Influence of Constellations on Current and Future Missions

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Abstract

The first large constellations have been launched in recent years, and new ones are planned. This new trend is leading to an increase in the number of objects orbiting around the Earth [1], crowding some regions of the orbital space. While the introduction of such a large number of spacecrafts will bring social and economic benefits, for example to global connectivity, it also introduces new challenges. Indeed, placing many satellites in the same "orbital location" requires new regulations in terms of Space Traffic Management [2]. Particular attention should be given to the end-of-life phase of the missions [4], to have a future sustainable evolution of the satellite population around the Earth. In addition to this, large constellations are already influencing other scientific fields: for example, light pollution is jeopardizing astronomy studies. For this reason, many works have focused on the present and future impact of this type of space mission [3][4][5].

The aim of this work is to investigate the effect of constellations on the environment around the Earth, studying their interaction with the population of active and uncontrolled objects. This is achieved firstly by investigating the severity of potential fragmentation on sets of active objects. Such a procedure can be used to understand the impact that the addition of constellations can have on the use of space for future missions. Indeed, previous studies [6][7] were conducted considering single plane of constellation at a time, showing already their influence in the generation of higher risk areas in case of in-orbit fragmentation. This new study includes sensitivity and parametric analyses on the deployment of more than one plane in a constellation placed in different locations in terms of Keplerian orbital elements. A risk indicator [6] composed of probability and severity terms is used to assess the impact of missions (considering different mission phases) on the space environment.

1 INTRODUCTION

The number of launches, and hence the population of objects orbiting around the Earth is growing in recent years [1], influencing the short- and long-term sustainability of the space environment. Parallel to this, the number of breakup events (both explosions and collisions) has also increased, placing many new fragments in orbit, and increasing the risk in specific regions of the space environment.

Satellite constellations, and even more the large constellations in Low Earth Orbit (LEO), have led to an acceleration of the process, necessitating the introduction of new policies and the revision of existing ones in terms of Space Traffic Management [2].

Past works analyzed both the long- and short-term effect associated to the introduction of constellations and large constellations on the space population [3] [4] [5] [6], reaching the conclusion that in order to lower the risk, a careful analysis on the Collision Avoidance Maneuver (CAM) capabilities and on the Post Mission Disposal (PMD) strategy is required.

The model presented in this work investigates the likelihood and the associated effects of fragmentation of the satellite(s) during each phase of a mission. The computation is performed selecting specific study parameters based on the orbital region of interest, and knowing the mission profile, the spacecraft characteristics, the orbit characterization, and operational aspects (e.g., the collision avoidance maneuver efficacy, the post mission disposal capabilities and reliability). The model is applied to a synthetic OneWeb like constellation to show the evolution of the impact of the mission on the space population, investigating both the single satellite and the entire constellation.

The paper is organized as following: Section 2 briefly describes the main feature of the metric adopted for the study, focusing on the model of constellations. Section 3 introduces the OneWeb case scenarios, whose results are presented in Section 0. A conclusive section summarizes the main achievement and future works.

2 ENVIRONMENTAL IMPACT MODEL

The computation of the environmental impact of a generic mission follows the procedure described in [8][9][10] and is defined as a risk indicator, using the formulation of the Environmental Consequences of Orbital Breakups (ECOB) index [11] as a basis. In this section, a short summary is given along with a description of its modification when introducing constellations.

