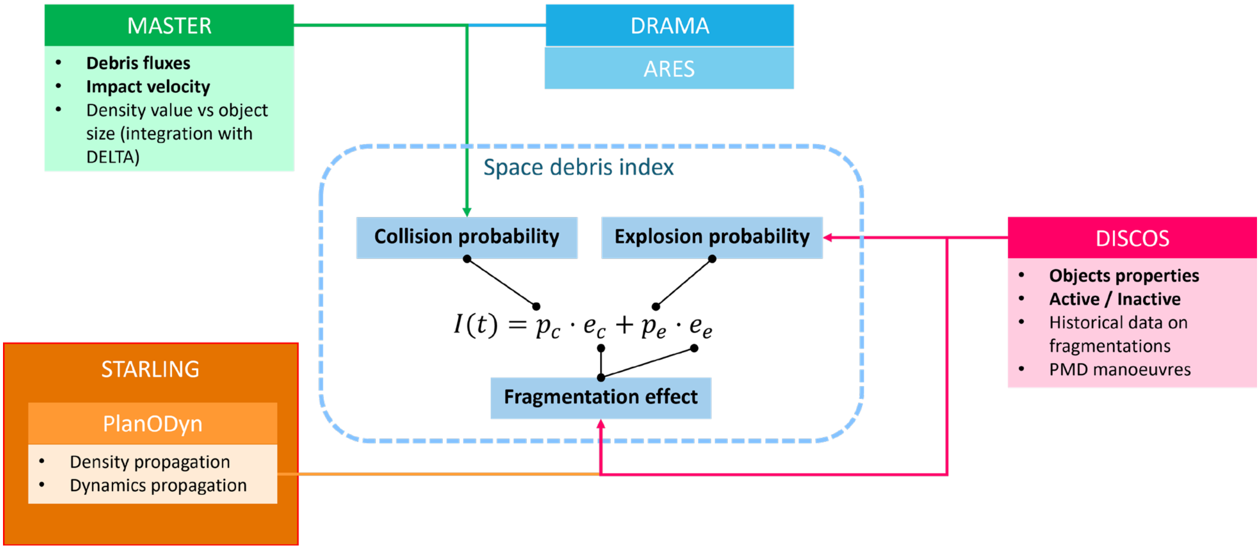

Figure 1: block diagram of the THEMIS computational core for the space debris index.

2.1 THEMIS effect maps

Effect maps are built for the whole orbit domain of interest; the orbit region that THEMIS can tackle are Low Earth Orbit (LEO), medium Earth orbit, geostationary Earth orbit or geostationary transfer orbit, therefore the debris risk index for a missing in any of these regions can be computed. Each one of these regions is divided in orbital elements bins, defined to capture the relevant orbital dynamics in each of these regions.

For each bin of the domain the effect term of collisions e_c and explosions e_e is pre-computed by the STARLING 2.0 tool developed at Politecnico di Milano [9][11][12]. To compute the fragmentation (either a catastrophic collision or an explosion) effect, synthetic fragmentations are triggered in each orbital bin of the orbital region considered. Fragmentations are modelled through a probabilistic reformulation of the standard NASA break-up model [13] as a collision or as an explosion. A novel technique to evaluate the phase space domain in Keplerian elements and area-to-mass ratio occupied by the ejected fragments was developed [9][11]. Such a technique allows reducing the computational cost for each fragmentation.

Each resulting cloud is then propagated through a continuum approach that numerically integrates the evolution of the phase space density along the orbit evolution characteristics [14]. The PlanODyn propagator [15][16] is adopted for the semi-analytical orbit integration under atmospheric drag, J_2 perturbation, solar radiation pressure and third-body perturbation. The propagated characteristics are eventually interpolated through a binning approach for sparse distributions proposed in [17].

