RESULTS OF REFERENCE LONG-TERM SIMULATIONS FOCUSSING ON PASSIVE MEANS TO REDUCE THE IMPACT OF SPACE DEBRIS

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ABSTRACT

Long-term simulations of the space debris environment show an increase in the number of debris objects in low Earth orbit region. Over the next one hundred years, fragments from collisions and/or explosions are expected to become the dominant part of the debris population.

Developing remediation measures for space debris is part of on-going research. Long-term simulations act as evaluation framework for understanding the effects on the space debris environment. The paper presents first the results of a comparison of two simulation codes on the basis of simple validation scenarios, which show a high level of conformance.

In a second section, the paper presents a set of scenarios for the evolution of the debris population from LEO to GEO with the aim to single out and highlight the driving factors of the future environment evolution. Amongst others, the scenarios include an approach where the collision algorithm distinguishes between the main part of the spacecraft and the appendage, and generates less debris in case the appendage is hit. Despite the positive / reducing effect of mitigation measures, the results of all scenarios show an increase of number of objects in the LEO region.

Furthermore, we present an evaluation of the last state of an object about to re-enter Earth's atmosphere. The according orbital elements are recorded during the simulations and the information is then used for characterizing re-entry conditions. It serves as input for the design for demise approach, which aims to define predetermined breaking points in the structure of spacecraft and thus, limits the risk of space debris surviving re-entry.

Keywords: Long-term simulation; Passive mitigation; LUCA; SDM; ReDSHIFT.

1. INTRODUCTION

The catalog of trackable space debris is continuously increasing. Fueled by severe collision events, such as the Iridium-Cosmos collision in 2009, the catalog contains more than 18400 today; omitting a far greater number of smaller, currently non-trackable and therefore unavoidable objects. Recent developments in space business also put space debris and the potential consequences more and more in the focus of attention.

1. In recent years, the so-called class of nano satellites (weight $<$10 kg) became increasingly popular. This caused a jump in the annual total launch rate from ~130 up to ~200. This can be clearly identified, because the number of launches for mini spacecraft and above ($>$100 kg) remains more or less constant and for micro satellites (10-100 kg), there is only a slight increase [1]. This new trend is quite important for the space debris population. As of today, these nano and micro satellites have very limited propulsion capabilities. Consequently, their ability to perform any post mission disposal maneuvers is also very limited and the majority of the nano/micro satellites remain in orbit as debris. [2] analyses the orbits of the recently launched CubeSats and states that 35% of the satellite do not naturally decay within 25 years.
2. With the privatization of the space market in the US, several new players appeared in the space business. The announcements of some of these companies to establish large communication networks in space (Internet-for-everyone), made the community sit up and take notice. Although satellite constellations are not a novelty, the proposed number of constellation satellites in these networks were high. The numbers range from a couple of hundred to several thousand

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satellites per constellation. This would mean a considerable impact for the environment and formed the term mega-constellations, keeping in mind that up to now a total of close to 8000 satellite have been sent to orbit since the beginning of the space age. [3][4]

The effects of increasing numbers of small satellites and proposed constellations like OneWeb are currently studied under an ESA contract [5], [6], [7].

The work presented in this paper is part of an ongoing research initiative called ReDSHIFT funded by the EU. It started at the beginning of 2016. The acronym stands for "Revolutionary Design of Spacecraft through Holistic Integration of Future Technologies". It aims to link challenges of sustainable spacecraft operation, mitigation and demise with the disruptive opportunities offered by additive manufacturing for innovative spacecraft design and exploiting synergies with electric propulsion, atmospheric and solar radiation pressure drag, and astrodynamical highways.

Many of the proposed and envisaged mitigation practices still face technological challenges until they are adopted in real missions. That is why long-term simulations are used to asses their effect on the space debris environment. The common approach is to run different scenarios, each modeling different mitigation practices. Results are retrieved by comparison against a reference scenario, or amongst each other. Within the frame of the project, long-term simulations of the space debris environment used at the beginning of the project to demonstrate the current state-of-the-art and the prospect of the currently adopted mitigation guidelines on the space debris population. They are later used again to judge on the positive effect of a proposed strategy or spacecraft technology and thus drive the reasoning of future mitigation guidelines.

For a proper assessment of the evolution, it is necessary to respect all relevant physical effects of the space environment, as well as the behavior of spacecraft itself including operational practices. In terms of the population, it is basically important to include every effect that adds to or removes objects from the population.