2.1 General overview

The index is computed as:

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

where $\mathrm{p_c}$ and $\mathrm{p_e}$ represent the collision and explosion probabilities, and $\mathrm{e_c}$ and $\mathrm{e_e}$ represent the collision and explosion effects, respectively. The probability term (*p*) quantifies the collision probability due to the space debris background population and the explosion probability of the analyzed object. The severity term (e) is associated to the effects of the fragmentation of the analyzed object on the sustainability of the space environment.

evaluated using the Starling 2.1 tool [12][13][14][15] to generate artificial fragmentations, propagate the cloud of fragments and estimate the collision probability against a set of reference targets. Following the approach in [16], 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, operational, end-of-life disposal). To assess the impact of the entire mission on the space environment, the value of the total index is computed as

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

where t_0 is the starting epoch, t_{EOL} is the epoch at which the operational phase starts, t_{end} 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 [16]. The first term of Eq. (2) refers to the operational phase of the object. The second and the third terms refer to the Post-Mission Disposal

(PMD) phase where it is contemplated that the End-Of-Life (EOL) disposal may fail [16]. The reliability of the PMD is included through the parameter α to be set between 0 and 1.

The effect of CAM can be also considered. Indeed in the case the spacecraft is active, the computation of Eq. (1) is performed twice, CAM capabilities, so that at a generic time epoch of the mission the index is

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

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 is a coefficient between 0 and 1. The β parameter can be directly set by the user or can be computed using the ESA ARES tool based on the fractional risk reduction, which measures the efficacy of the avoidance strategy [17].

2.2 Constellation analysis

When computing the impact of a constellation, where multiple objects are considered, additional steps are needed. In particular, the index is not computed for all the objects in the constellation but only for some representative objects (i.e., one for each plane of the constellation), which are then used to derive the global impact of the constellation. The reason behind this choice is that not all the Keplerian orbital parameters are of interest when computing the debris index in different orbital regions [7][9][11]. For instance, for the LEO region, the semi-major axis and the inclination are the parameters of interest.

The constellation is divided according to the planes, specifying: the number of objects in each plane, the number of years needed to deploy each plane, and the plane lifetime, intended as the time between the beginning of the first operational phase of the first satellite of the plane and the beginning of the end-of-life phase of the last satellite of the plane.

Moreover, three phases are considered (both for each plane and for the entire constellation):

- Deployment phase: for the plane it ends when all the satellites are operational, while for the constellation when at least one plane is operational.
- Operational phase
- Decommissioning phase: for the plane when the first satellite after the last replenishment starts the PMD phase, while for the constellation, when the last plane starts the decommissioning phase.

As said, a single satellite is considered for each plane, whose characteristics will be used for all the satellites in that plane. Then, the procedure for the evaluation of the impact of the entre constellation can be summarized as:

- Evaluation of the environmental impact of each representative object.
- Evaluation of the environmental impact of each plane.
- Evaluation of the environmental impact of the entire constellation.

The computation of the index for the single spacecraft follows the procedure summarized in Section 2.1, allowing to gain the information about the evolution of the index per epoch, per phase, and the total index for each reference object. This information is then used to evaluate the impact of each plane.

To do so, first the plane lifetime is used to count the number of replenishments to be considered. Indeed, considering a general case, the lifetime of each spacecraft can be lower than that of the plane or of the constellation. Thus, the number of replenishments is computed as:

$$N_{repl} = \frac{T_{plane}}{T_{obj}} \tag{4}$$

being T_{plane} the operational lifetime of the plane, and T_{obj} the operational lifetime of the reference spacecraft. Thanks to this, the index evolution for the replenishment of each single object can be evaluated replicating the information for the single spacecraft and considering the new object operational at the beginning of the PMD phase of the previous one. A simple example of the procedure is summarized in Table 1, where the replenishment is considered to happen three times (the x means that the satellite has no impact at that epoch).

Table 1. Spacecraft replenishment structure.

Epoch	S/C 1	S/C 2	S/C 3
01-01-2023	Launch	x	x
01-01-2024	Injection	x	x
01-01-2025	Operational	x	x
01-01-2026	Operational	x	x
01-01-2027	Operational	Launch	x
01-01-2028	Operational	Injection	x
01-01-2029	PMD	Operational	x
01-01-2030	PMD	Operational	x
01-01-2031	PMD	Operational	Launch
01-01-2032	x	Operational	Injection
01-01-2033	x	PMD	Operational
01-01-2034	x	PMD	Operational
01-01-2035	x	PMD	Operational
01-01-2036	x	x	Operational
01-01-2037	x	x	PMD
01-01-2038	x	x	PMD
01-01-2039	x	x	PMD

The contribution of all the satellites involved in the replenishment is summed up for each epoch to obtain the evolution of the index over the replenishment.

