DECOUPLED ANALYSIS OF THE EFFECT OF PAST AND FUTURE SPACE ACTIVITY ON THE ORBITAL ENVIRONMENT

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ABSTRACT

Over the past decades, international guidelines and standards have been established to limit the increase of debris in orbit. In particular, over the past years a significant effort has been made to avoid accidental fragmentations thanks to passivation of space objects as well as limiting their resident time in protected zones after End of Life. In addition many studies have been conducted at international level to identify the needed level of compliance with mitigation guidelines in order to guarantee a stable orbital debris environment over the next 200 years, as well as to identify the situations under which Active Debris Removal (ADR) operations were needed to guarantee such environment stabilization. Nevertheless, almost the totality of such studies were done considering very optimistic hypothesis affecting both the background population (i.e. the population resulting after more than 60 years of space activity) as well as the future population (i.e. no explosions, new rocket bodies perform direct re-entry, only objects of sizes bigger or equal than 10cm are considered into the simulations).

Today, the reality is that the objects present into the background population continue to explode, at a frequency of between 3 and 12 explosions per year, and that the so called New Space is leading to the launch of an unprecedented amount of new operational satellites, sometimes without maneuverable capability into circumterrestrial orbit.

The work presented on this paper seeks to analyze in a decoupled manner the role that the background population and that a hypothetical future population, including the so called New Space effects (i.e. mega-constellations), have on the medium (50 years) and long term (100 years) evolution of the orbital population. In addition, the population minimal size has been extended down to 1cm, as a collision with centimeter size objects can also lead to lethal or catastrophic break-up.

Keywords: Orbital Debris; Guidelines; New Space; Large Constellations.

1. METHOD

1.1. The MEDEE evolutionary model

The CNES software called MEDEE [1] is a thridimensional evolutionary model, allowing to analyze in statistical terms, the meddium and long term evolution of the man-made orbital population. More precisely, the orbits are semi-analytically propagated and multiple inputs are taken into account: background objects, launch predictions (traffic), compliance with end-of-life guidelines, success of collision avoidance maneuvers, etc. Randomness is present in some of the (many) variables involved [2], hence the name of semi-stochastic model and the need to perform Monte Carlo campaigns. For a given simulation, two antagonistic mechanisms ("source and sink") confront each other on a large scale: on the one hand, the appearance of new objects, either launches or fragments, and on the other hand, the disappearance of existing ones, by atmospheric re-entry or active debris removal. A few tens of MC runs are sufficient for a good convergence of the mean (or median) of the numbers of objects and collisions over time, but several more orders of magnitude seem necessary to reach a reasonable confidence in higher order moments such as the covariance [4] . Some notable technical aspects of MEDEE include:

- The orbit propagations are semi-analytical thanks to the STELA propagator[3].
- The collision probabilities are usually computed according to the Cube method [5] because of its computational complexity which is linear rather than quadratic in the number of objects.
- The effects of fragmentations, which include collisions and explosions, are determined according to the empirical model of NASA known as "Standard Satellite Breakup Model"[6], noted "NASA Standard BU Model" hereafter. The latter distinguishes between catastrophic collisions (fragmentation of the two objects involved) or not (fragmentation of the less massive object only and cratering of the

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other) according to a criterion based on the ratio of masses and relative speed.

Except for those in J2-mean (on the RAAN only) which artificially simulate station keeping, the propagations performed in this study classically model the following orbital perturbations:

- Earth gravitational potential (the order represented depends on the type of orbit)
- Atmospheric drag
- Solar radiation pressure
- Lunar-solar effects

The geomagnetic indices are assumed constant at 15 while the solar flux is a mean projection based on a mixture of low, mean and high past 11-year solar cycles.

1.2. Simulation cases

Over the past years, MEDEE and similar tools from other Inter-Agency Space Debris Coordination Committee (IADC) members have been used to analyze the influence on the orbital situation of various factors, including their couplings, such as solar activity, end-of-life measures, ADR, large-constellations

The high degree of uncertainties in some parameters, or even their completely unpredictable nature at times, and the approximations of the model make it impossible to make predictions as such, but rather help to identify trends and understand how the complex system under study works. In oder words, the results of such environmental models allow to identify a range of possible futures rather than to predict a specific one.

Given these uncertainties in prediction, the work reported here aims to explore scenarios which, rather than trying to accurately represent the current situation and plausible future situations, attempt to frame possible evolutions and evaluate the effectiveness of international recommendations by making as few questionable assumptions as possible. Thus, two study cases have been identified:

1. "No traffic evolution" : An evolution, from the current estimated population, with no more human activity. In particular, there are no launches, end-of-life actions, or collision avoidance. Different explosion rates in orbit are investigated. A first evaluation without the "small" objects (i.e. the subgroup of the population for which internal collisions are neglected) is first performed. A second part aims at including these small objects, from the initial population stage (and not just from the first fragmentations).
2. An evolution without background, but with a realistic traffic extrapolated from the current situation and from known large-constellation projects. End-of-life measures (post-mission disposal, noted PMD hereinafter) are assumed to be successful at 90%. Again, small objects (the subgroup of the population for which internal collisions are neglected) will be included.

In particular, these scenarios should answer the following questions: in the present situation, if no more satellites were launched, is it too late to avoid the Kessler syndrome without ADR? Are the current international guidelines adequate to operate space, including to maintain large-constellations, if they were well respected from the very beginning?

