Investigation of the space debris environment for a sustainable evolution of the space around the earth

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Abstract. The sustainability of the space environment around the Earth is becoming an increasingly important issue in the space sector. Indeed, the space population is evolving over time. Therefore, careful mission design together with mitigation guidelines and policies are essential to regulate its evolution and to avoid the proliferation of derelict objects around the Earth. The main objective of this research is to connect different models that share the same goal: the sustainable evolution of the space environment around the Earth. In this view, the research focuses on the definition of metrics to assess the influence of missions (already occurred or planned) on the space environment and of a carrying capacity that the space can support, and on the characterization of in-orbit breakup events.

Introduction

The sustainability of the space environment around the Earth is becoming an increasingly important issue in the space sector. Indeed, the space population is evolving over time [1].

On one hand, there is the deployment of many satellites, including large constellations, that place many satellites in specific orbital regions. This requires new mitigation policies and careful mission design, with special attention to end-of-life strategies. To help this, several risk metrics are being developed to assess the impact of missions on the space environment, each of which seeks to capture the main elements influencing it. Bastida Virgili and Krag [2][3] proposed a criterion to select candidates for Active Debris Removal (ADR) missions, while Lewis [4] introduced a criterion which includes capacity and health scores to measure the efficacy of mitigation measures and the influence of spacecraft on the operational orbital region, respectively. Rossi et al. [5] proposed the criticality of spacecraft index to rank abandoned objects. Letizia et. [6] defined a risk indicator, ranking all space objects considering the effect of their fragmentation on other operative satellites.

On the other hand, new breakup events occur frequently increasing the background population of inactive objects. Examples are the recent CZ-6A breakup occurred on the 12th of November 2022 and the Cosmos 1408 breakup occurred on the 25th of November 2021. Indeed, some events are still difficult to predict (e.g., collision between objects) while others are unpredictable (e.g., explosion of a rocket body). These new uncontrolled objects, posing a threat to the population of objects orbiting the Earth, are to be tracked as soon as possible after the event to investigate their origin that is to determine the epoch and location of the event and the object(s) involved. In the past years, several tools have been developed to detect fragmentations. Romano et al. [7] and Andrisan et al. [8] developed tools which estimate the epoch and position of the breakup by studying the average distance between the objects in the debris cloud. Differently, Frey et al. [9] and Muciaccia et al. [10] focused their works on the long-term evolution of orbits (years) considering an averaged dynamic and determining the epoch of the breakup by detecting a convergence of objects in the space of inclination and right ascension of the ascending node. Dimare et al. [11] identify fragmentations by defining a similarity function of the orbital elements of the observed objects. Once the characteristics of the event are known, risk analyses can be carried out by modelling the distribution of the fragments right after the event and its evolution over time, and by studying their interaction with other orbiting objects.

The main objective of this PhD research is to connect different models that share the same goal: the sustainable evolution of the space environment around the Earth. In this view, the research will focus first on the definition of metrics to assess the influence of missions (already occurred or planned) on the space environment and of a carrying capacity that the space can support. This is necessary to regulate the evolution of the population of active objects and to avoid overcrowding of specific regions of space, giving the possibility of use to future missions as well. Then, the research will investigate models to characterise breakup events. The latter is essential to limit the proliferation of space debris (i.e., uncontrolled objects) generated by collision between the fragments and the active satellites. Indeed, knowing the characteristics of fragmentation it is possible to define satellite at risk and thus to plan collision avoidance manoeuvers useful to decrease the effect of the fragmentation. By combining the models, we will then have monitoring of a large part of the population of objects orbiting the Earth.

A schema of the activities is shown in Figure 1, while a description of each activity is presented in the following sections.

