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Kick-off of the beta testing by spacecraft operators for THEMIS software for tracking the health of the environment and missions in Space

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Abstract

The THEMIS software, developed within the ESA Space Safety Programme, is devised for "Tracking the Health of the Environment and Missions in Space". The impact of a space mission is measured in terms of risk that the undeliberate fragmentation of such mission might cause on the overall active spacecraft population. This paper presents the advancements of the THEMIS 2.0 project that has finally deployed the tool online for use by the space community of space operators, manufacturer, regulators and space debris experts. A sensitivity analysis was performed to assess the influence of the software settings on the index computation. The resulting effect maps and index values are then compared to analyse how the peaks of highest collision risk move for different settings, how the different effect maps influence ranking of objects in orbit and how the evolution of the debris index changes accordingly. Several new capabilities were added to the tool as a result of the sensitivity analysis to unlock more uses by space operators.

Keywords: Space debris indicator, Debris risk, Space sustainability, Fragmentation risk, Space label

Acronyms/Abbreviations

API	Application Programming Interface
CAM	Collision Avoidance Manoeuvre
ECOB	Environmental Consequences of Orbital Breakups
ESA	European Space Agency
LEO	Low Earth Orbit
PMD	Post Mission Disposal
THEMIS	Tracking the Health of the Environment and Missions In Space
WUI	Web User Interface

1. Introduction

The solution to the space debris problem can be reached by engaging with space operators and by supporting them to evaluate and minimise the effect that each mission brings to the space object population environment. The THEMIS software, developed within the European Space Agency (ESA) Space Safety Programme, is devised for "Tracking the Health of the Environment and Missions in Space". The impact of a space mission is measured in terms of risk that the undeliberate fragmentation of such mission might cause on the overall active spacecraft population. Such formulation is thought to give an estimation of the increased operational effort that all spacecraft operations will have to sustain in case an object fragments in another orbital bin. The THEMIS debris indicator can be then used for evaluating possible mission design options in terms of orbit selection, and spacecraft characteristics. When the THEMIS index of each active object in the population of active satellites is aggregated, it is used as a measure of the overall space carrying capacity. This metric can be exploited to compare various future scenarios of the evolution of the space environment and evaluate the risk of operating in a specific orbital slot.

This paper presents the advancements of the THEMIS 2.0 project that has finally deployed the tool online for use by the space community of space

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operators, manufacturer, regulators and space debris experts. As part of the first task of the project, sensitivity analyses are performed to assess the influence of the software settings on the index computation. Some of the parameters analysed affect the computation of the severity part of the risk index, others influence the collision and explosion probabilities of the object. The resulting effect maps and index values are then compared to analyse how the peaks of highest collision risk move for different settings, how the different effect maps influence ranking of objects in orbit and how the evolution of the debris index changes accordingly.

Several new capabilities were added to the tool as a result of the sensitivity analysis to unlock more uses by space operators.

The paper also introduces the currently ongoing beta-testing phase, where 20 spacecraft operators, space debris experts and regulators have been involved in using the software, performing some guided exercises and asked to provide feedback in their use and their applicability to preliminary mission design, space safety operations and end-of-life disposal design. The interaction with the end-users of the tool will enable to improve the software and enhance its applicability to sustainable mission design and the evaluation of mitigation guidelines.

2. THEMIS space debris risk approach

As described in [1]-[6], the evaluation of the impact of a space mission on the space debris environment is done through a risk metric that computes the probability of collision and explosion of a single mission on its orbit during the mission lifetime and the consequent effect that such a fragmentation event would have on the current population of active object, which depends on the orbital slot the fragmentation is generated from and on how the fragment cloud evolves and impacts other operational satellites. The space debris index in THEMIS follows the formulation of the Environmental Consequences of Orbital Breakups (ECOB) index [7] 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 objects in a given orbital region. The index evaluation at a single time epoch is computed as

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

where p_c and p_e represents the probability of collision and explosion, and e_c and e_e the severity of collision and explosion (i.e., the effects of the breakup in a given orbital region), respectively. The evaluation of the indicator is done during the whole mission lifetime including the launch phase, the operational phase from t_0 till t_{EOL} and once the End-Of-Life (EOL) disposal phase starts t_{EOL} until t_{end}. The disposal phase is also weighted with the Post-Mission Disposal (PMD) reliability α, ranging between 0 (fail) and 1 (fully reliable). In the case the disposal is not successful, the simulation is halted at t_{f} taken as 100 years.

$$I_{tot} = \int_{t_0}^{t_{EOL}} I_t \, dt + \alpha \cdot \int_{t_{EOL}}^{t_{end}} I \, dt + (1-\alpha) \cdot \int_{t_{EOL}}^{t_f} I \, dt \tag{2}$$