2. NO TRAFFIC EVOLUTION

2.1. Long-term evolution of objects > 10cm

This scenario assumes that absolutely no launch is performed. Moreover, no end-of-life, collision avoidance or ADR measures are taken. In other words, it is as if humanity no longer carried out any space activities. There are thus only three types of events in action:

- Natural re-entries, in the strictest sense of the term since there is no end-of-life maneuver
- Explosions
- Collisions (catastrophic or not)

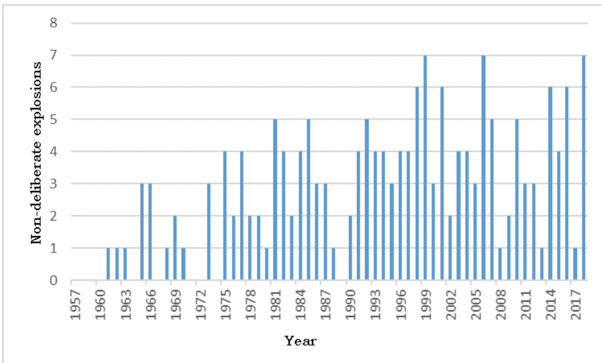

Figure 1. Number of non-deliberate explosions observed up to 2018 (Anz Meador et al [7])

In this simulation, a constant annual explosion rate (of objects heavier than 500kg, of any type) is considered. The values investigated are 1, 3 and 12 explosions per year. In reality, according to NASA, from 1990 to 2018, there have been between 1 and 7 accidental explosions per year [7]. The exact variations can be seen on the

Fig. 1. Note that ESA has more pessimistic figures (annual average of 11.6 non-deliberate fragmentations between 1988 and 2018, of which less than 1 % were collisions [9]).

Fig. 2 shows the LEO populations (averaged over 30 Monte Carlo) resulting from the different explosion rates. Fig. 3 represents the cumulative number of catastrophic collisions.

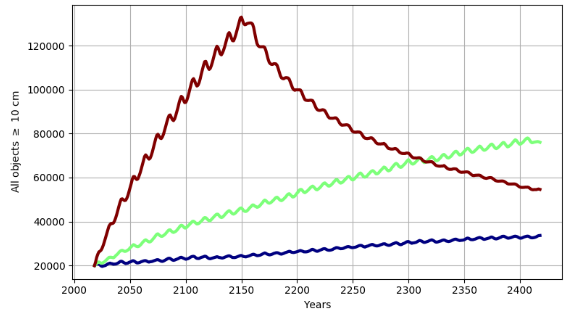

Figure 2. Evolution of the population without traffic and without small objects. Blue is one explosion per year, green is three, red is twelve (one per month)

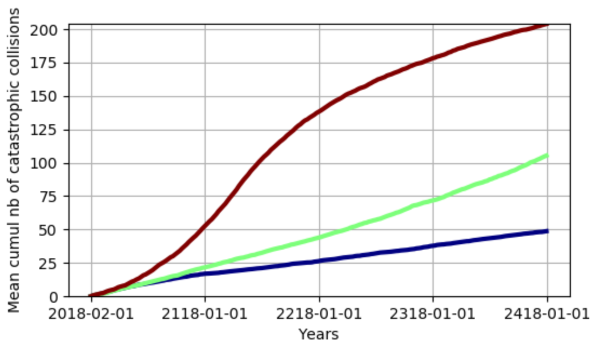

Figure 3. Cumulative catastrophic collisions as a function of time without traffic and small objects. Blue is one explosion per year, green is three, red is twelve (one per month)

In summary, explosions dominate the source & sink and cause a general increase in population. The fragments generated by the explosion will generate further collisions. These different chain reaction patterns are evident after a few years for non-catastrophic collisions and a few decades for the catastrophic collisions. After a century, there is almost three times more catastrophic collisions when the explosions take place once a month rather than once a year.
In the scenario with one explosion per month, and giving the mass limit that has been considered for an object to explode, we are in a situation where there are no further objects to explode. In this situation, re-entries take over almost immediately and the trend is thus reversed. Even if we push the simulated times to 400 years, only the rate of one explosion per month actually exceeds this tipping point, while the rate of three per year seems to be just about it. Moreover, it can be seen that the maximum reached is much lower, because there have been fewer chain reactions of fragmentations and the atmosphere had more time to ”clean up”. After four centuries, the population with the highest number of objects is the one with the intermediate rate.

2.2. Evaluation of the lost mass

The previous results shows that there is a strong correlation between explosions and collisions. This correlation is quite intuitive, as the fragments generated by an explosion, will be at the origin of future collisions. Nevertheless, previous results have been obtained with a population whose minimal size is 10cm. Moreover, several studies shows that even a collision with a centimeter size particule can have catastrophic collisions [8]. One of the consequences of this 10cm size threshold, besides avoiding collisions with smaller particles, results on the virtual removal of fragmented mass from the simulation.

Indeed, whether for an explosion or a collision, the NASA Standard BU Model provides a distribution of generated fragments. The part corresponding to the smallest sizes is simply removed from the simulation since the associated diameters are generally lower than the limit. The question is therefore to know if the amount of material thus artificially removed appears negligible or not. MEDEE allows to find a posteriori the total mass lost over time, however it is not known precisely how many fragments are lost at each fragmentation (potentially thousands or even tens of thousands), as well as the respective mass they would have had.
For information, radar data suggest that the NASA Standard BU Model overestimates the number of debris created around 1cm while it underestimates it around 1mm [10].

2.2.1. One explosion per year

This Monte Carlo contains 50 runs. Fig. 4 shows the average and cumulative mass loss for one explosion per year. It can be seen that several tons are virtually removed from the simulation. Nevertheless, relatively to what re-enters the atmosphere, it is several orders of magnitude less, as shown in Fig. 5. The 2700 tons reentered after 200 years is a little more than half of the total mass of the original population (about 4700 tons). The mass virtually lost in the simulation is therefore not a major contributor in the sink & source mechanism. Note that the peak shortly after 2020 corresponds in fact to a re-entry of the international space station.