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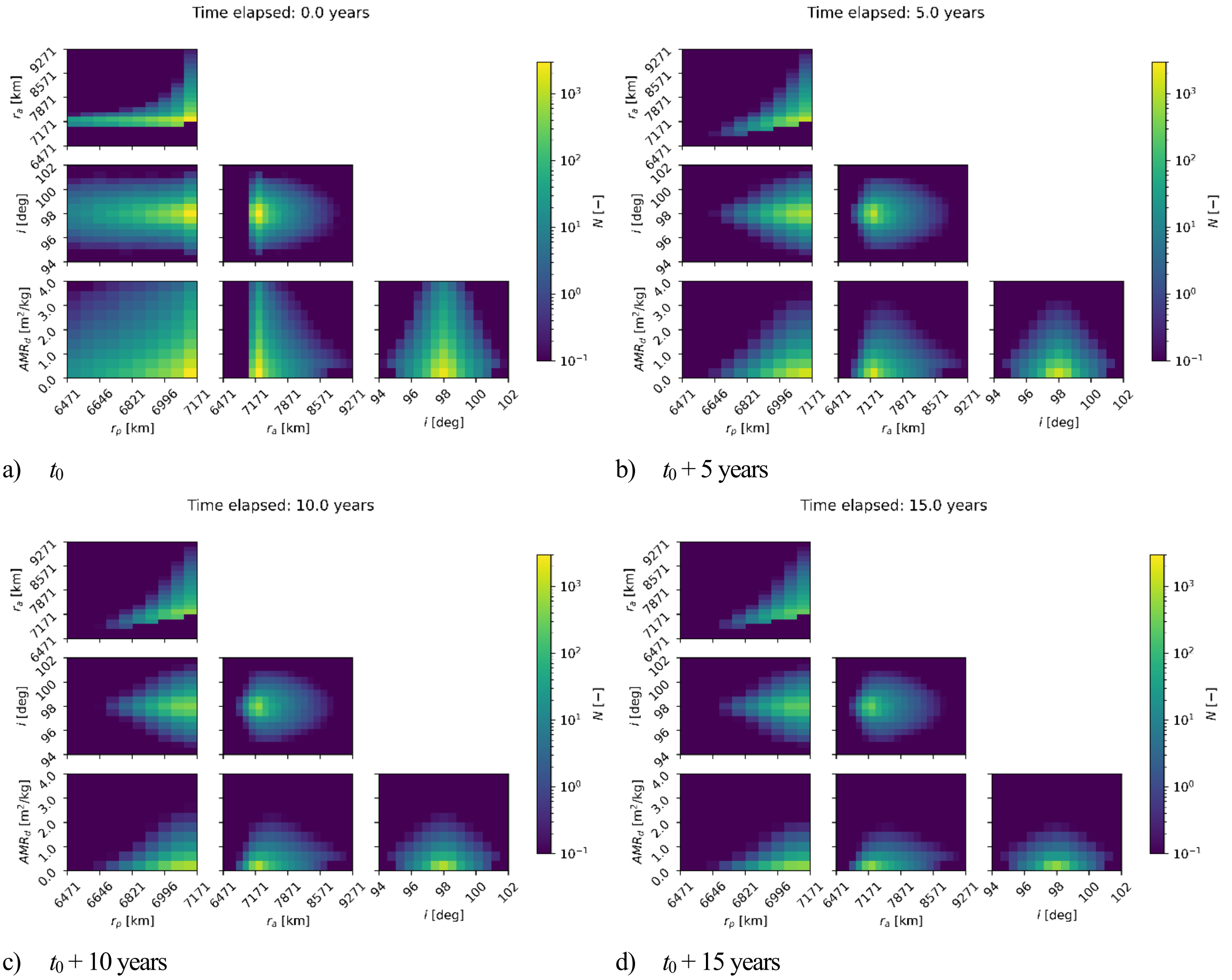

Figure 2: Cloud propagation through STRALING 2.0. Fragment number per each bin of the domain in radius of apogee, radius of perigee, inclination, and area to mass ratio (AMR_d which is the same for both drag and solar radiation pressure) for different year time frames. Payload Explosion in Sun-synchronous orbit.

The impact rate between each debris cloud and a given target can be evaluated directly from the fragment density in orbital elements as proposed in [12]. Also, in this case the collision probability among the target and the cloud can be computed through an analogy with the gas kinetic theory.
The effect terms of both collisions and explosions in Eq. (1) depend on the characteristics of the fragmentation, and on the evolution of the cloud of debris and its interaction with the objects' population. Following the proposal in [3] the effect is computed as the cumulative collision probability over a certain number of years over a set of targets which are deemed as representative of the overall active spacecraft population at each time epoch. The operational satellites and their operational status and orbit are extracted from ESA DISCOS [6].
However, with respect to [3], a new formulation is introduced in the following; indeed, the effect e are computed as:

$$e = \frac{1}{A_{TOT_{ref}}} \sum_{i=1}^{N_t} p_c(t_e)\, A_i \tag{4}$$

where $A_{TOT_{ref}}$ is the cumulated spacecraft's cross-section of the representative targets computed at a reference epoch, A_i is the cumulative cross-section of the objects belonging to the i^{th} bin of the targets at the epoch of the analysis, and p_c is the collision probability.