Different types of PMD can be selected (e.g., direct re-entry, target time disposal, re-orbit, no disposal, etc.). Through the Web User Interface (WUI) or the API the user can indicate not only the mission phases but also the spacecraft characteristics, such as mass, cross sectional area, propulsion technology for deorbiting. Also, the operational capabilities are taken into account for the computation of the indicator in terms of Collision Avoidance Manoeuvre (CAM) efficacy. In the case the spacecraft is active, the computation of Eq. (1) is performed twice, with and without CAM capabilities, so that, at a generic time epoch of the mission the index is

$$I = \beta \cdot I_{CAM} + (1-\beta) \cdot I_{no-CAM} \tag{3}$$

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 [2].

3. THEMIS 2.0 capabilities extensions

First, a sensitivity and configuration options analysis was performed with the goal of assessing the impact of some default choices in the modelling and computation of the debris index. The analyses were described in [12] and [13].

As a result of that analysis, multiple capabilities are being included in the THEMIS 2.0 software extension. The new additional capabilities allow a more flexible and extensive use of the tool and, from a design point of view, required the modification of the different subsystems of the software, namely the THEMIS Core (TC), the API, the Backend (BE), the Frontend (FE) and the Database (DB). The foreseen capabilities and the system they affect are shown in Table 1. The capabilities already implemented will be described in the following.

Table 1- THEMIS 2.0 capabilities.

ID	Capabilities	TC	Config. / Input	API	BE (triggers)	Frontend	DB
CAP-01	Define time of debris cloud propagation	**x**	**x**	**x**			**x**
CAP-02	Define upper threshold of ejection velocity for catastrophic collisions	**x**	**x**				
CAP-03	Update frequency of targets population (add scheduler)			x	x		x
CAP-04	Store name of the target map and different target maps	**x**	**x**	x			**x**
CAP-05	Define the debris-size threshold	**x**	**x**	x			**x**
CAP-06	Improved (from THEMIS 1.0) post-mission disposal design	x	x	x		x	x
CAP-07	Define time-step for saving the density snapshots	x	x				
CAP-08	Define index saving (change the 1-year fixed time step)	x	x				
CAP-09	Improve the model for large constellations	x		x		x	x
CAP-10	Compute missions outside the already defined regions (LEO, MEO, GEO, GTO)	x	x				
CAP-11	Improve index computation in GEO (update orbital elements definition)	x					
CAP-12	Consider risk from small space debris for capacity computation	x	x	x			
CAP-13	Test that SW1 vs SW2 give same results	**x**	**x**				
CAP-14	Refactor the software infrastructure						
CAP-15	Include passivation model	x	x	x	x	x	x
CAP-16	Improve data saving and exchange						
CAP-17	Integrate with DMF	x		x			
CAP-18	Include different user privileges depending on the role			x		x	x

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CAP-19	Calculate the index for a list of objects	**x**		x			**x**
CAP-20	Aggregate the index on a DELTA run to compute the space capacity	x		x		x	x
CAP-21	Extrapolate additional proxies of space capacity from DELTA results	x		x			x
CAP-22	Add plots and processing options for the outputs	**x**		x		x	
CAP-23	Improve Frontend					x	x
CAP-24	Index computation using explosion/collision	x	x	x	x	x	x

CAP-01: Define time of debris cloud propagation allows the expert user to define the time for which the cloud generated from a fragmentation is propagated in order to compute the effects on active objects for the effect map. As described in [12], the effect term of the index e_c is calculated by triggering and propagating synthetic debris clouds in each bin of a grid in orbital elements. The effect of each fragmentation cloud is then assessed in terms of collision risk of the generated cloud against a population of representative targets that are chosen to represent the snapshot of active missions in space at a reference given epoch. The initial fragments' density distribution is modelled, through a probabilistic reformulation [8] of the NASA Standard Breakup Model [9]. The fragments are propagated in all the orbital elements using a continuum approach to integrate not only the orbital elements but also the density of objects in the Keplerian element space as described in [10]. Then, the cumulative number of impacts of the cloud against each representative target is computed over the considered time frame [11]. The representative targets' cross-sectional area is assumed to be unitary since the result is rescaled a posteriori. The effect is computed as

$$e = \frac{1}{\boldsymbol{A_{TOT_{ref}}}} \sum_{i=1}^{N_t} P_{c_i}(\Delta t = 15 \text{ ys})\, A_{t_i} \quad (4)$$

where $\boldsymbol{A_{TOT_{ref}}}$ is the cumulative cross-sectional area in the bins hosting a target at a reference epoch and A_{t_i} is the total cross-sectional area of the i-th bin.

$$P_{c_i} = 1 - e^{-\emptyset \cdot A_i \cdot \Delta t} \quad (5)$$

with $\emptyset$ the debris flux in 1/km^2/year, Δt is the time considered in years, A_i is the average cross-sectional area of the i-th bin.