The influencing factors to be considered in the long-term evolution are:

- orbit dynamics[1]
- air-drag of the residual atmosphere
- on-orbit explosions
- collisions
- surface degradation
- slag from solid rocket motor firings
- launch rates of future missions
- operational practices, e.g. collision avoidance on active satellites
- mitigation practices, e.g. doing an end-of-life maneuver or removing a certain number of large objects from the population with active debris removal missions.

When simulating all these effects simultaneously, it is possible to assess a baseline of the expected evolution of the space debris environment. Typical time-frames for these predictions are several decades up to 100-200 years. Although these simulations return exact numbers as results, they must not be considered as quantitative truth. There is a great level of uncertainty in the models and the analysis are always based on assumptions which might turn out to be inaccurate. So the long-term evolutions do not attempt to state the exact orbital debris situation in the future. The real value comes from running comparison scenarios which allow for qualitative deductions.

2. VALIDATION RESULTS

Within the first year of the ReDSHIFT project, two long-term evolution models for the simulation of the debris environment are being used in order to test the effectiveness of the current and of the novel (i.e., devised within the project later) mitigation measures. In a first step, it is necessary to validate the results of the tools against each other. Therefore, three validation scenarios were defined and simulated by the two long-term simulation codes. Namely they are, the Space Debris Mitigation long-term analysis program (SDM) developed at IFAC, Italy [8] and the Long-term Utility for Collision Analysis (LUCA) developed at TU Braunschweig, Germany [9]. The idea of these scenarios is to ensure that both simulation codes produce comparable results. The results are expected to show similar trends and/or the same order of magnitude of events in the simulation. Special care was taken to define simple cases in the beginning to limit the number of influencing factors. This way the potential sources of error are reduced. This makes it easier to isolate the root cause of a deviation and take corrective actions. The three validation scenarios were defined as follows:

- **No release scenario:** In this scenario, the initial LEO population as of January 2013 is used and propagated over a time frame of 100 years. The only source of new objects are those of collisions calculated internally by each of the tools. Other effects, such as collision avoidance, internal explosions, and post mission disposal are turned off completely. Both tools used their own approach for the solar activity forecast.

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[1] Considering only perturbations affecting the long-term evolution. These are: solar radiation, third-body perturbations from Sun and Moon, Geopotential of the Earth. Short periodic effects such as tides are omitted, also short-periodic terms of the Geopotential and the third-body perturbations are omitted.

- **Reference scenario:** This scenario is identical to the no release scenario, but additionally a repeating launch traffic, based on launches as between 2005 and 2012, is considered and subsequently added to the population.
- **Break-up model comparison:** For this comparison, two different fragmentation events are modeled. As outputs, the characteristics of the created fragmentation clouds are of interest. For brevity in context of this paper, the results of the break-up model comparison will not be shown. They will be part of course in the report on ReDSHIFT.

Figure 1 is exemplary for various different plots which were produced to compare the results of both models. It shows the mean effective number of objects in LEO over the simulation time of 100 years, averaged over 50 Monte-Carlo runs. The plot shows the data of the second validation scenario which includes the standard IADC launch traffic (see above). The scenario was executed with three programs, LUCA version 1 and 2 and SDM 4.2.[2]

It can be seen how all the quantities considered follow very similar patterns and all lie well within the 1σ boundaries of the MC averaging. This makes us confident that the two models are consistent and that the results of the two codes in the next step, the reference scenarios, can be safely used as baseline for subsequent analysis in the project. We emphasize that we are interested in spotting "differences" either between a given reference scenario (detailed in next section Sec. 3) and a number of "mitigation" scenarios or between the current scenarios with "classical" mitigation measures and future scenarios with ReDSHIFT advanced mitigation measures. This way of proceeding further diminish the importance of small inconsistencies between the two models, since those differences will be analyzed mainly within each single model (i.e., SDM vs. SDM and LUCA vs. LUCA).

3. REFERENCE SIMULATION RESULTS

The main purpose of the reference simulations is to show the effectiveness of the currently adopted mitigation measures on the long term evolution of the debris population. For this reason it was decided to limit the number of scenarios by varying input parameters for mitigation measures one-by-one. In this way we ensure a clear separation of the effects of the different mitigation measures. Moreover, the effect of a few significant factors leading to possible significant uncertainties in the future evolution were analyzed. In particular, we considered two scenarios were a significantly different launch traffic is foreseen with the launch of two different mega constellations. Subsequently, a scenario were we assume that all satellites have (as it is usually the case) an appendix attached to them (such as antennas or solar panels) is considered. In the source code this becomes important when we consider the possible statistical effects of collisions. Whenever a collision happens on an appendix, only this part of the satellites is destroyed hence creating a significantly smaller debris cloud, with respect to a similar event happening on the whole body of the satellite. The scope of the reference simulations was widened in comparison to the validation cases of the previous section. The simulation time frame is now 200 years, and the population covers the population from LEO to GEO. In detail, the following scenarios were conducted:

- **01: Reference scenario:** This is the baseline reference scenario. As sources, launched objects, collisions and explosion events (2-3 per year until 2028) are considered. All active objects perform collision avoidance with 80 % success and an end-of-life maneuver compliant with the IADC mitigation guidelines with 80 % success rate. In GEO, only objects >1 m can be avoided. The post mission disposal success rate is set to 60 % for objects which do not naturally comply with the 25-year recommendation of the guidelines. Objects in LEO perform an end-of-life manoeuvre to an eccentric 25-year orbit, whereas in GEO, objects are place into a graveyard orbit.
- **02: Collision Avoidance case:** In the scenario, the collision avoidance success rate is increased to 100 %. GEO objects can also avoid objects >10 cm.
- **03: MitigationSuccessRate: Mitigation compliance case:** In this scenario, the mitigation success rate is increased to 90 %.
- **04: Mitigation10yLifetime: Mitigation compliance case:** In this scenario, the mitigation success rate is increased to 90 %, LEO objects de-orbit to a disposal orbit with 10-years lifetime.
- **05: Active debris removal case:** In this scenario, a certain number of objects is actively removed per year. The variation was set to 2 or 5 objects to be removed per year.
- **06: Mega-Constellation scenario:** In this scenario, a one mega-constellation is included. The basic parameters of the constellation are: 1080 satellites in total in 20 orbital planes; 50 years of operational lifetime; semi-major axis of 7478 km; eccentricity of 0.00001 and inclination of 85.0 degrees. The built-up phase is 3 years, satellites which reach their designated end-of-life time are continuously replenished over the 50 years of total operational lifetime. The satellites have a mass of 120 kg and a cross-sectional area of 1 square meter.
- **07: Effect of appendices:** In this scenario, for propagation and collision rate determination, two different cross sections are used. The collision rate algorithm distinguishes between the main body of a

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[2] LUCA was undergoing a major code refurbishment and upgrade in 2016; the ReDSHIFT scenarios were used also to validate the previous version against the latest; therefore we present two results from LUCA in the plot.

satellite and the appendix (e.g. solar panel / antennas). It then, triggers the break-up model with different input parameters according to the predicted type of event. The possibilities here are: main-body against main-body, main-body against appendix)

As a result, Fig. 2 presents a scenario overview with which we can assess the effects of the different mitigation measures and of introduction of a mega-constellation. All curves show the typically repetitive swinging pattern which is the result of the the solar activity and its repetitive intensity cycle, which causes the atmosphere to expand or deflate. The solar activity was modeled by randomly selecting a past cycle and using that as prediction for the future.

The increase of the collision avoidance from 80 to 100 % (red curve) is the one which is closest to the green curve of the baseline reference scenario. It has the lowest relative effect. The next in line are two variations really close to each other, shortened "allowed" residual lifetime from 25 years to just 10 years (light blue curve), and the difference in the modeling approach for appendages. The strongest effect can be seen for the ADR scenario (dark blue curve). The trend for the number of objects in the LEO region actually leaves the 1σ standard deviation of the reference scenario in the second century of the projection time of 200 years. However, this ADR scenario considers five successful removal missions per year throughout the whole 200 years, which is already a very ambitious goal. Yet, it is the only case that ends the simulation at the same levels for number of objects in LEO as in the beginning in 2013. The results of the mega-constellation scenario is depicted in orange color. After the built-up phase (3 years) and the first replenishment launches, the steep increase from the start levels off for the rest of the operational time. At the end of the operational lifetime, the remaining satellites of the constellation are gradually removed, and the numbers are decreasing slightly. However, from the year 2210 onwards the orange curve follows the mean trend of the other scenarios, but with an offset of approximately 2000 objects more. In accordance to other recent studies [Ref needed], the curves show a clear trend. Even with today's launch rates, the simulation results tell us that the space debris population will grow. Recently announced constellations with several hundred or even more than thousand new satellites in LEO will acuminate the consequences of space debris.