After that, considering the number of years for the deployment, the evolution of the index per epoch of the plane can be evaluated. This is done computing the number of objects deployed per year as:

$$N_{depl} = \frac{N_{obj-plane}}{t_{depl}} \tag{5}$$

with $N_{obj-plane}$ the total number of objects in the plane, and t_{depl} the number of years required for the deployment. Since the division could result in a non-integer value, the value is rounded to the largest integer. In this way, a higher number of objects are launched in the early years of the constellation deployment phase.

At this point, the index evolution over time of the plane is computed generating the index evolution over the replenishment for all the objects in the plane and summing up their contributions considering the shift due to the year of deployment.

The evolution per phase is computed summing the index associated to each phase, while the total index is computed summing the contribution of each phase as:

$$I_{t-plane} = \int_{t_0}^{t_{op}} I\,dt + \int_{t_{op}}^{t_{dec}} I\,dt + \int_{t_{dec}}^{t_f} I\,dt \qquad (6)$$

with t_0 the first epoch of the deployment phase, t_{op} the epoch at which the operational phase of the plane begins, t_{dec} the beginning of the decommissioning phase of the plane, and t_f the final time.

Once the information about each plane is evaluated, the computation of the impact of the entire constellation can be performed. First, a check is performed on the epochs of the first satellite of each plane to know the shift between the launch of each plane. Then, knowing the shift, the index is computed summing the contribution of each plane at each epoch, associating the proper phase at each epoch following the logic previously introduced. From the latter, the index per phase is computed as the sum of the contributions related to each specific phase, while the total index of the constellation is computed summing the contributions of each phase:

$$I_{t-const} = \int_{t_0}^{t_{op}} I\,dt + \int_{t_{op}}^{t_{dec}} I\,dt + \int_{t_{dec}}^{t_f} I\,dt \qquad (7)$$

with t_0 the first epoch of the deployment phase of the first plane of the constellation, t_{op} the epoch at which the operational phase of the constellation begins, t_{dec} the beginning of the decommissioning phase of the last plane of the constellation, and t_f the final time.

It is important to note that no reliability value is considered for the removal phase, accounting just for the failure of the single spacecraft with the PMD reliability. In addition, no failure of the satellites is considered during the operational lifetime and no spare objects are considered.

3 OneWeb LIKE CONSTELLATION SCENARIO DESCRIPTION

A OneWeb like constellation is used as test case for the evaluation of the index of a LEO constellation. For this purpose, the constellation is composed of 3 planes characterized by different semi-major axes and inclinations. As described in Section 2.2, three reference spacecraft are considered (one per each plane), whose design properties are summarized in Table 3.

Three phases of the mission are considered: one year for the launch phase, one year for the orbit injection phase, and 10 years for the operational phase. After the operational phase the satellite will start the re-entry phase.

All the satellites have CAM capabilities (considered in all the phases except the end-of-life), and the post mission disposal will be performed in such a way to be compliant with a re-entry in 25 years.

Table 2. OneWeb satellite – design characteristics.

Name	Class	CAM efficacy	Mass [Kg]	Area [m^2]	PMD type	PMD reliability
OneWeb	Payload	0.99	148	2.96	Target time (25 years)	0.99

Table 3. Constellation satellites – mission characteristics. Table 3 includes the main mission parameters for each reference spacecraft. Each plane of the constellation will have 700 satellites, that will be deployed in 3 years, and will have a lifetime of 53 years. During the operational phase of the constellation, 5 replenishments (computed using Eq. (4)) will be performed.

