RISK INDUCED BY THE UNCATALOGUED SPACE DEBRIS POPULATION IN THE PRESENCE OF LARGE CONSTELLATIONS

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ABSTRACT

The number of artificial objects in orbit continues to increase [1] and, with it, a key threat to space sustainability. In order to avoid such situation, several responses outlining mitigation procedures, including the Inter-Agency Space Debris Coordination Committee (IADC) Space Debris Mitigation Guidelines [2], the United Nations Committee on the Peaceful Uses of Outer Space Mitigation Guidelines [3], the International Organization for Standardization Space Debris Mitigation Standards [4] and a multitude of other national and international documents have been, and continue to be, developed to limit the expected growth of the debris population.

Planned, large constellations of satellites in low Earth orbit (LEO) raise new questions about space sustainability, which previous studies started to tackle [5,6]. On this paper we analyse the effects of these constellations on the long term evolution of the orbital environment when more realistic conditions, than those used on previous studies, are considered (e.g. explosions [7], lower respect of mitigation practices [7,8,9], objects < 10cm)..

1 INTRODUCTION

Since the first orbital launch in 1957, the number of artificial objects in Earth orbit has been increasing [1]. This has led to a corresponding increase in the threat to active satellites from hypervelocity collisions, putting in jeopardy crucial services that benefit human society. Therefore there is growing pressure on space users to implement mitigation measures aimed at preventing the proliferation of space debris and enabling the sustainable use of space [10].

Several responses outlining mitigation procedures, including the Inter-Agency Space Debris Coordination Committee (IADC) Space Debris Mitigation Guidelines [2], the United Nations Committee on the Peaceful Uses of Outer Space Mitigation Guidelines [3], the International Organization for Standardization Space Debris Mitigation Standards [4] and a multitude of other national and international documents have been, and continue to be, developed to limit the expected growth of the debris population.. These guidelines, standards and laws aim to prevent the generation of debris in the short-term, through measures typically related to spacecraft design and operation, and the growth of the debris population over the longer-term, by limiting the lifetime in key orbital regions after the end of mission. A fundamental assumption was that nature and scale of future space activities would continue to be similar to what was observed during the 1990s. However the proposed deployment of constellations of satellites in LEO to provide regular internet access to regions lacking necessary infrastructure [11], and the enhancement to space traffic beyond what was anticipated, represents a potential source of disruption to the long term sustainability of the space environment. While previous studies have already started to characterise and comprehend the impacts of such new space uses [1,6], the present study aims at enhancing our vision of the risks and threats they entail in a more pessimistic environment.

2 SIMULATIONS CHARACTERISTICS

2.1 General model settings

A Monte-Carlo (MC) approach was used to simulate the evolution of the orbital population over a period of 200 years from 2013, with the Model for the Evolution of Debris on the Earth's Environment (MEDEE) [12], the evolutionary model at the French space agency (Centre National d'Etudes Spatiales, CNES). Previous studies [14, 13] have shown that a limited amount of MC simulations (i.e. >40) give statistically significant results for the mean number of space objects present in the population, while a significant higher number of realisations (>100) are needed to reach such significance for the standard deviation. The solar activity used in our propagation model (a key factor to drive the evolution of objects in LEO) is of medium strength, as it consists in a repetition of an 11 year-long cycle, with maximum F10.7 solar flux at 180 and minimum at 70.

2.2 Background population

For the purposes of all the simulations, the background (non-constellation) population consists of all objects larger or equal to 10 cm in size, wholly or partially

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residing in or crossing the LEO region on 1 January 2013, and derived from the Meteoroid and Space Debris Terrestrial Environment Reference (MASTER)-2009 model [15, 16]. Additionally, the non-constellation launch traffic repeats launches to LEO from the historical period January 1st 2005 to December 31th 2012 in 8 years cycles.