Figure 3 shows the representative targets in year 2023 with and without considering a OneWeb-like constellations. On those targets the total effect is computed following Eq. (4) and is also shown in Figure 3e and Figure 3f for the two cases.

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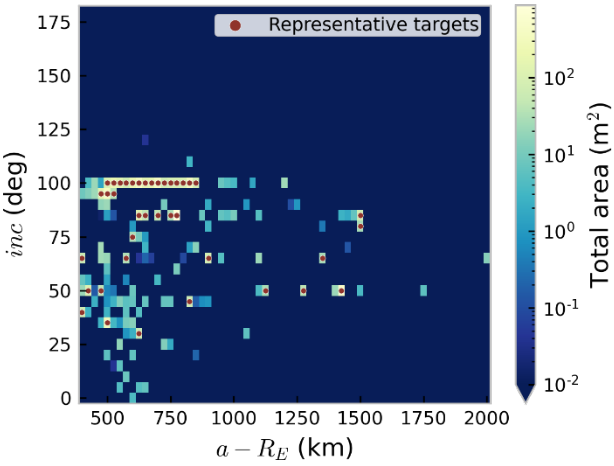
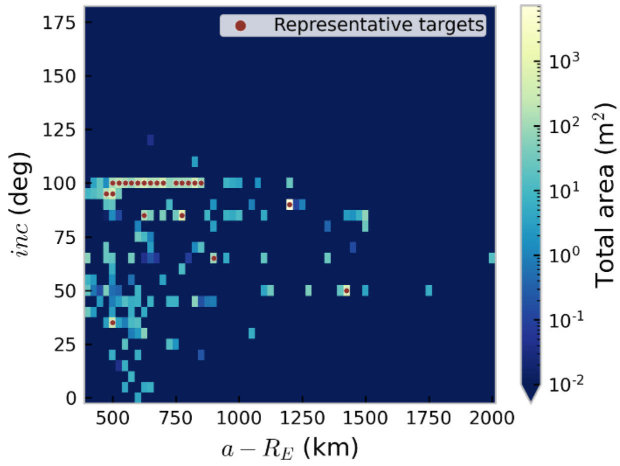
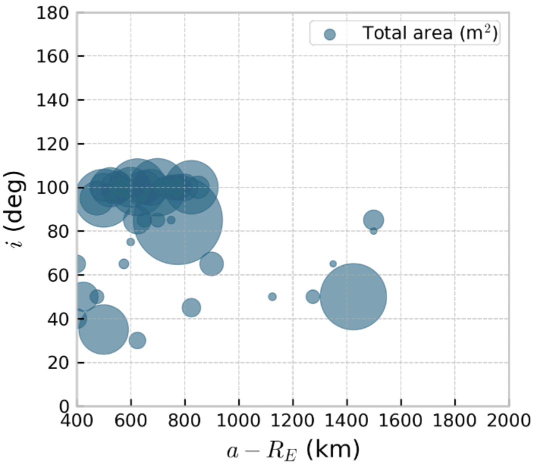


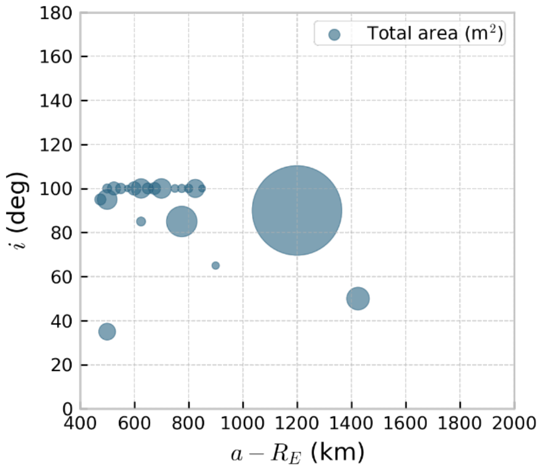
a) Representative targets in year 2023 without the Starlink and OneWeb constellations