Table 3. Constellation satellites – mission characteristics.

Name	a [km]	i [deg]	# object in the plane	Year to deploy	Operational lifetime
OneWeb 1	**7580**	**87.9**	**700**	**3**	**53**
OneWeb 2	**7580**	**50**	**700**	**3**	**53**
OneWeb 3	**7000**	**87.9**	**700**	**3**	**53**

Following the procedure highlighted in Section 2.2, the impact of the mission will be evaluated for the single satellite first, and then for each plane and for the entire constellation. In this way, not only is it possible to assess the impact of the entire constellation, but also to understand how it changes according to the location around the Earth of the satellites belonging to it.

4 OneWeb LIKE CONSTELLATION SCENARIO RESULTS

This section presents the results of the case scenario introduced before.

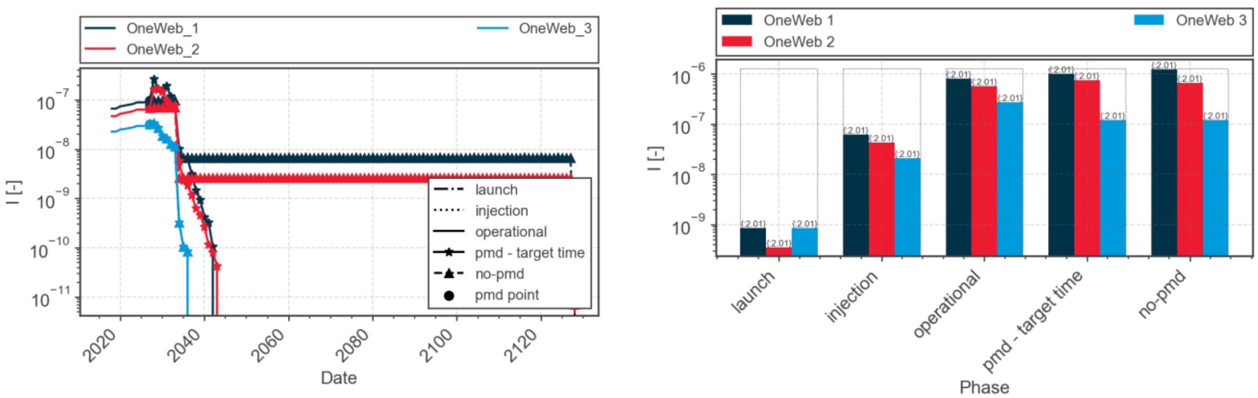
4.1 Single spacecraft

The first step is to investigate the impact of a single spacecraft of the constellation. Figure 1(a)**Errore. L'origine riferimento non è stata trovata.** shows the evolution over time while Figure 1(b) shows the evolution per phase for each reference object of the constellation.

Looking at the evolution over time, the OneWeb 1 and OneWeb 2 are characterized by a similar behavior. The difference between them is mainly driven by the different inclinations considered, involving a different value of the effect term. This can be appreciated looking at the severity maps displayed in Figure 2. The latter are maps representing the severity of a generic fragmentation (with specific inclination and semi-major axis parameters) on a population of objects. In this case, the population is composed of some representative objects of the entire population of active objects orbiting in the LEO region. The fragmentation of a satellite placed in a darker region has a worse consequence on the background population considered. On top of them, the evolution of the mission is displayed using dots with different colors (specified in the legend).

