

Baseline Values and Sensitivity Analysis of the THEMIS Space Debris Index

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Abstract. Fragmentations caused by explosions or collisions contribute a significant share of the growing space debris population. These present a risk to active spacecraft and have caused collisions in the past. Each satellite has the potential to fragment and thereby threaten spacecraft in its vicinity. Politecnico di Milano developed a tool for Tracking health of environment and missions in Space (THEMIS) under a European Space Agency (ESA) project. It quantifies a mission's environmental impact using a space-debris index based on the Environmental Consequences of Orbital Breakups (ECOB) approach. In this approach, the probability and severity of a potential fragmentation are combined. THEMIS is undergoing beta testing and is being upgraded in a follow-up project. Since the approach is new, questions about interpreting the Index values have been raised. In this paper, reference values for selected missions in LEO and MEO, covering Earth observation, telecommunication and navigation applications are investigated. The sensitivities of index changes to orbital parameters, satellite properties and collision avoidance as well as post mission disposal strategies are estimated.

Introduction

The threat posed by space debris is increasingly recognised as a risk to active space missions. The number of objects in space has been rising steadily over the last years, and this trend is projected to continue [1]. Debris objects as small as 1 cm in size can damage or destroy satellites upon impact [2, 3]. The majority of space debris objects, and a large portion of the overall space object population, consists of fragments that originate from explosions or collisions of satellites and rocket stages [1]. Each mission has a risk of fragmentation, potentially increasing the risk for other satellites. Politecnico di Milano developed the Tracking health of environment and missions in Space (THEMIS) tool under an ESA project to quantify a mission's impact on the space environment [4]. Following the Environmental Consequences of Orbital Breakups (ECOB) approach, probability (p_c and p_e) and effect (e_c and e_e) of a potential collision (c) or explosion (e) of the spacecraft are estimated to calculate a space debris index I at a given instance via Eq. 1 [5].

$$I = p_c \cdot e_c + p_e \cdot e_e \quad (1)$$

Indices over all instances of a mission are aggregated to obtain the total Index of a mission. This Index quantifies the impact of the analysed mission on its environment as a measure of the increased risk to other satellites following a fragmentation of another mission. The probability of explosion p_e is retrieved from statistical data [4], while the probability of a collision, significant enough to cause a catastrophic event, p_c is estimated using ESA's MASTER software [6, 4]. For both explosions and collisions, the effect of the fragmentation (e_c and e_e) is estimated by propagating the fragment density and calculating the rate of impact on a set of representative



targets [4, 7, 8, 12]. With the latest available reference population, only the impact of non-maneuvrable objects is considered in the analysis. The analysed satellite can be modelled to be disposed at the end of its operational life or to decay naturally. Collision avoidance is modelled by removing a part of the collisions with trackable objects, proportional to the efficacy of the collision avoidance.

The THEMIS tool is now in the beta testing phase [9]. During the presentation of the tool to beta testers, questions on the interpretation of results were raised. Since the use of THEMIS and the underlying ECOB approach is not yet well established, this paper aims to provide reference values for a selected number of representative missions. Alongside those, the sensitivity of the index to certain design parameters, mass, area, orbit, Post-Mission-Disposal (PMD) and Collision Avoidance Manoeuvre (CAM) strategy are estimated.

Reference Objects

THEMIS can currently be used to estimate indices of objects in Low Earth Orbit (LEO), Medium Earth Orbit (MEO), Geostationary Transfer Orbit (GTO) and Geostationary Orbit (GEO). The calculation for GEO is being upgraded in the ongoing THEMIS 2 project and results may change in the near future. Therefore, this paper focuses on presenting results for LEO and MEO regions.

Satellites are selected to cover mission applications with the highest relevance, Earth observation, Telecommunication and Navigation. For LEO Earth observation, satellites similar to the ESA Envisat (OBS1) and Sentinel 1D (OBS2) satellites are selected. For LEO Telecommunication, one satellite similar to the ones of the Starlink constellation (COM1) and one similar to the Oneweb constellation (COM2) are used. In MEO, a satellite similar to the ones of the Galileo constellation (GNSS) and a satellite like the ones of the O3b constellation (COM3) are investigated. For each case, only one satellite is modelled, not the entire constellation. The launch epoch is set to November 2025 for all cases to show the impact of the launch of a new satellite of the given type.

Table 1 lists the reference input values. For all cases the eccentricity is assumed to be close to 0. For the baseline, reliability of both CAM and PMD is set to 90%. For missions representing Starlink, Galileo and O3b the latest satellite models of that constellation are used. Data on mass and area are retrieved from the ESA DISCOS database [11], while orbital data are retrieved from Space-Track [10]. For each case the index is first estimated using the settings described to get a baseline value.