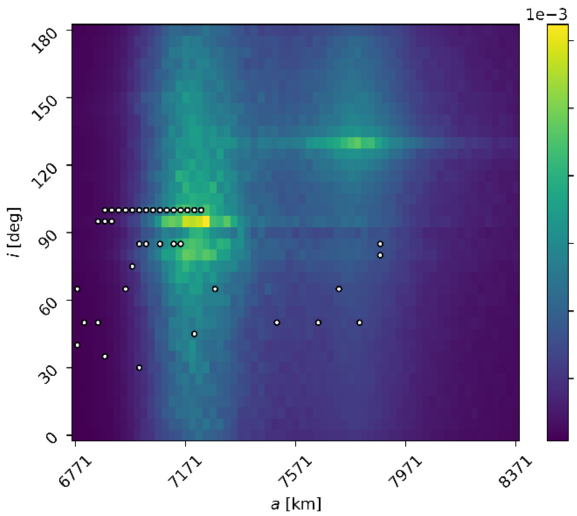
b) Representative targets in year 2023 without the Starlink constellation and adding a OneWeb-like constellation



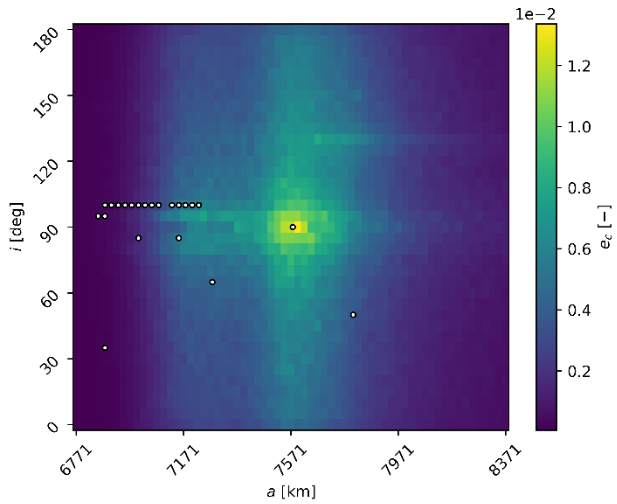
c) Representative total area of the targets in year 2023 without the Starlink and OneWeb constellation



d) Representative total area of the targets in year 2023 with the Starlink constellation and adding a OneWeb-like constellation



e) Effect maps of collision with the targets in year 2023 without the Starlink and OneWeb constellation



f) Effect maps of collisions with the targets in year 2023 with the Starlink constellation and adding a OneWeb-like constellation

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Figure 3: Effect maps in LEO for catastrophic collisions (reference mass = 10000 kg) considering the reference targets in year 2023 without Starlink and OneWeb constellations (left column) and with a OneWeb-like constellation (right column). A) and B) Representative targets in year 2023 without (a) and with (b) the OneWeb-like constellation. C) and D) Representative total area of those targets. Effect maps of collision with those targets.

3. Computation of the space debris index for some missions in LEO

A first output of the tool can be the evolution of the debris index in Eq. (3) for a given mission profile and considering different possible Post Mission Disposals (PMDs). Figure 4 show the evolution of the debris index during the operational and PMD phase of a single satellite of the OneWeb constellation whose characteristics are reported in Table 1.

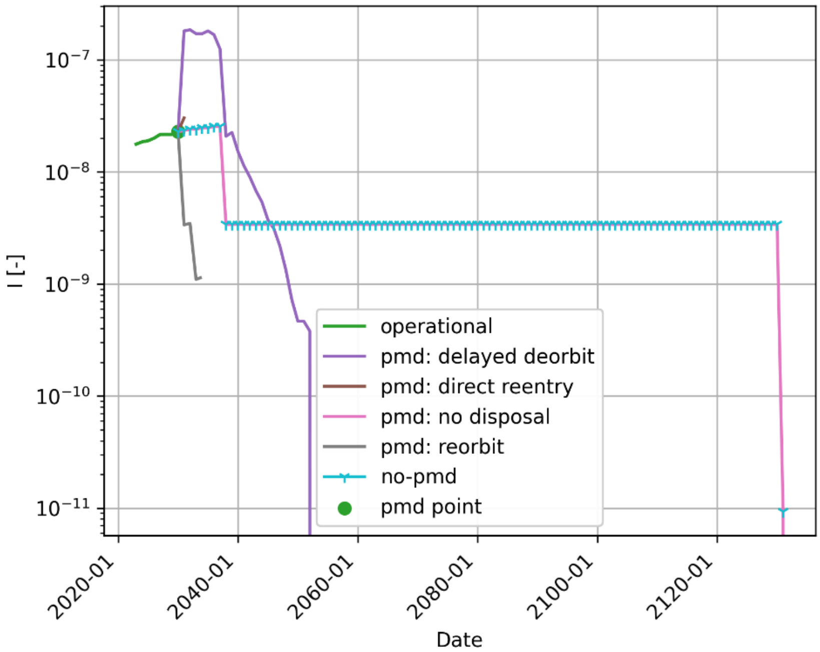

Figure 4: Index evolution for a single OneWeb satellite whose characteristics are shown in Table 1.