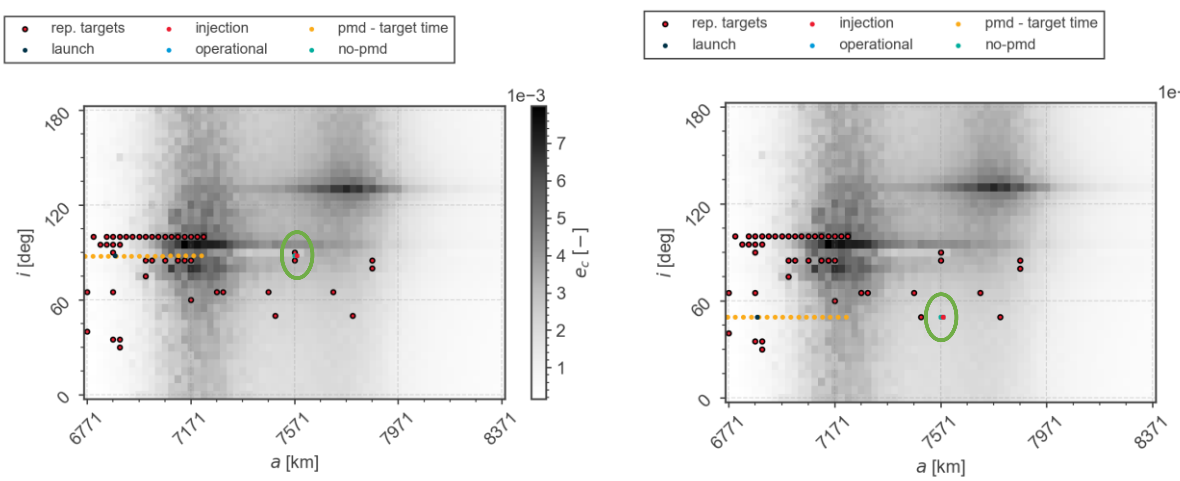
From Figure 2 (c) and (d) it is possible to note how the OneWeb 2 is always in a lighter region (especially during the end-of-life phase in yellow) with respect to the OneWeb 1, resulting in a lower impact on the population.

The shape of the OneWeb 3, instead, is completely different. This because the satellite is located at a lower altitude, characterized by lower severity (Figure 2 (e)) and allowing for a faster re-entry even with a failed disposal phase (less time in orbit).

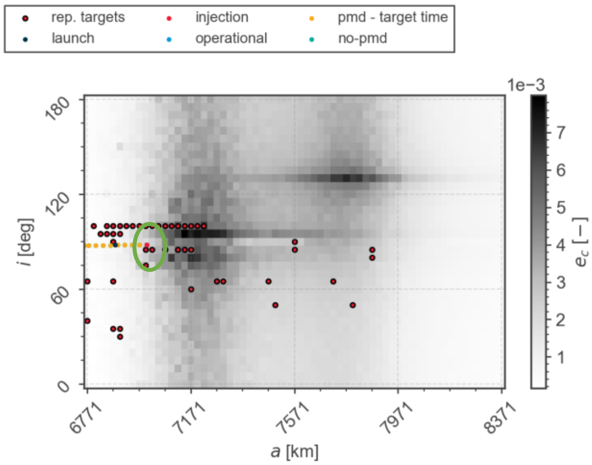


(a) Index evolution over time **(b) Index evolution per phase**

Figure 1. Index evolution – Constellation single satellite.



(c) OneWeb 1 **(d) OneWeb 2**



(e) OneWeb 3

Figure 2. Severity maps in LEO against the representative active objects population.

These results show that the location of the plane of a constellation can have a significant relevance during the mission design. This is because, from the point of view of the impact of the mission in case of a breakup, the severity of a fragmentation will be different according to the semi-major axis and inclination considered. In addition, the results also give an idea about the influence of the post mission disposal strategy and time required to re-enter, as spending a lot of time in the darker region of the severity map will increase the impact on the population of objects already in orbit.