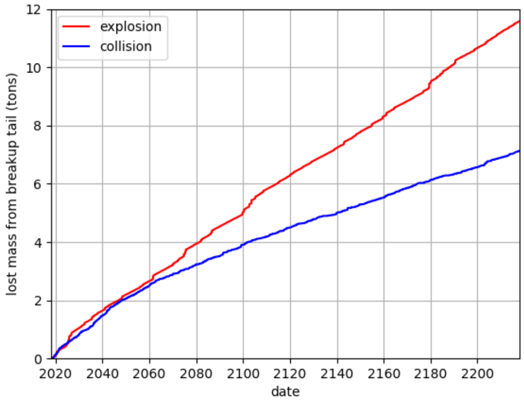

Figure 4. Lost mass for an explosion rate of 1 per year

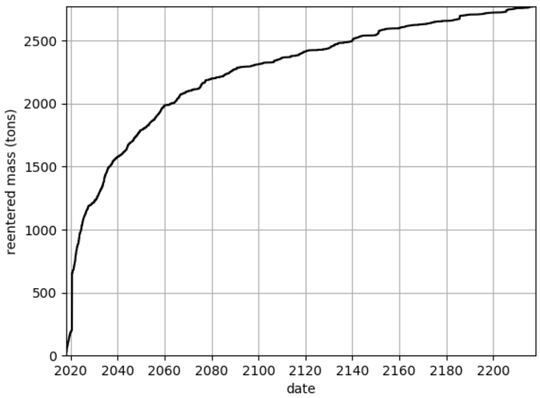

Figure 5. Re-entered mass for an explosion rate of 1 per year

In order to visualize where this mass disappears, its altitude was retrieved, using other debris from the same clouds. Fig. 6 shows the log-log scale distributions of mass and altitudes for fragments virtually removed from the population (Monte Carlo average). It is noteworthy that the mass of virtually removed fragments due to collisions span several orders of magnitude (from milli- to decagram), in contrast to the explosions for which fragments masses are essentially clustered around 1kg or so. This is partly due to the fragmentation models themselves which are different, but also to the fact that with our assumptions, only large objects explode. In comparison, collision losses are rather split into two groups, which probably correspond to the respective clouds of massive objects (such as a rocket bodies or satellite of several tons) and others. The altitudes are also different: explosions occur up to GEO altitude because of rocket bodies in GTO orbit, while collisions are concentrated on the two most occupied areas in LEO.

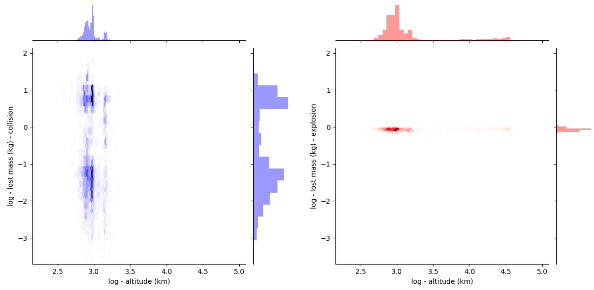

Figure 6. Distribution of mass lost by fragmentation as a function of altitude for an explosion rate of 1 per year. Blue is the distribution for collisions, red is explosions

2.2.2. Three explosions per year

This campaign contains 50 simulations. Without surprise, Fig. 7 and Fig. 8 show that the losses due to explosions are about three times higher than before, since the event rate has been multiplied. Collision losses have slightly increased, as more explosions lead to more collisions. Reentries remain relatively unchanged, compared to the one per year case.

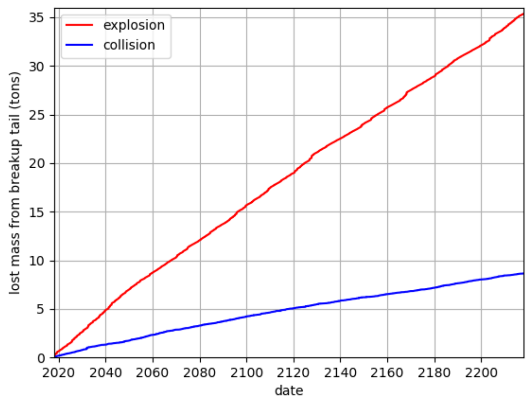

Figure 7. Lost mass for an explosion rate of 3 per year

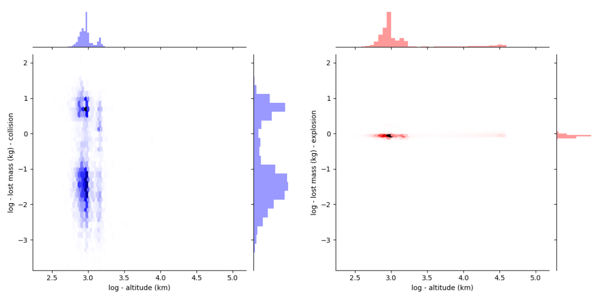

Figure 8. Distribution of mass lost by fragmentation as a function of altitude for an explosion rate of 3 per year

2.2.3. One explosion per month

We still consider here a Monte Carlo of 50 runs without objects smaller than 10cm. Compared to the previous case, the explosion rate has been multiplied by four. We can observe the same factor in the mass losses due to explosions [Fig. 9], until the moment when no more objects are eligible (heavier than 500kg here), which happens after about 150 years.

The losses due to collisions have almost doubled, due to the stimulation of the latter by the explosions. Re-entered mass is also slightly greater [Fig. 10], because of the increased number of fragments and their re-entries. Note also that this re-entered mass is only one order of magnitude higher than the one artificially lost in the explosions.