Table 1 Reference settings

Mission	Mass/kg	Area/m ²	SMA/km	Inc/°	Mission duration /years	PMD
OBS1	8110.0	74.39	7162	98.5	10	25 year eccentric
OBS2	2185.0	84.40	7064	98.2	12	25 year eccentric
COM1	730.0	33.88	6946	70.0	5	5 year circular
COM2	147.0	3.46	7571	86.4	7	5 year circular
GNSS	733.0	9.22	29601	57.2	15	graveyard disposal
COM3	1700.0	27.340	29601	0.0	15	graveyard disposal

Sensitivity is estimated for changes of: +1 kg mass, +1 m² area, +1 km SMA, +1° inclination and RAAN, +1 year PMD lifetime, and +1 percentage point in CAM/PMD reliability. Changes of this order may be possible during the design phase. The resulting changes are given both as absolute changes as well as percentage change with relation to the baseline value of the given mission $100 \cdot \frac{I_{sensitivity} - I_{baseline}}{I_{baseline}}$. For the relative values, the change in Index is given relative to a

1% change for mass, area and remaining lifetime. This is done to stay consistent across the varying masses, areas and lifetimes of the reference missions.

Results

The reference values for the evaluated missions are presented in Table 2. The heat maps in Figure 2 show both absolute changes (left) and relative percentage changes (right) in the index for design parameter modifications.

For the baseline values, Indices can vary by multiple orders of magnitude (8.84×10^{-5} to 3.43×10^{-8}), even in the same orbital region and the same application. The highest absolute value can be found for the first LEO observation mission. This is also the heaviest satellite placed in one of the most densely populated regions. The MEO communications constellation has the second highest value, only slightly lower. This is due to the fact that multiple satellites of the same constellation are placed in a narrow inclination band. The fragmentation of one of them would have a significant effect on the other satellites of the constellation. The second LEO Earth observation mission has a value around one order of magnitude lower than the first. The two communications satellites have similar values, around 2 orders of magnitude lower than that of OBS2. For COM1 this is due to the fast decay of satellites from low orbits, while for COM2 it is due to low mass, area and low density of objects at the altitude of the satellite. The lowest value overall is that of the GNSS mission, around half the value of that of the LEO communications satellites.

The sensitivity of the index to changes of the parameters varies between orbital regions and mission definitions. Regarding relative values, an increase in mass consistently increases the index. A 1% increase in mass increases the index by between 0.7 and 10%. An increase in area on the other hand increases the index by 0.6 to 2% for each percent of area change for the communications constellations in LEO and the first LEO observations satellite. It decreases the index significantly for the 2nd observation satellite. The reason for this is that, while the collision cross section is increased, the orbital decay is significantly sped up due to the higher area to mass ratio, reducing the impact over the satellite's lifetime. Similarly, increasing the SMA can either increase or decrease the index significantly depending on the orbit. In MEO changes to SMA or area have only little effect. Increasing the inclination by just one degree significantly lowers the index, in some cases by more than 20% for both Earth observation satellites and the constellation in MEO. It has little effect on the other missions though. Increasing PMD reliability and reducing PMD lifetime can significantly improve the index value for missions that are in densely populated regions and do not decay naturally. Increasing the reliability of the disposal by 1 percent point has an effect that is around 10 times larger than reducing the lifetime by 1%. For regions that are sparsely populated or where atmospheric drag is significant, changes in PMD have no effect. Increasing the reliability of CAM has a significant effect on objects in LEO but the effect is close to 0 in MEO.

Table 2 Baseline Index results

Mission	Index baseline value	Orbital Region
OBS1	8.84×10^{-5}	LEO
OBS2	7.84×10^{-6}	LEO
COM1	9.24×10^{-8}	LEO
COM2	7.03×10^{-8}	LEO
GNSS	3.43×10^{-8}	MEO
COM3	6.01×10^{-5}	MEO