Moreover :

- Payloads are maintained on their initial orbit, and a mean mission lifetime of 8 years is considered (i.e. a keplerian propagation with J2 effect is considered for payloads during their mission lifetime)
- Payloads ensure 100% collision avoidance with the catalogued population during their mission (i.e. objects > 10cm).
- Payloads (at the end of their mission) and Rocket Bodies (R/B) are immediately disposed on lower orbits that ensure a maximum post-mission lifetime in LEO of 25 years, at success rates depending on the scenarios (cf. §2.5).

2.3 Constellation description

The constellation we model throughout all our simulations corresponds to a generic constellation (i.e. none of the large-constellations projects have been specifically considered) having the following characteristics [5]:

- 1080 satellites at 1100 km of altitude, and 85 degrees of inclination, as of January 2021 (includes spare satellites)
- All satellites have 200kg of mass and 1m² effective cross-section
- All satellites have 5 years of operational lifetime, during which they are maintained on their orbit
- All launcher stages comply with immediate direct re-entry, and therefore do not appear in our simulations
- No mission-related objects are released
- 18 objects per launch (for constellation build-up and replenishment)
- 20 orbital planes
- 20 launches in 2018, 2019 and 2020 each to build up constellation
- 12 launches per year for replenishment inserted in the nominal orbit (starting in 2021, last replenishment launches in 2070). It means that for the first 4 years after operational start, there will be more satellites than required, and after operational end, still 4 years with operational satellites.
- After mission, objects are disposed of at success rates depending on the scenarios, to ensure a maximum post-mission lifetime in LEO also depending on the considered scenario (cf. §2.5)
- 50 year global mission duration (2021-2071)
- Collision avoidance is performed during LEOP and during the 5 years mission, with respect to constellation and non-constellation objects > 10cm, at success rates depending on the scenarios (cf. §2.5).

2.4 Topics of the study and scenarios groups

In this study we focus on the analysis of the effect of three variables on the long term evolution of the space debris population, in the presence of large constellation:

- uncatalogued debris (i.e. objects smaller than 10 cm in LEO)
- Explosions [7]
- Up to date Post Mission Disposal (PMD) success rate [7].

The first topic is the main objective of the present study, but the other ones are both scarcely studied in the literature and prone to generate large number of debris, thus their importance in our work. However, in order to keep the problem computationally feasible, we have decided to analyse the effect of the uncatalogued population in LEO apart from the last two variables.

2.4.1 Uncatalogued space debris population (< 10 cm), scenarios group A

Studies performed with reference space debris evolutionary models usually focus on objects > 10cm for 2 main reasons:

- Computation time (i.e. including smaller objects increase substantially the number of objects in the population and therefore the computation time)
- Catalogues of objects in LEO are limited to objects bigger than 10 cm (order of magnitude) due to current limitations on sensor capabilities.

However, debris of sizes lower than 10cm (that we call “small” debris in the scope of this paper) can still harm or destroy operational objects in a collision [25]. A limitation of our study is that the initial background population is composed of objects residing or crossing the LEO region bigger than 10 cm, therefore we use the standard NASA Break-up model to introduce the “small” objects (> 1 cm) on the environment after collisions and explosions. Such approach still allows to study the effect of the uncatalogued population on the long-term evolution of the space debris population, as such small population is characterized by high area to mass ratios, and therefore by having a high decrease rate of the semi-major axis, and the analysis is performed for 200 years.

2.4.2 Non-collisional explosions, scenarios group B

Previous studies focused on other key drivers like solar activity [17, 18, 19], or PMD success rate [20, 21]. In most of these studies, and either to isolate specific effects or to study the long term evolution of the environment under optimistic hypothesis the "no explosion" hypothesis was retained. However, explosions still occurs nowadays [7]. Therefore, we have decided to analyse the effect of non-collisional explosions on the long term evolution of the environment, with the following approach:

- Random number of explosions between 5 and 12 per year, based on real statistics [7]
- Debris are generated with the standard NASA Break-up Model [22, 23], with a higher limit of 250 debris for the objects bigger than 10 cm. Such limit is empirical and is derived from the analysis of catalogued debris by space-track (www.space-track.org) for objects exploding during the last years.
- Only objects heavier than 50kg may explode. Only R/B and background payloads, in the initial population or launched before January 1st 2020 may explode (i.e. we consider that after January 1st 2020 all R/B and payloads are 100% passivated).
- Constellation satellites are always 100% passivated.