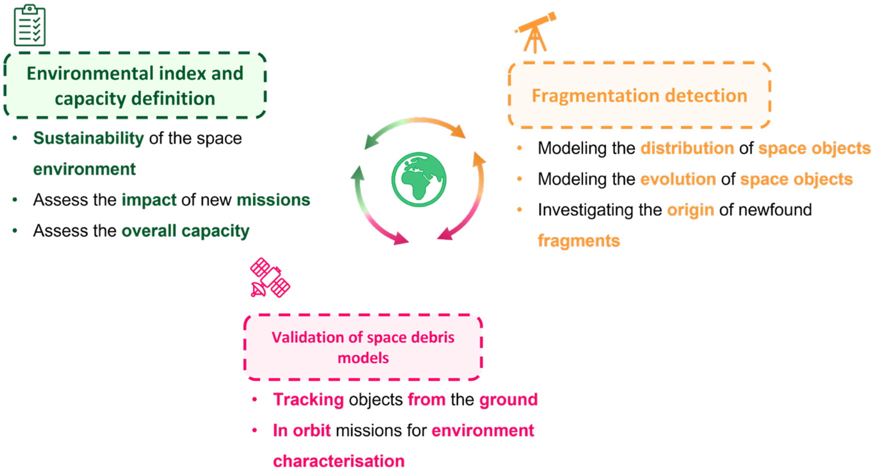

Figure 1. ***Schema of the Ph.D. activities.***

Environmental index and capacity definition

The model evaluates the impact of a generic mission during its entire lifetime, taking into account several aspects of mission design.

First, the mission profile is divided into phases (e.g., operational, deorbiting, etc.) to investigate the weight of each on the total mission index, that is computed as

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

where I is the index evaluated at a single epoch, t_0 is the starting epoch, t_{EOL} is the epoch at which the operational phase ends, t_e is the epoch at which the disposal ends, t_f is the epoch at which the object would naturally decay from its initial orbit and α is a parameter associated to the reliability of the Post Mission Disposal (PMD) strategy and varies between 0 and 1. The first term is used to compute the index of all the phases before the PMD, while the latter is computed using the last two terms. The index at a single epoch is evaluated following the ECOB formulation [6]

$$I = p_c \cdot e_c + p_e \cdot e_e \tag{2}$$

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. In case the satellite is active and can perform Collision Avoidance Manoeuvres (CAM), the evaluation of the index at a single epoch is computed as

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

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 (ranging from 0 to 1) and is considered fixed along the entire mission profile.

Grid definition

The parameters (i.e., the probability of collision and the collisions and explosions effects) previously introduced are computed on a grid based on Keplerian orbital elements. The set of orbital elements is not fixed but it varies depending on the orbital region under analysis. Indeed, each orbital region is characterised by a peculiar distribution of the objects. As an example, for the specific case of the LEO region, a two-dimensional grid in semi-major axis and inclination [6] is used. The grid is defined from 0 deg to 180 deg in terms of inclination and from 6771 km to 8371 km in terms of semi-major axis, and the selection of the bin size can be chosen arbitrarily (default cell size of 10 km in semi-major axis and 10 deg in inclination).

Probability of collision

The probability of collision is evaluated adopting a flux-based model of the space debris environment and exploiting the analogy with the kinetic gas theory [12]. The value of the average debris flux is extracted from ESA MASTER 8 [13], considering the debris population at a specified epoch. In addition, MASTER 8 is also exploited to evaluate the averaged impact velocity, used to filter out the flux of particles able to generate catastrophic collisions. Studies were carried out to investigate the influence of parameters on the value of the collision probability, such as the collision avoidance maneuver capabilities of satellites or the size of the trackable debris from the ground (see Fig 4).

Probability of explosion

The probability of explosion is derived from historical data from the ESA DISCOS database [14]. A preliminary investigation has been performed on the type of explosion events and the type of objects involved. From the information available in DISCOS, a list of event families along with a list of object classes have been defined. Then, two methods have been compared to compute the explosion probability: the Kaplan-Meyer estimator [6], commonly used in medical sciences to estimate the survival rate of patience, and the Nelson-Aalen estimator [15], used to directly evaluate the cumulative hazard rate function associated to the fragmentation events for the different classes of objects.