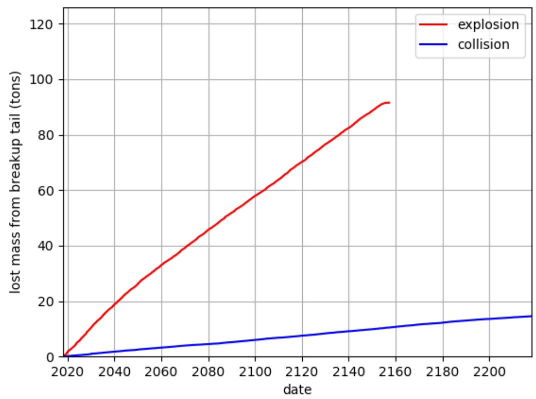

Figure 9. Lost mass for an explosion rate of 1 per month

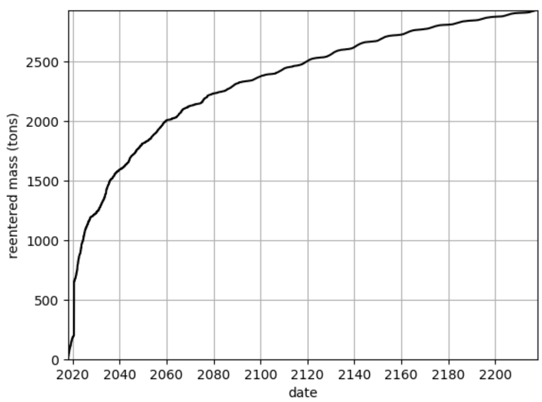

Figure 10. Re-entered mass for an explosion rate of 1 per month

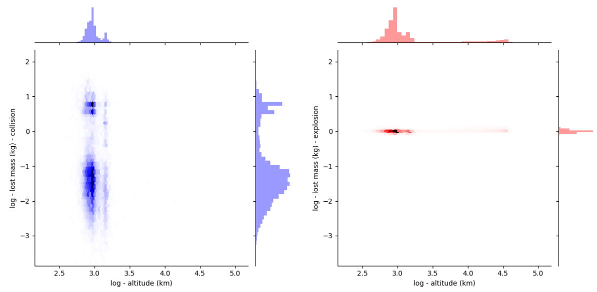

Figure 11. Distribution of mass lost by fragmentation as a function of altitude for an explosion rate of 1 per month

2.3. Propagations with small objects

The previous simulations indicated that cutting-off the small debris removes a non-negligible mass from the orbital population. Including the latter could lead to additional fragmentations and thus to a more pessimistic evolution of the population. In order to take into account this class of objects, it is possible to rely on models (MASTER from ESA and ORDEM from NASA) which, based on impact measurements, provide estimates of the number of smaller objects.
In order to get a reference, a no-explosion case is simulated as well. It is a very optimistic scenario, because in reality there are still launch vehicle stages that are highly likely to fragment in the years to come.

2.3.1. Hypothesis

This section reviews the selection of MEDEE input values in detail.

- The duration of the simulation is one century, since we already know the long term effects without small objects.
- The diameter of detectable objects is still 10cm in 2019 and since 1cm debris can already create critical damage, small objects are defined between 1 and 10cm.
- There is no traffic so there are no launch files or constellations.
- Since we consider that there is no more human intervention, no end of life action is performed. For the same reason, there is no collision avoidance or ADR.
- Payloads follow an average J2 dynamics on the RAAN, and perform collision avoidance maneuvers, during 8 years right after launch (mission duration). This can be interpreted as automated station keeping. It applies to payloads launched during the 8 years timespan before the simulation start date.

As a reminder, there are a total of 4 different scenarios analyzed: without explosion, with an explosion rate of 1 per year, with an explosion rate of 3 per year, with an explosion rate of 1 per month.

Generation of the population used The idea here is to start with a population containing objects smaller than 10cm. It is built from populations provided by ESA.

- A population of objects greater than 10 cm valid on 02/01/2018 (population provided by ESA)
- A population of objects greater than 1cm representative of 2005, with updates to include the Chinese ASAT of 2007 and the Iridium-Cosmos collision of 2009.

At the end of the process, there is a total of 521378 individuals in the extrapolated population, of which 521222 have a maximum perigee below 2000km and 284316 have a maximum apogee below 2000km of altitude.
Counting the actual number of LEO objects, we obtain 327112, including 19929 larger than 10cm. Fig. 12 visually compares the population with objects $> 10cm$ with the one of objects $> 1cm$. It can be seen that at a given height, the background is 10 times denser in one case than in the other. Note that there is however only about 2.5 tons of difference between the two in terms of total mass.

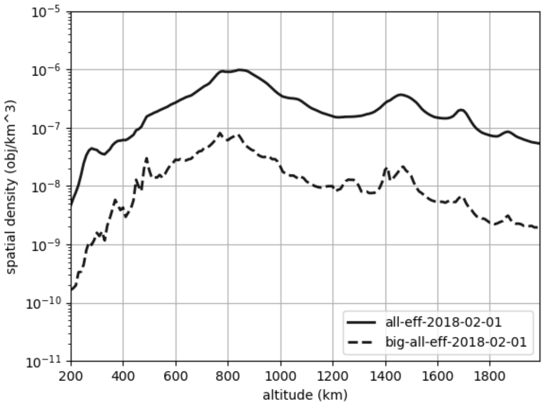

Figure 12. Comparison of effective spatial densities in 2018 for objects larger than 10cm (dashed line) with the reconstruction of a population down to 1cm (solid line)

2.3.2. Results

The final average spatial densities are given in Fig. 13. We can see the global effect of the "sink" (atmospheric drag moves the density to lower altitudes and attenuates the peaks) and of the "source" (the fragments increase by density stripes). We can also see that the shape of the curves is the same whatever the explosion rate: it is essentially the shift on the ordinate axis that differs.

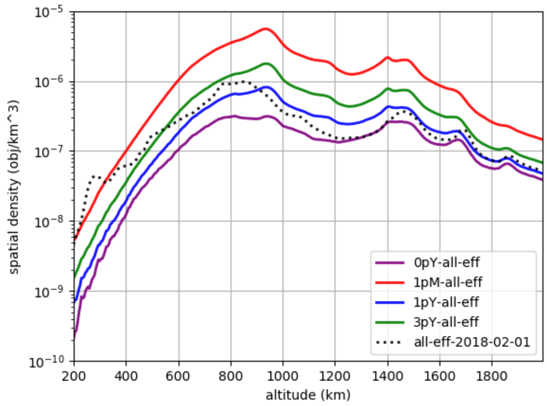

Figure 13. Effective spatial densities without traffic. Purple is the no-explosion case, blue is 1 explosion per year, green is 3 explosions per year, and red is 1 explosion per month. Dotted black is the initial density (1 century earlier)

Fig. 14 shows the evolutions of the average numbers of objects (small only on the one hand and all combined on the other hand), Fig. 16 shows the accumulation and the distribution in altitude of catastrophic collisions. Fig. 15 shows the final total population distributions and Fig. 17 the cumulative number and altitude distribution of non-catastrophic collisions.
The Monte Carlo with one explosion per month is restricted to 25 runs instead of 50 because of the very important increase of number of objects compared to the $> 10cm$ objects simulation.
The population size of objects larger than 10cm is very close to that obtained when small objects are not included. In contrast, collisions, whether catastrophic or not, are much more common. In particular, there is a multiplicative factor between two and five for the former depending on the explosion rates.