2.4.3 PMD success rate, scenarios group B

The 90% PMD success rate baseline scenario (computed on objects having an orbital lifetime > 25 years), is consistent with previous studies [5, 6, 21, 24], which have shown that compliance to mitigation guidelines is of paramount importance regarding space sustainability in the future. However, the actual rate of compliance in recent years shows that the mitigation guidelines compliance, and in particular the 25 years rule, is far from the hypothesis of 90% [8, 9]. Therefore, more pessimistic assumptions concerning PMD success rate has been considered in this study:

- For the background population, two different PMD success rates hypothesis (the PMD success rate is computed based on objects having orbital lifetimes greater than 25 years) have been considered depending on the scenario (cf. §2.5.3):
    - 20% of PMD success rate for the whole simulations
    - PMD increasing from 20% in 2013 to 90% in 2050 (linearly) and 90% after 2050.
- For the constellation, 80% or 90% PMD success rate is assumed, depending on the scenario (cf. §2.5.3).

2.5 Detail of the considered scenarios

2.5.1 Baseline PMD90 scenario

Our baseline scenario has only background population, with no constellation, and no explosion. PMD success rate is set to 90% throughout the whole simulation.

Table 1: Baseline PMD90 scenario

Baseline PMD90	No constellation
	No explosion
	Background PMD 90%

2.5.2 Scenarios group A

Simulations in this group show the effect of objects < 10 cm over two reference scenarios: baseline and a constellation scenario.

Table 2: Scenarios group A

Baseline + small	Baseline PMD90 +
	1cm < Debris < 10 cm generated by collisions
SA1	Baseline PMD90 +
	Constellation at 1100km: - Direct injection at 1100km - 100% collision avoidance during 5 year mission - 90% success rate impulse PMD on an eccentric orbit aiming at 25 years lifetime (same as background PMD)
SA1 + small	SA1 +
	1cm < Debris < 10 cm generated by collisions

2.5.3 Scenarios group B

Our 2nd group of scenarios focus on explosions and PMD rates. All objects are above 10 cm.

Table 3: scenarios group B

SB1	Explosions
	Background PMD 20%
	No constellation
SB2	Explosions
	Background PMD 20% to 90% in 2050 (linearly), then 90%
	No constellation
SB3	SB2 +
	Constellation at 600km: - Direct injection at 600km - 100% collision avoidance during 5 year mission - 100% success rate electric PMD in 2 years

SB4	SB2 + Constellation at 1100km: - Electric deployment from 450km to 1100km in 50 days - 100% collision avoidance during 5 year mission - 80% success rate electric PMD in 2 years
SB5	SB2 + Constellation at 1100km: - Electric deployment from 450km to 1100km in 50 days - 90% collision avoidance during 5 year mission - 90% success rate electric PMD in 2 years
SB6	SB2 + 3 simultaneous constellations at 600km, 1100km and 1200km: - Electric deployment from 450km to altitude in 50 days - 90% collision avoidance during 5 year mission - 80% success rate electric PMD in 2 years

3 RESULTS

3.1 Group A: effect of debris < 10 cm

On this paragraph we analyse the effect of the un-catalogued population on the long term evolution of the environment, particularly concerning the effect of "small" debris on the proliferation of the mean number of objects > 10cm (cf. Figure 1) and on the number of collisions (cf. Figure 3).