Fragmentation effect

The evaluation of the effects of a fragmentation is performed on a set of spacecraft targets that is representative of the entire population of active objects. The data of the operational satellites are extracted from ESA DISCOS, where information about the activity status, the orbital region and the orbital elements, and the physical properties (i.e., mass and area) can be retrieved. The targets are defined by looking at the distribution of the cross-sectional area of operational satellites on a grid in terms of Keplerian parameters (described before).

Then, the effect terms of both collisions (e_c) and explosions (e_e) depend on the characteristics of the fragmentation, and on the evolution of the cloud of debris (propagated using a continuum approach [16]) and its interaction with the objects' population. Specifically, the resulting increase in the collision probability for operational satellites is used for the assessment of the consequences. The effects map is generated by evaluating the probability of collision with the representative targets. For each bin belonging to the grid, a fragmentation (collision or explosion) is generated and propagated for 15 years; over this time span, the cumulative probability of collision with the population of representative targets is estimated, and the effects e are computed as:

$$e = \frac{1}{A_{TOT}} \sum_{i=1}^{N_t} P_c(t = 15 \text{ ys})\, A_i \tag{4}$$

where A_{TOT} is the overall spacecrafts' cross-section, A_i is the cumulative cross-section of the objects belonging to the i^{th} bin, and P_c is the collision probability.

Fragmentation detection

The model characterise the breakups that occurred in orbit by evaluating:

- Epoch and location of the event
- Involved object(s)
- Mass and energy associated tot he event (useful to model the distribution of the generated fragments)

Two methods are considered. A short-term investigation analysing the possibility of fragmentation in a window of days and making use of osculating orbital elements (SGP4 [17]) for the propagation of the orbital elements of the objects, and a long-term investigation analysing the possibility of fragmentation in a window of months or years and making use of mean orbital elements (PlanODyn [18]) for the propagation of the orbital elements of the objects.

The general workflow of the two methodologies is the same. First, a set of unknown objects is generated from public catalogues. All the objects in the set are then propagated backwards to study the evolution of their orbits, and thus to identify possible clusters in a specific phase space in terms of Keplerian orbital elements. Whenever a possible breakup is identified (i.e., a cluster is detected), the model examinate the fragments selected to characterise them in terms of families by using a hierarchical clustering method [19]. In addition, a second set of objects including only satellites is scanned to identify the parent(s) of the fragmentation by comparing the location of the satellites at the estimated epoch of the event and the location of the event itself.

The difference between the two models lies in the way epoch and location of the fragmentation are estimated.

The short-term routine uses a triple-loop filter to identify a cluster of objects in terms of their proximity to each other. The filter, comparing two objects at a time, is composed by an apogee/perigee filter which checks that the relative geometry of the orbits can lead to close encounters. If this filter is passed, the model evaluates the minimum orbit intersection distance (MOID) [20]. If the MOID between the orbits of the two analysed objects is below a defined threshold, a last temporal filter is considered. The latter consists of generating angular windows around the MOID, then converting them into time windows using Kepler's equation, and finally checking the possibility of having both objects in the same window at the same time. This filter is coupled with the propagator to perform the investigation inside the window under analysis.

The long-term routine detects the fragmentation using the right ascension of the ascending node (RAAN) as study parameter. Indeed, near the event epoch, all the fragments generated will share this Keplerian orbital parameters, making it useful for the purpose of the analysis.

The information coming from the previous analysis (i.e., the epoch and the location of the fragmentation, and the parent(s)) are than used to characterise the fragmentation in terms of total mass and energy involved. The latter are used as initial condition to generate the cloud of fragments with the NASA standard breakup model [21].

Main results

The environmental index model can be used for several types of analysis. First, the index can be used to investigate the impact of a single mission on the space population. An example is shown in Figure 2, where the picture shows the evolution of the index over time.