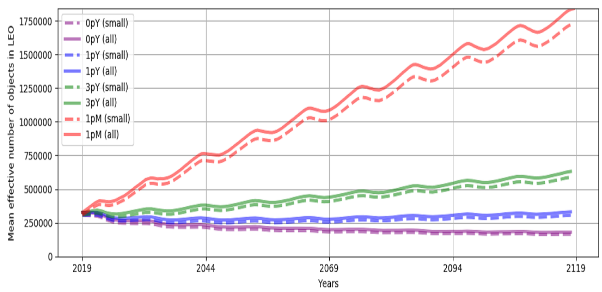

Figure 14. Average number of objects without traffic. Dashed lines are small objects, plain lines are the total population. Purple is the no-explosion case, blue is 1 explosion per year, green is 3 explosions per year, and red is 1 explosion per month

Table 1. Average collision record after 100 years (without - with a small object involved)

Collision pair	New deb.-RB/P.	Old deb.-RB/P.	Deb.-deb.	RB/P.-RB/P.	Other	Total
0 exp./y	3.5 – 32.4	10.7 - 105.9	2.9 – 32.2	4.4 – 0.	1. - 2.5	22.5 - 172.9
1 exp./y	7.8 – 91.2	10.5 – 104.	5.6 – 56.3	4.1 – 0.	1. – 3.4	29. – 254.9
3 exp./y	16.8 – 194.7	10.2 – 98.5	10.6 – 127.1	3.9 – 0.	1.2 – 4.5	42.8 – 424.8
12 exp./y	34.7 – 442.9	9.1 – 84.8	64.2 – 774.4	2.5 – 0.	2.4 – 11.8	112.79 – 1314.

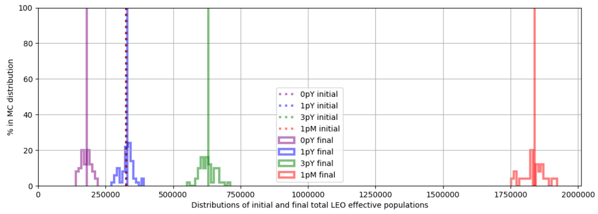

Figure 15. Total population distributions after 100 years (plain lines). Dashed vertical line is the initial distribution and plain vertical lines are distributions means. The color code is the same as in Fig. 14

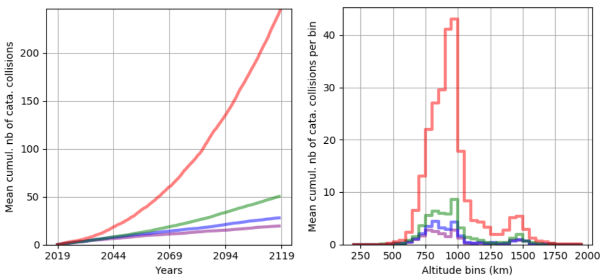

Figure 16. Average number over time (left) and final average distribution by altitude bin (right) of catastrophic collisions. The color code is the same as in Fig. 14

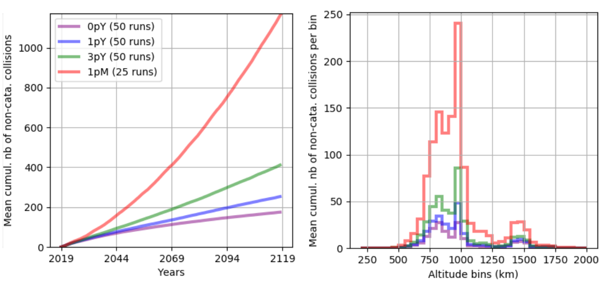

Figure 17. Average number over time (left) and final average distribution by altitude bin (right) of non-catastrophic collisions. The color code is the same as in Fig. 14

If we focus now on Fig. 14 and Fig. 16, we can see that the final distributions do not overlap and thus the different patterns are unambiguously discernible from each other after 100 years. In terms of averages, the complete population follows the same general evolution as that of the objects of 10cm and more, except for the case of one explosion per year.

Indeed, in this configuration, the total number of objects decreases a little at the beginning before increasing to, after 100 years, be approximately at the initial level. Depending on the run, the number may be higher or lower. The only case for which all types of populations always decrease is the one without explosions. From three explosions per year onwards, the average cumulative number of catastrophic collisions is clearly non-linear in time, evidence of explosion-collision chain reactions. These are clearly shown in the figures reported on the Tab. 1 (average detail of the final collision totals). It also results that more than 85% of the collisions take place with an object of less than 10cm.

Nevertheless, fragments are still dominated by explosions, as shown in Fig. 18 which shows as a function of time the Monte Carlo average of the real count of new debris smaller than 10cm, as well as the proportion resulting from collisions. Note that in this figure, there are only 15 runs instead of 25 for the monthly explosion rate because of the prohibitive post-processing times in this configuration.

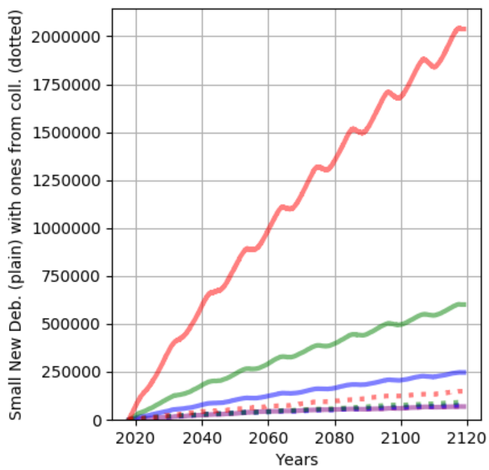

Figure 18. Actual number of new small debris. Dotted lines are debris from collisions , plain lines are all new debris. The color code is the same as in Fig. 14

Conclusion As a first step, an analysis of the mass lost by fragmentation in MEDEE by limiting the size of the objects to 10cm showed that this mass is in fact distributed in a number of objects representing most of the fragments. Moreover, the individual masses of the debris created are not negligible from a kinetic energy point of view which is used by the NASA Standard BU Model to determine the type of collision (i.e. catastrophic / non catastrophic). New simulations without traffic, but including a subpopulation below 10cm from the initial date, were therefore carried out in a second phase. They confirmed trends already observed on MC without small objects:

- Collisions alone are not sufficient to generate a Kessler-like phenomenon from the current background
- From a certain value for the explosion rate, these dominate the "sink & source" and the population increases on average, at least in the medium term.