Table 1: OneWeb satellite - mission characteristics

Parametre	Value
Mass	148 kg
Area	2.96 m^2
CAM capabilities	Available
CAM efficacy	0.9
Semi-major axis	7580.87 km
Eccentricity	0.0002237
Inclination	87.9002 degrees
Launch epoch	01-01-2023
Mission lifetime	8 years
PMD reliability	0.9
PMD – option 1	Direct re-entry
PMD – option 2	Delayed deorbit (maximum 25 years)
PMD – option 3	Re-orbit at 500 km
PMD – option 4	Natural decay

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When multiple missions are to be compared, it is also possible to show the evolution of the index for different missions considering also the PMD and no-PMD case. As an example, Figure 5 shows the evolution of the debris index for different objects in LEO, namely: Cosmos-2507, Envisat, EPS L9, Midori-2, H-II LE5B.

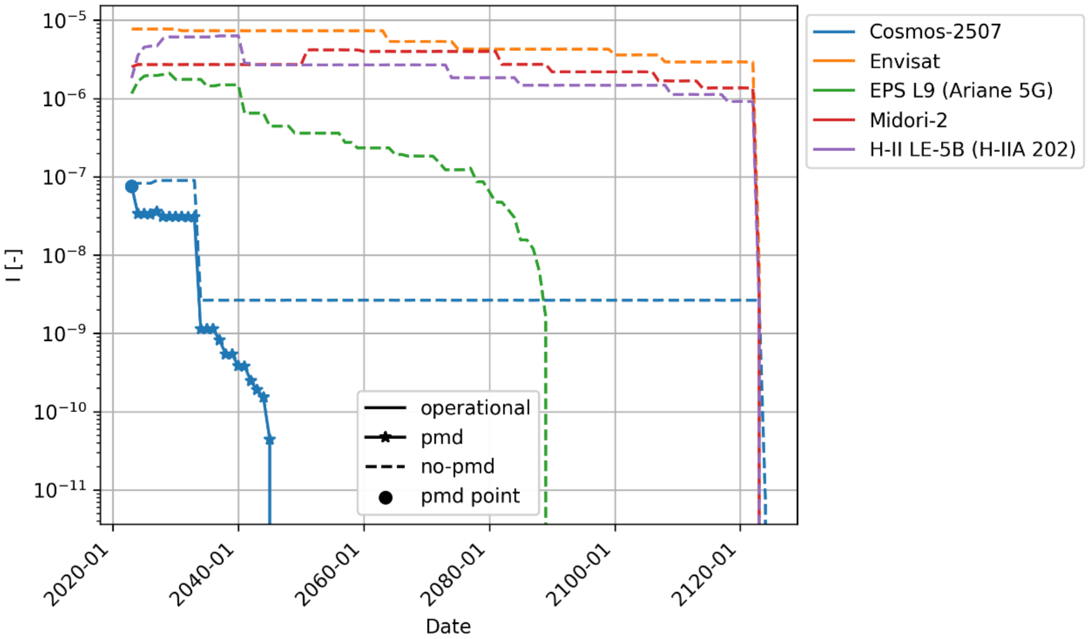

Figure 5: Index evolution for different objects in LEO, namely: Cosmos-2507, Envisat, EPS L9, Midori-2, H-II LE5B.

6. Conclusion

This paper presents the code structure and mathematical development of the THEMIS space debris index. The formulation with respect to the literature has been improved properly to compute the relative velocity when computing the collision probability in the effect term and to call the data from the space object population from the DISCOS database and the information about debris fluxes and relative velocities for computing the probability of collision maps from the MASTER 8.0 ESA tool. The THEMIS tool has also a capacity mode that is needed to evaluate the share of the overall space capacity used-up by a mission. This will be the focus of a future publication. Example are shown of scenarios in LEO but the tool is already able to evaluate the index also in medium and geostationary Earth orbit and also in geostationary transfer orbit.

Acknowledgements

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