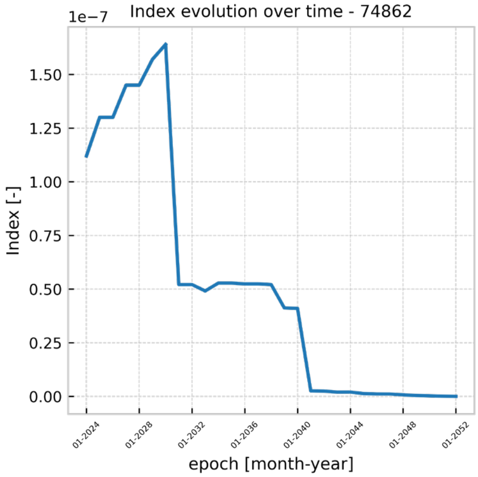

Figure 2. Index evolution over time of a payload.

Then, the same procedure can be applied to the entire population of orbiting objects to investigate the most critical regions and the share of the index associated to specific class of objects (e.g., rocket bodies). Figure 2 shows the distribution of the index (the marker size is proportional to the index value) on a semi-major axis and inclination grid.

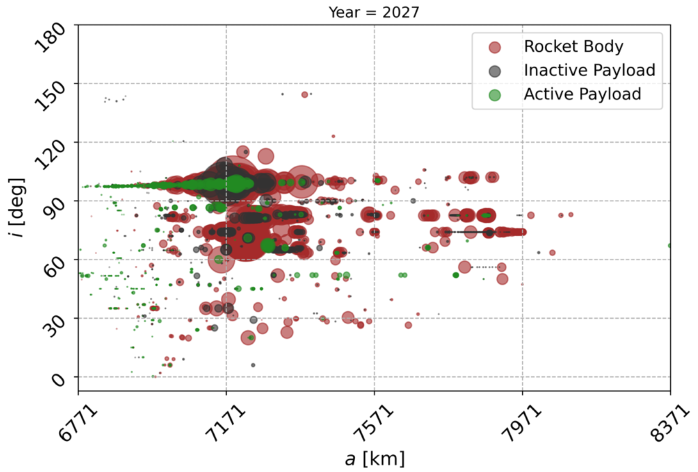

Figure 3. Index value for objects in LEO on a semi-major axis and inclination grid (marker size is proportional to the index value).

As visible from the picture, the most critical region is that at around 7171 km in terms of semi-major axis and 90° of inclinations.

Regarding the fragmentation event, several studies were conducted on past and recent fragmentation. An example of application is shown in Figure 2, considering the Cosmos 2251-Iridium 33 breakup. The initial set of objects included about 2000 objects (19 belonging to the collision event) available on SpaceTrack on 16th of February 2009 (i.e., 6 days after the event). The model was applied to the fragmentation and was able to properly detect the epoch (10th February 2009) and location of the fragmentation, along with the involved fragments and parent(s).

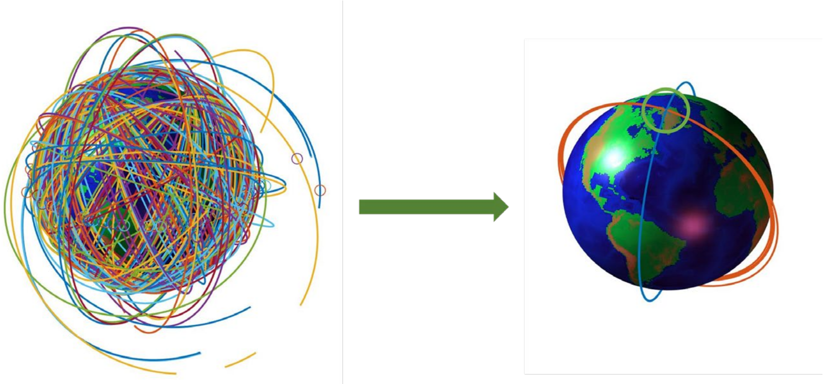

Figure 4. Cosmos 2251 - Iridium 33 breakup. Set of initial objects (left) and final set including only the involved families (right).

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