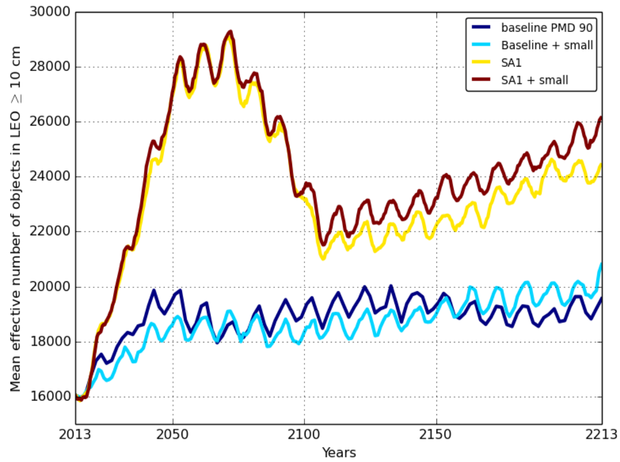

Figure 1: Mean population of objects > 10 cm in LEO for group A scenarios.

As we can see on Figure 1, the constellation scenarios clearly show the > 10 cm population steeply rise, stabilise, and then decline after the end of the constellation mission [5]. It then reaches equilibrium with a slow rise, because of the 10% constellation PMD failures in itself and its consequences in terms of collisions.

Moreover there is little to no difference in terms of mean-number of objects > 10 cm, when the small debris are considered at least in our 200 years scope. Such difference falls well within the dispersion of the results.

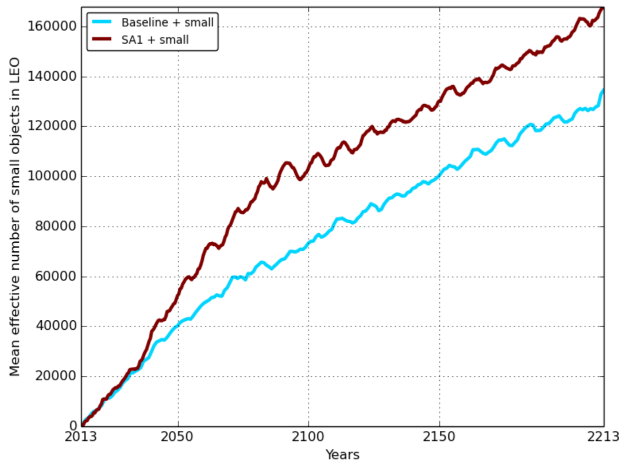

Figure 2: Mean population of 1 cm < objects < 10 cm in LEO for group A scenarios.

Additionally, Figure 2 shows a very steep increase of the small objects population, starting from 0 as there is no small object in our initial population. The small objects population after 200 years is approximately 7 times larger than the objects > 10 cm. When constellations are considered, the increase of small debris is bigger, due to additional collisions with abandoned constellation objects.

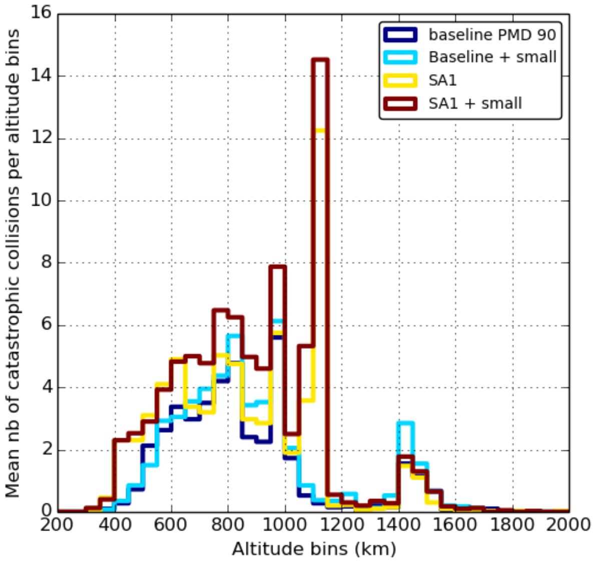

Figure 3: Mean catastrophic collisions distribution in 50 km altitude bins, in group A. No collision between small debris.