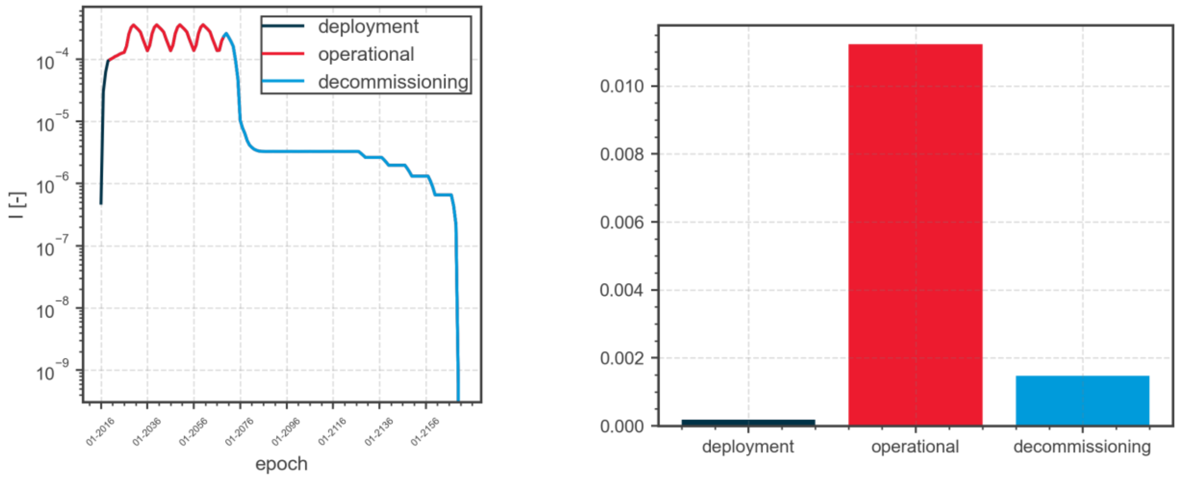
4.2 Entire Constellation

Finally, by summing up the contribution of all the satellites in each plane and those related to each replenishment, the evolution of the entire constellation can be computed and the results are show in Figure 3 (index evolution over time (f) and per phase (g)).

First, the index increases until the deployment phase begins. In this phase, the number of satellites is constantly increased, leading to an increment in the overall index of the mission.

Then, as visible, the operational phase is the phase that is characterized by the highest environmental impact. This is because, differently from the single satellite, the constellation accounts for many satellites during this phase: the new ones launched for replenishment and those already in orbit that will enter in the re-entry phase. This reflects into a periodic behavior, as the new satellite are launched while the old ones enter the post mission disposal phase (following the path presented in Table 1), adding and removing satellite periodically.

After this phase, the index tends to decrease during the decommissioning phase until all the satellites are re-entered.



(f) Index evolution over time **(g) Index evolution per phase**

Figure 3. Index evolution – entire Constellation.

5 CONCLUSIONS

The short- and long-term sustainability of space is becoming a priority in the space sector. The number of launches, the number of satellites, and the number of space debris has been increasing rapidly in recent years, threatening the future stability of the space environment. Thus, it is essential to define worldwide mitigation rules to regulate the evolution of the space population.

The introduction of Constellation and of Large Constellation, deploying many objects, is a challenge and represents a change in the way space around the Earth is used. It is thus necessary to understand the interaction between the constellations, the already in-orbit population of satellites and the background population of space debris.

The aim of the model presented in this work was to investigate the impact of mission composed by single objects and by several objects (e.g., Constellations) on the space environment around the Earth, allowing to understand the main drivers for the current and new mitigation guidelines. This is done investigating the probability and severity of possible explosion and collision of satellites along their mission lifetime. In this way, it is possible to investigate the impact of specific mission phases (e.g., the end-of-life) along with some mission design parameters specific for each mission.

The results showed how the location of the satellite in a constellation can play a fundamental role in the sustainable evolution of the space environment, possibly influencing the future launches and re-entry strategies.

Improvement to the current model is ongoing, involving the introduction of additional failure possibilities and spare satellites in case of constellation. In addition, further analysis will be performed to better understand the influence of the CAM efficacy and of the post mission disposal reliability of the adopted strategy.

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