While the default time for propagation of the cloud is $\Delta t = 15$ years, the expert user can choose a different propagation time, this would trigger the computations of new maps that have the form of the one represented in Figure 1. For example, Figure 2 shows the effect map considering $\Delta t = 50$ years. Both maps do not include the Starlink constellation in the representative target maps [12].

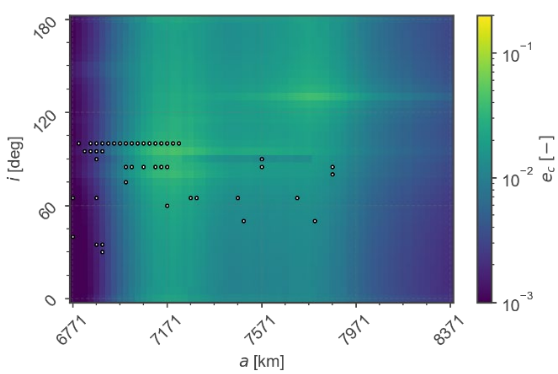

Figure 1. Collision effect maps in LEO for debris cloud propagation $\Delta t = 15$ years The dots are representative targets position.

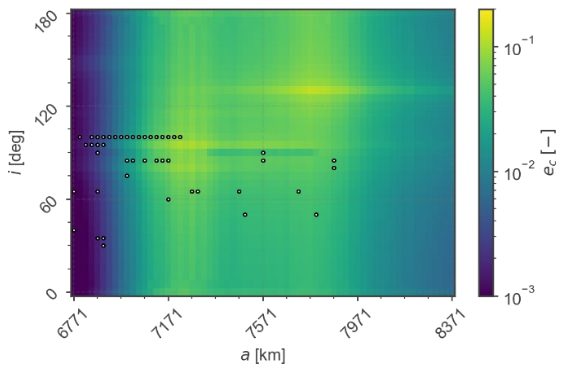

Figure 2. Collision effect maps in LEO for debris cloud propagation $\Delta t = 50$ years The dots are representative targets position.

The other capability implemented is **CAP-04: Store name of the target map and different target maps**, that allows the user to use a user-defined target map. In Eq. (4) the target object list affects the computation of A_{t_i}**,** the total cross-sectional area in each bin hosting a target, and A_i, the average cross-sectional area of the i-th bin.

As a default setting the targets are taken from the ESA DISCOS database and the maps are referred to a given epoch when the targets are computed. Therefore, the effect maps need to be recomputed if the reference epoch of the target is changed. As explained in [2] representative targets are determined based on a minimum threshold of cross-sectional area; in other words, in each bin a representative target is placed with a cross area that is the sum of the cross areas of the objects in that bin, if the sum is above a certain threshold. As an example, Figure 3 shows the representative targets in year 2023 without considering a OneWeb-like constellations.

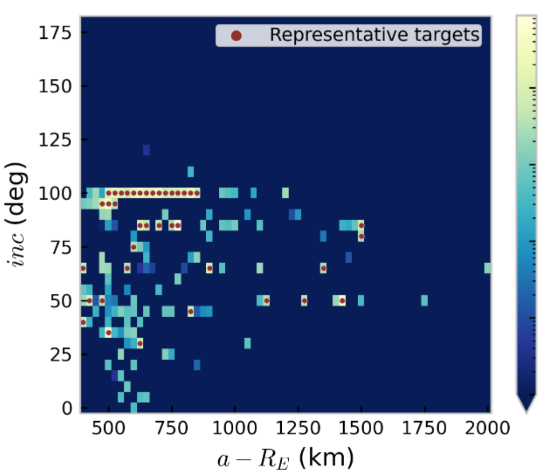

Figure 3. Representative targets in year 2023 without the Starlink and OneWeb constellations. The colour bar represents the cross-sectional area of the bin.

Different alternatives for the update of the frequency of the target were investigated in [13]. An automated trigger will be implemented to update the maps each year, using the latest DISCOS population of active objects. However, if a significant change in the representative targets is recorded, such as the appearance of a new target in a new position or a change in the total area of the population, the targets are updated. THEMIS is being also designed so that users can input their target map, for example considering a new fleet of satellites or adding a large constellation to the environment to have some future prediction of the effect maps considering planned missions.