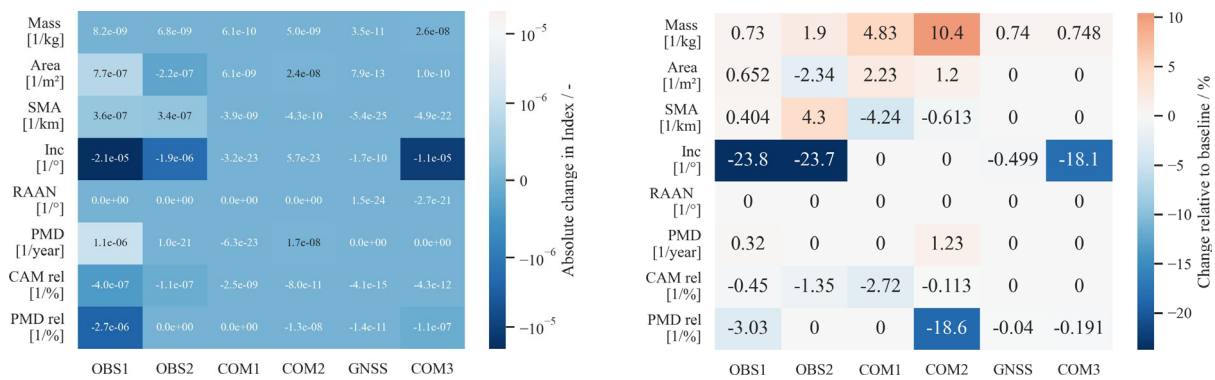


Figure 1: Absolute (left) and relative (right) sensitivity of index to changes in design parameters.

For a given mission, the sensitivity to mass, area, PMD and CAM parameters remain constant across values. For parameters related to the orbital region like SMA, inclination and RAAN however, the dependencies are more complex. Figure 2 shows the Index for an Envisat-like mission across different altitudes and inclinations. Multiple local maxima and minima can be identified. Depending on the location, the direction in which the index decreases switches. The exact location of extrema depends on other mission parameters like mass, area and PMD strategy. The index typically decreases with decreasing altitude below 800 km and with increasing altitude above 1500 km. The specific sensitivities have to be estimated individually for each case.

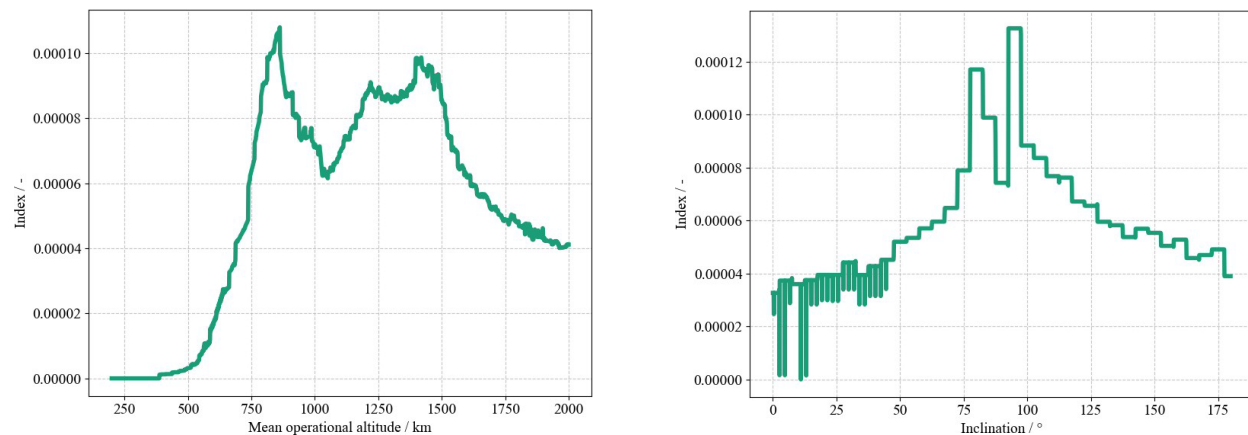


Figure 2: Sensitivity of relative index to changes in orbital altitude (left) and inclination (right) for Envisat-like mission.

Conclusion

Results of the Space Debris Index calculated with THEMIS were presented. The values can vary by multiple orders of magnitude depending on the orbit and spacecraft characteristics. Large satellites in densely populated Sun Synchronous Orbit (SSO) regions are found to have the highest index values but satellites in certain equatorial orbits can have similar values. The lowest indices are found in very low or very high LEO at the location of large communications constellations and for GNSS satellites.

The sensitivity of the index to design parameters also varies across missions. The most impactful changes to the index can be achieved via varying inclination or PMD reliability. Significant changes can also be made by changing mass, area, CAM reliability and SMA for some missions. Changes in RAAN and duration of PMD are small.

These results can be used as reference values to interpret the THEMIS index. The sensitivities can furthermore help to identify ways to effectively reduce the index of a mission during the design phase. In general, densely populated regions should be avoided when possible. If placed at an

altitude where orbital decay due to drag is slow, a high post-mission disposal reliability can decrease the index.

The results presented were obtained using a version of THEMIS that is currently under development. Changes in the implementation or the space environment like the deployment of a large constellation or significant space debris producing events can change those results.

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