This tends to suggest that ADR on massive targets with a non-negligible chance of exploding could be effective on the current background, a conclusion consistent with simulations performed in the framework of the IADC, but which did not take into account potential explosions. A question remains for non-zero explosion rates: will the population immediately decrease when all eligible objects have exploded as in the simulations without small objects, or will there be inertia in the system?

3. NO BACKGROUND EVOLUTION

The idea of this scenario is to consider an empty initial population with an evolution of the launch rate as it is expected in the next decades, in particular due to mega-constellations. We will be able to see if, having wiped the slate clean, the current recommendations of the IADC are adequate or not to prevent the situation from degenerating. Similar to the French Space Operation Act (which in addition requires to fully passivate, and therefore avoid explosions), they stipulate that at the end of a mission in LEO, the satellite must re-enter in maximum 25 years.

3.1. Hypothesis

This section reviews the settings defined for MEDEE.

- To remain consistent with the no-traffic scenarios, the start date is in 2018. The simulation duration is reduced to 50 years, because of the high number of "large" objects and the economic uncertainty of maintaining mega-constellations for generations.
- In order to be consistent with the other scenarios, small objects are considered between 1 and 10cm.
- The launches file is provided by ESA. It includes launches from 2005 to 2012. The first cycle encountered is therefore 2013 to 2020. According to spacelaunches.com, there were 672 launches between 2011 and 2018 against 524 between 2005 and 2012, that is 28% of increase. Instead of using a repeated eight-year cycle, We therefore started with this percentage for the first cycle encountered, and defined a linear evolution per cycle up to 50 % increase in 50 years.
- The simulated constellations are representative of the mega-constellations to come. We have in total 9 "orbital shells":
  - 5 between 1100 and 1325km with a total of 3500 objects
  - 1 at 550km for about 1600 satellites
  - 3 between 300 and 400km for a total of about 7500 objects

  Depending on the case, the inclinations vary between 42 and 88 degrees. We consider an electrical orbit-raising for shells above 400km (in one or three months according to the altitude) whereas the others are directly injected in their operational orbit. No Rocket Body or Mission Related Object is supposed to remain in orbit. Each shell launch plan is repeated every ten years: with their five-year lifetime (and sometimes two or three years of progressive deployment plus deployment delays between shells), this means that there is a gap of a few years without a satellite for some constellations, which is not realistic but allows two things:

  - To make sure that we do not launch objects at exactly the same place and thus that we do not artificially create collisions.
  - To have a clear distinction between LEOP + start of operations and end of operations + end of life.

  It should be noted that an optimistic assumption is made on constellations launchers, that are supposed to re-enter very quickly and are therefore never included in the population.
- It is considered that, as suggested in [12] for example, 90% of the missions manage to do PMD (here to perform a re-entry, not a re-orbit above 2000km). The effects of the maneuvers are immediate. Note that constellations below 600km do not perform maneuvers to respect the 25-year recommendation.
- Collision avoidance (possible only with objects greater than 10cm and if there was no previous non-catastrophic collision) is assumed to be successful at 100 % during the mission (5 years for constellations and 8 years for other satellites).
- Since we start without background, no ADR is planned.

- In international guidelines, it is now precised that the probability of accidental break-up of a spacecraft or launch vehicle orbital stage in Earth orbit shall be less than 10-3 until its end of life [12]. This threshold is taken into account in the simulation, with a minimum mass for objects in the constellation to be allowed to explode fixed at 150kg.
- As there is no background, no historical fragmentation is taken into account.

A variant of this basic scenario has also been defined: the idea is to simulate the case where the different orbital planes of the same shell are separated in altitude. [13] suggests that a 1km separation on a constellation beyond 1000 km of altitude allows to reduce significantly the internal collisions and that this gain does not really progress from 2-3km. Such a separation of 1km has therefore been studied here (only for constellations above 400 km). Note that to maintain the angular separation between the different planes of the same shell, it is necessary to play on the inclination so that the drift due to J2 is the same according to the formula :

$$\dot{\Omega} = -\frac{3}{2} J_2 \left(\frac{R}{a(1-e^2)} \right)^2 \sqrt{\frac{\mu}{a^3}} \cos i \qquad (1)$$

In practice, this produces sub-degree differences in inclination. Finally, a third variant of the scenario has been tested, without any mega-constellation, to serve as a kind of reference case. Note that the explosions rate has been preserved, which means that, since tens of thousands of "small satellites" are missing, the explosions involve objects that are generally larger and therefore potentially create more debris. The cases with and without mega-constellations are therefore not completely equivalent as far as explosions are concerned. In summary, there are 3 scenarios in total:

- One without mega-constellations
- One with mega-constellations without altitude separation between the orbital planes of the different shells
- One with the mega-constellations and 1km of separation

3.2. Results

The mean over Monte Carlo of the populations below 10cm and total as a function of time is given in Fig. 19, which allows us to see that the former constitutes the vast majority of the latter at all times. It is also important to note that the dispersion in relative values is particularly large (see final distributions in Fig. 20). To better capture it, 100 simulations rather than 50 were performed. Depending on the occurrences, there can be a factor of two on the number of objects (when there are large constellations), or even four (when there are none). Moreover, the worst case without constellations is above the best case with.

The two simulations with large constellations present a very similar trend: unless explicitly stated, further comments concerning large constellations will therefore apply to scenarios with and without plan separation.