CAP-05: Define the debris-size threshold is connected with the debris flux used to calculate the collision probability in Eq. (1) that is extracted from MASTER data [14]. MASTER provides fluxes for various debris sizes; however, THEMIS restricts the analysis to a specific size range to focus only on debris relevant to catastrophic collisions. The lower bound of the size range is determined by the minimum debris diameter required to cause a catastrophic collision. Two approaches are considered: a variable, energy-based threshold [13] is used by default, while expert users can instead directly define the diameter threshold for catastrophic collisions.

CAP-19: Calculate the index for a list of objects allows users to input a list of objects and get the total value for the index for each object in the list. This capability allows to have a ranking of objects based on their risk as for example is done in [15].

Other capabilities that have already been included are more related to the software development, for example, CAP-13: Test that SW1 vs SW2 gives same results, CAP-14: Software infrastructure refactoring, CAP-17: DMF integration and CAP-22: Add plots and processing options for the outputs.

4. THEMIS beta testing phase

4.1 Beta-testers' exercises

The first part of the THEMIS beta testing phase concerns the use of the tool through the WUI, which will only be accessible to the users selected for this activity. The interface the testers will have access to is that of THEMIS 1.0, the first version of the software; in parallel to this phase, the software is still being improved in its THEMIS 2.0 version, which is not yet available for user-level utilisation.

As part of the activity, two exercises have been assigned as a guideline to help users become familiar with the tool:

1. Evaluation of a mission composed of a single spacecraft in LEO

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2. Evaluation of a mission composed of multiple satellites (i.e., constellation) in LEO

For both missions, the mission parameters (e.g., orbit semi-major axis and inclination) have been specified, as well as the physical properties (mass and cross-sectional area), the propulsion type, and the timelines of the different phases. In this way, the tester can easily carry out an initial simulation and compare the results with a mission with the same characteristics that has already been computed and is available for all users to view.

Afterwards, the tester is required to carry out further mission assessments that include:

- missions different from the default one
- missions with different properties to perform comparison

The first type of additional evaluation is to understand if the tester is able to perform the evaluation of his own mission, properly specifying the characteristics. The second, instead, is thought to allow the user to make use of the mission comparison features, with the aim of assessing their clarity and level of completeness.

4.2 Beta-testers' feedback

The tool testing phase will be followed by a user feedback phase, aimed at understanding user satisfaction. Indeed, in order to be deployed on a large scale, the tool must be properly usable by the user and user-friendly. The requested feedback has been divided into different categories to have a more comprehensive overview.

The first step concerns the *overall satisfaction* with the experience of using the tool. This includes the clarity of the WUI, ease of use, and understanding of the results. Indeed, the idea is that the tool will not only be used by experts in the field, but above all by operators from various sectors (e.g., satellites, policy, etc.), thus requiring a general level of clarity for any kind of user.

The second step concerns the *detection of bugs* that may be present in the beta version of the tool. This is essential, as their identification will be followed by a quick fixing process, given that the tool is still under development and improvement. This ensures an overall quality enhancement once THEMIS is released to the public.

The third step, instead, concerns *suggestions for* possible *improvements*, ranging from the interface (enhancing the user experience and the information available in the WUI) to the display of the results (their quantity and comprehensibility), as well as potential capabilities to be added or improved. This would ensure a better development of the tool based on the needs of the actual end user of the tool.

The final step concerns possible *open feedback* from the user, always aimed at improving the current version of the tool.

5. THEMIS future uses

As part of the ongoing THEMIS 2.0 project, the integration of the tool with other space-sustainability services through its API is being investigated. Beyond the current uses of the THEMIS tool:

- to allow different users to assess the impact of a space mission on the space environment based on mission information such as orbit, mass, cross-section, and risk of fragmentation due to accidental collisions or explosions.
- to determine the share of the capacity of space used by that mission under analysis.
- to allow the computation of the overall space capacity used by orbiting spacecraft.
- to analyse possible definitions and proxy of the capacity threshold.

Some future users are being evaluated:

- to support the definition of a capacity threshold
- to support the definition of new mitigation guidelines
- to facilitate the environmental evaluation of single missions during the licencing process
- to support the definition of spacecraft mission insurance process for the on-orbit segment.

6. Conclusions

This paper presents the new capabilities implemented in the THEMIS software and how they can be used by operators and users. To involve spacecraft operators, the Beta testing phase has been kicked off and will gather the feedback of the final users of the tool. This will also enable them to have an experience of the future uses THEMIS would be used for, of the licencing process, insurance process and assessing the consequences of not performing a collision avoidance manoeuvre.

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