In terms of collisions, Figure 3 confirms the results of Figure 1: new collisions at 1100 km for the SA1 scenarios with respect to the baseline one, and just a few additional catastrophic collisions in the "small" scenarios when compared to their respective counterpart.

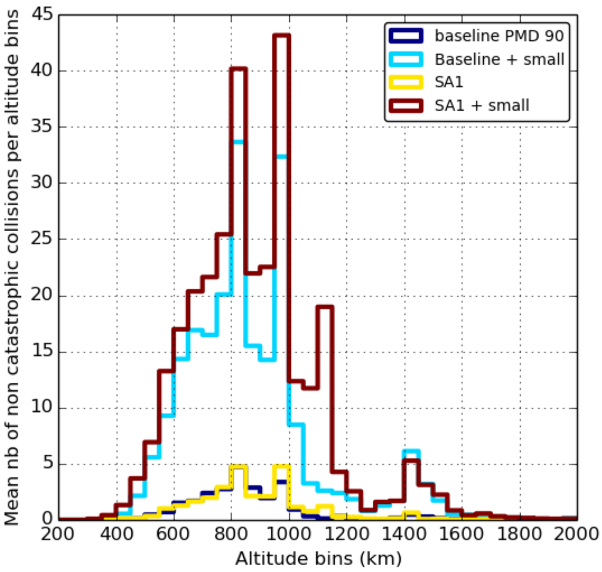

Figure 4: Mean non-catastrophic collisions distribution in 50 km altitude bins, in group A. No collision between small debris.

However, Figure 4 clearly demonstrates the consequences of small debris on the environment : 10 times more non-catastrophic collisions, at all altitudes, than the "non small" scenarios, especially in crowded altitudes (800 km, 1000 km, and 1100km with constellation scenarios). This increase on non-catastrophic collisions is tightly linked with an increase on the risk induced by the space environment.

It is not surprising that collisions with small debris are mostly non catastrophic, from an energetic point of view, as the mass of colliding objects is key to determine the amount of energy involved.

However, even if a non-catastrophic collision with a 1 cm to 10 cm object may not completely fragment the bigger object, its consequences from an operational point of view may range from a loss of power input, to loss of control means and other functions, or complete loss of the mission and of the satellite.

Therefore, in our otherwise optimistic scenarios, small objects may not generate many catalogue size objects, but at least create much harder conditions in terms of collision risks and mission sustainability, for mega-constellations as well as background traffic.

In terms of risk, the integrated collision risk, induced by the increase of the uncatalogued objects, to the operational constellation satellites is less severe than expected (i.e. low number of collisions with operational satellites) as their operational lifetime is relatively low (i.e. 5 years) compared to the time needed for uncatalogued objects to build up at these altitudes. However, the consequences may be more severe for any subsequent space activity.

Additionally, even if we have scarce knowledge of the uncatalogued objects density in the present space environment, we can suppose that their density vs altitude pattern follows that of the catalogued objects. Therefore, it is likely that if we had a realistic population of uncatalogued objects in our initial population, their impact would be notable in dense regions like 800km and 1000km, but not in the somewhat unpopulated 1100km region.

3.2 Group B: effect of explosions and PMD success rates

Before focusing on the population, and in order to give an idea to the reader about the explosions fragments, let's have a look at the number of debris produced by the explosions for SB1 and SB2. Similar figures are reproduced for all the scenarios considering explosions.

Figure 5 shows that most of the explosions generate around 220 objects, when the fragmented mass is enough. Therefore when the fragmented mass is higher, the mass of the respective debris are higher.