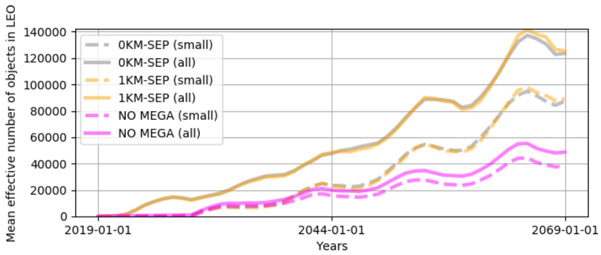

Figure 19. Average size of effective LEO populations as a function of time. Pink is scenario without constellations, grey is with constellations and no altitude separation, yellow is with constellations and 1km altitude separation

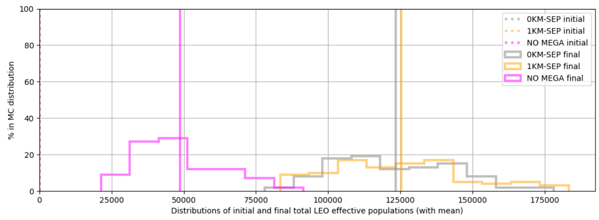

Figure 20. Distribution of the total effective LEO population size at the end of the simulation. Inital distribution (dotted) is not visible because population a relatively too small, and vertical bars represent the means

A detail in three categories is given on the Fig. 21 : intact, large debris and small debris (all new by construction of the scenario). It helps to clearly discriminate the period of solar activity from the period of constellation deployment.

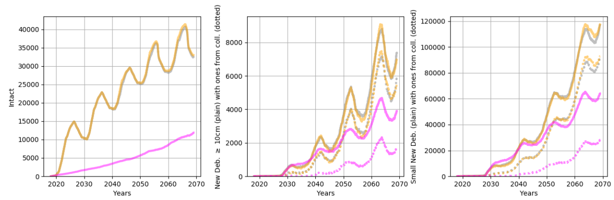

Figure 21. Object counts by category. Dotted lines are new debris frome collisions, plain lines are all new debris

For the case without constellations, during the first ten years almost all objects are active: they do not explode and avoid collisions. Then explosions start to occur and the number of debris rises. Collisions appear a little later and after 50 years, they represent a little less than 50% of the debris in orbit. The number of fragments in orbit increases in time-average following a pseudo-periodicity due to the solar activity. Indeed, the density at low altitude oscillates, as can be seen on Fig. 22.

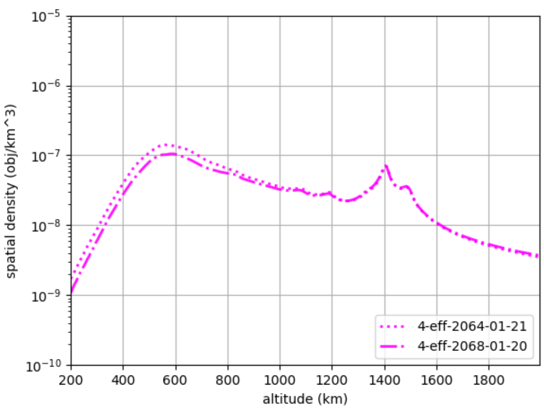

Figure 22. Averages in 2064 (dotted) and 2068 (dashed) of the LEO spatial densities of the fragments without constellations

Regarding the mega-constellations, at each (re-) deployment of the shells there is a peak in the number of intact objects, since more than 10000 active satellites are launched in a few years. During the first ten years, which corresponds roughly to the deployment and mission of the first generation, the debris situation is pretty stable and similar to the one without constellation because the objects are active. The first fragments are due to explosions, but they are quickly dominated by the consequences of collisions. The average accumulation of the latter (Fig. 23) seems to indicate a slight oscillation (even more visible for non-catastrophic cases, and also in the no-constellation configuration), probably due to solar activity. The long-term acceleration of the collisions occurrences causes a significant difference in amplitude in the altitude distribution after 25 and 50 years (Fig. 24). In opposition to the scenario without traffic, many collisions do not involve small objects: 40% on average with constellations (25% without). The detail of the pairs involved is given in Tab. 2.

Two main observations arise from this:

- With altitude separation, objects in constellations collide only slightly less with each other but also a bit more with the rest, which explains why there is no a significative difference between scenarios with and without altitude separation.
- The debris generated because of the constellations then causes collisions with the other intact objects.

By analyzing Monte Carlo runs individually, it can be noted that an important part of the objects involved are satellites having performed a PMD, many of them being derelicts from the constellations. Besides, there is still

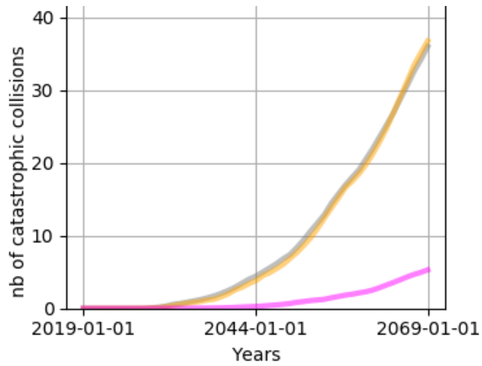

Figure 23. Cumulative collision (catastrophic collisions). The color code is the same as in Fig. 19

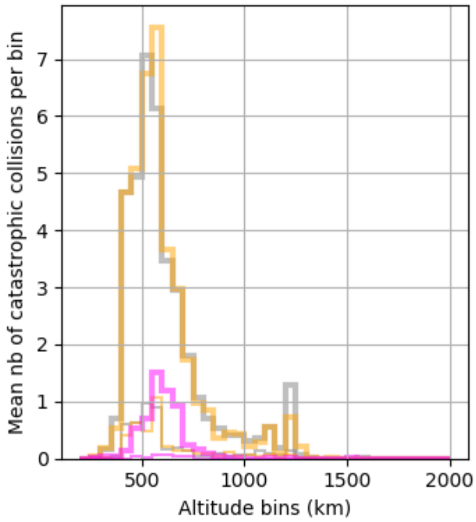

Figure 24. Altitude distribution (catastrophic collisions). The color code is the same as in Fig. 19

a considerable part of constellation satellites that did not perform a PMD (those operating at an altitude already low enough to re-enter in 25 years), and that are also involved in a catastrophic collision. We can therefore think that a 90% successful PMD for high LEO constellations, and no deorbiting maneuver for low LEO constellations is not sufficient to limit catastrophic collisions.

Now we can take a look at the spatial densities of effective LEO objects. This is particularly interesting because we start with a blank environment. Fig. 25 shows effective densities of fragments in the middle and at the end of the simulation while Fig. 26 does the same for all other objects.

With the large-constellations, there are two local peaks of debris density: one between 400 and 800km (which is also the global maximum) and one between 1000 and 1200. The former is also an extremum for the Monte Carlo without constellation. The only altitude where fragments density without constellation exceeds the one with them is between 1400 and 1500km, which is certainly due to explosions. The lowest fragment densities are located at the two altitudes boundaries: especially at

Table 2. *Average collision record after 50 years (without - with a small object involved))*

Collision Pair	Cst-cst	Cst-deb	Cst-RB/PL	Deb-RB/PL	Deb-deb	RB/PL-RB/PL	Others	Total
1km	13.2 – 0.	2.0 – 18.2	14.5 – 0.	2.2 – 36.	0.1 – 0.5	4.1 – 0.	1.9 – 1.4	38. – 56.
0km	13.8 – 0.	1.4 – 18.	13.2 – 0.	2.1 – 34.	0.1 – 0.3	4.1 – 0.	1.9 – 1.4	36.6 – 53.8
Without const.	0. – 0.	0. – 0.	0. – 0.	0.9 – 16.9	0. – 0.1	4.2 – 0.	0.8 – 0.6	5.9 – 17.6

low altitudes because of atmospheric drag but also at high altitudes because of the low launches density there. When there are no constellations, fragments density exceeds those of intact objects everywhere. This is not always the case with large-constellations, especially at shells below 400 km and those above 1000.

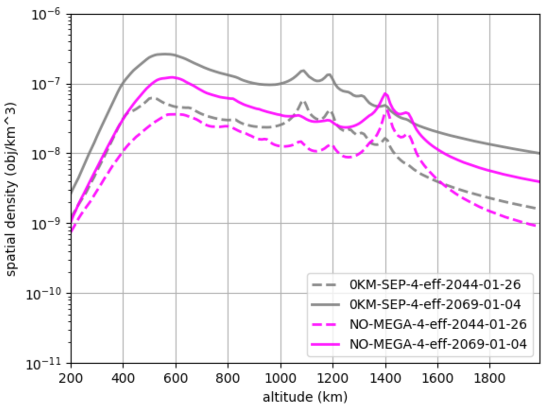

Figure 25. Spatial densities of fragments in 2044 (dashed) and 2069 (plain). Purple is scenario without constellations, grey is the one with constellations and no plan separation

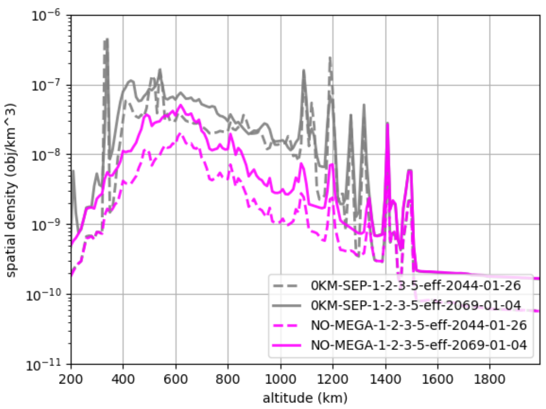

Figure 26. Spatial densities excluding fragments in 2044 (dashed) and 2069 (plain). The color code is the same as in Fig. 25

3.3. Conclusion

Simulations based on a non-existent background and modeling objects down to 1cm have been performed. By nature, the population can only increase from the initial date. Assumptions include collision avoidance of 100% with objects larger than 10 cm and compliance with PMD recommendations in 25 years of 90%. No ADR is performed. Outside of constellations, launches are gradually increasing (up to 50% in 50 years) from the 2005-2013 baseline.

These Monte Carlo campaigns show that:

- Without large-constellations, within the "sink & source" among the debris, explosions largely outnumber re-entries and collisions in the mid-term, even if the latter are accelerating. The fragments thus created quickly increase to tens of thousands, forming the major part of the total population.
- With large-constellations, explosions dominate at the very beginning, but very quickly fragments created by collisions dominates the environment. The average number of debris is almost 100000 (all origins) at the end, more than twice as much as without constellations.
- A 1 km altitude separation of shells orbital planes does not seems to have significant beneficial effect when compared to no-altitude separation.

The deployment and maintenance of several generations of large-constellations above 500 km strongly exacerbates the problem in LEO. Since satellites below 800km in particular do not need to maneuver in order to re-enter in 25 years, increasing the compliance rate does not seem promising.
On the contrary, shortening the maximum deorbiting time, for example by dividing it by two, would reduce in the same proportion the time spent by many derelict objects to slowly lose altitude and could thus have a beneficial impact on the orbital situation after several generations. This would also force satellites on lower orbits to maneuver at the end of their mission.

Some additional simulation perspectives to go further:

- Analyse further how the fragmentation rate in the scenario without constellation impact the long term simulation when compared to the large constellation simulations.
- Analyse further the influence of constellations below 600Km in the collisional process.

4. CONCLUSION OF THIS STUDY

In this paper we have pointed out the importance of taking into account small debris which are not yet observable by current means, i.e. debris between 1cm and 10cm. These contribute to more than 85% of the collisions modeled in our study. More generally, the use of fragmentation model has to be done with care to avoid artificially eliminating the mass of small debris because of numerical simulation parameters constraint.
Under the conditions of our first batch of simulations (no more space exploitation), collisions with objects larger than 1cm are not enough on their own to lead to an exponential production of debris, the primary driver being the number of explosions and the explosion-collision chain reaction pattern.
The importance of suppressing debris production by explosions is also highlighted by the hypothetical simulation, carried out in this study, involving the traffic of New Space in an imaginary environment which has not suffered the legacy of the space pioneers difficulties, that is to say a virgin environment. These simulations show that the actual figures related to the international guidelines are no longer sufficient to stabilize debris growth. And even starting the actual New Space launch traffic with no debris and a total adherence to the actual guidelines, the situation would be worse than today in about ten years.
The severity of this situation can fortunately be reduced by taking into account the advantage of the atmospheric drag below 800km that gave the opportunity to keep our influence on the environment reversible, which is not the case on the orbit above 900km where the human imprint is for eternity.

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