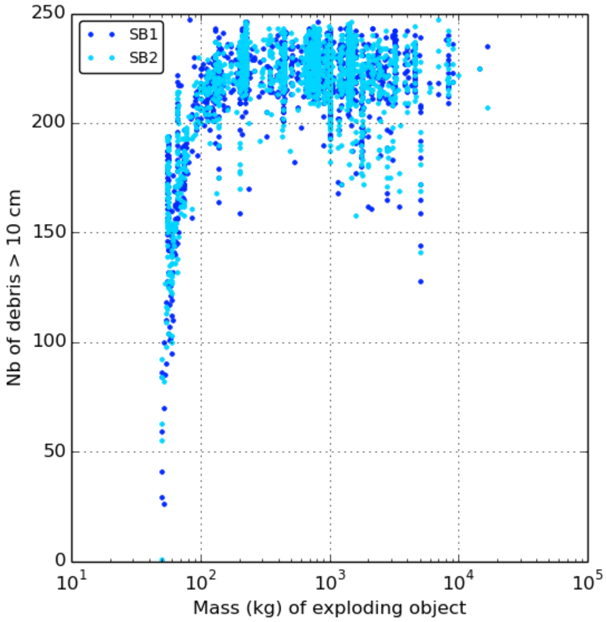

Figure 5: Number of debris depending on the mass of the fragmenting object, as generated by the NASA Break-Up Model, for a given MC run.

On the interpretation of Figure 6, the reader should bear in mind that the considered scenario generates around 1700 explosions in 200 years, and a mean number of 220 debris each. Therefore, the non-collisional fragments will be on the order of 374000, without counting the fragments induced by collisions with them.

Let's focus now on the population evolution for the non constellation scenarios: baseline, SB1 and SB2, in Figure 6.

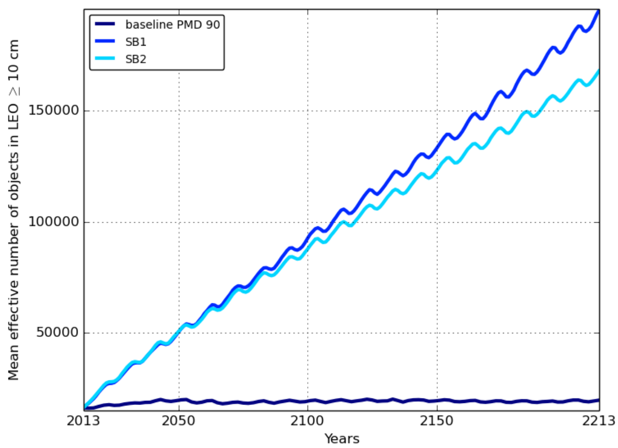

Figure 6: Mean population of objects > 10 cm in LEO for group B scenarios with no constellation

The striking result here is that low PMD success rate combined to a relentless occurrence of explosions produce steeply rising space objects population in our model, reaching 9 times more objects after 200 years 3.3 clearly the explosion rate, and the induced chain effect by the generated fragments, and not so much the PMD success rate, as the final population level in scenario SB2 with 90% PMD from 2050 to 2213 is only $1/6^{th}$ lower than SB1.

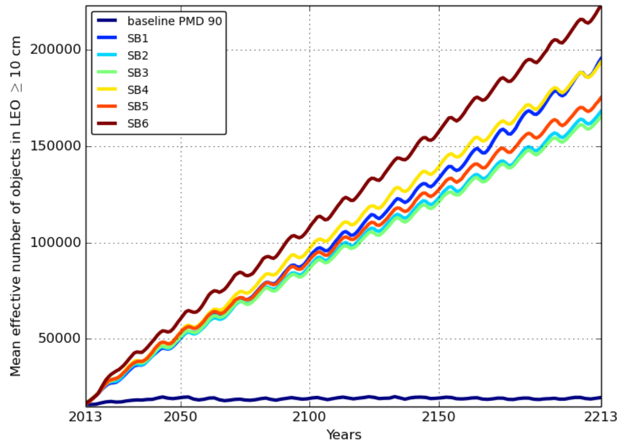

Figure 7: Mean population of objects > 10 cm in LEO for group B scenarios.

Figure 7 shows the mean population evolution for all the non-constellations and constellation scenarios. First, we observe that all scenarios present a significantly bigger population than the baseline population which is due, as explained before, to the acceleration of the space debris proliferation due to explosion fragments.

Additionally, the introduction of constellation at low altitude (SB3 at 600km) appears to have no effect in the long run with respect to its reference scenario SB2.

Then, from Figure 7 two main drivers on the proliferation of space debris can be observed:

- The PMD success rate, as already shown on previous work [5, 6, 21, 24].
- The number and distribution of constellations, coupled with the previous variable. SB6 with three constellations (two of them at high orbits) results in a significantly higher population than SB3.

Interestingly, the sensitivity of the population to the PMD success rate is way higher than the sensitivity to the collision avoidance success rate, as can be clearly seen when we compare the results of SB4 and SB5. This is due to the fact that lower PMD success rate has a direct impact on the number of objects staying at the constellation altitude, whereas lower collision avoidance success rate's impact lasts only for the mission duration.

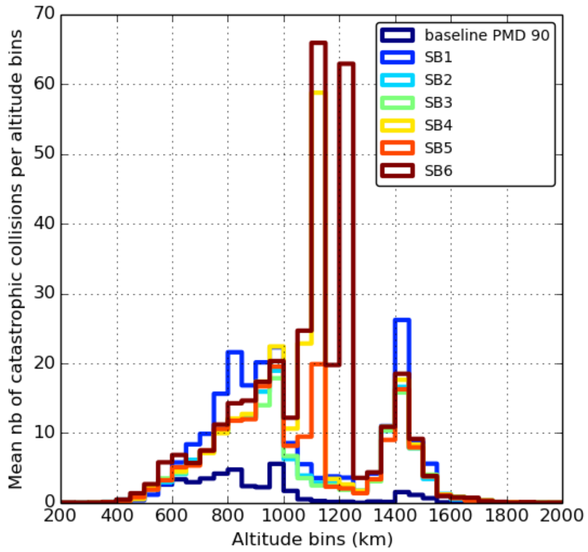

Figure 8: Mean catastrophic collisions distribution in 50 km altitude bins, in group B.

Additionally, Figure 8 shows the direct impact of a lower PMD success rate for the constellation at 1100km. : from SB5 to SB4 or SB6, 10% less PMD success rate induce 3 times more catastrophic collisions.

The higher collision level in SB6 at 1100km than SB4, may result from the 10% lower collision avoidance success rate (in SB6), as well as the interactions between collision induced debris at 1100km and 1200km.

4 CONCLUSION AND PERSPECTIVES

The study presented on this paper deviates a little bit from the optimistic scenarios usually on previous studies, on which no-explosions and a very good compliance with post-mission disposal (PMD) measures are considered. Moreover the uncatalogued population of objects (<10 cm) has been also consider in order to study its influence on the long term evolution of the space environment.

Scenarios implementing the uncatalogued space debris population, between 1 cm and 10 cm, highlights the fact that such low sized population present a major threat to any mission success, especially at key altitudes, even if it does not induce a Kessler-like effect in the population of objects above 10 cm.

Scenarios implementing less optimistic hypothesis including explosions and an actual PMD success rate, ends with a vast amount of objects above 10 cm.

In this context, the introduction of large constellations at high LEO altitudes poses two major concerns. First, passivation success and PMD success rate remain of paramount importance to avoid proliferation of debris and protect the sustainability of the concerned regions (1100km or 1200km), on which any abandoned satellite or fragment thereof will remain virtually forever. . Second, even in virtuous conditions of PMD success rate and passivation, a small number of collisions is bound to induce in the long run a build up of uncatalogued objects population, which in turn constitutes an important threat for the sustainability of space activities in these region.

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