Examining the results further, e.g. looking at the sources of origin of the newly generated debris and the number of catastrophic and non-catastrophic collisions, it is obvious that collisions are becoming a more and more dominant driver for the space debris environment. As a consequence, effective mitigation measures must confine the number of collisions. The simulation results can also be analyzed with a focus on that, e.g. Fig. 3 visualizes the number of collisions plotted as a histogram over orbit alti-

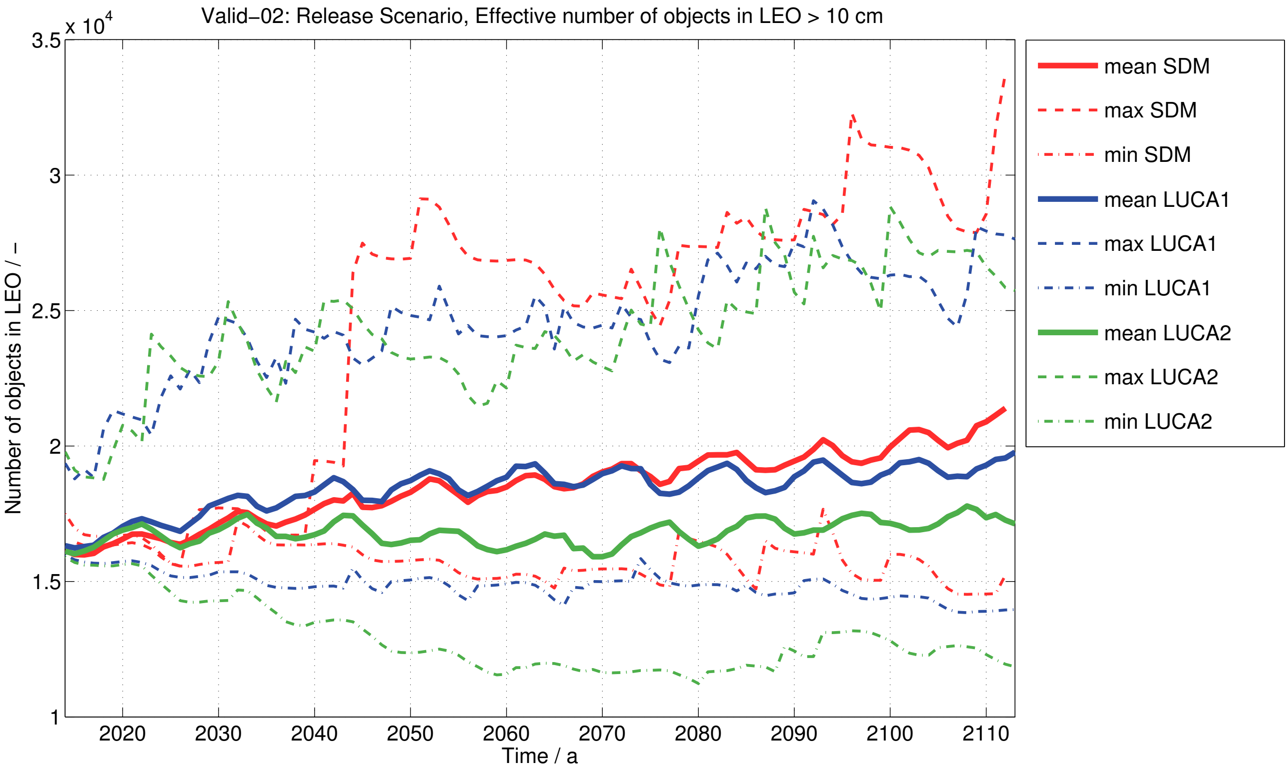

Figure 1. Effective number of objects in LEO orbit. The plot compares the results of three simulations, SDM in red, LUCA2 in green, and LUCA1 in blue. The mean values are plotted as solid line, minimum values of all MC runs as dash-dotted line, and maximum values as dashed line.

tude. This indicates the location of where collisions most frequently occur. As expected, there is a high peak at the densely populated altitude of 800 to 1000 km. Another smaller peak appears at an altitude of 1400 to 1500 km. For clarity, the plot shows only the data from three scenarios. The baseline reference is shown in green. The mitigation compliance scenario mainly reduces number of collisions at lower altitudes from 400 to 700 km. The ADR scenario (5 missions per year) cuts down the high peak at the sun-synchronous orbit from 10 to 5 which clearly marks the advantage of consequent ADR on the objects with largest mass and highest collision risk.

A warning should be raised looking at Fig. 4, showing the spatial density of objects in LEO for the Reference and the improved mitigation scenarios for the epoch 2213 (end of the simulated time span) as a function of altitude, compared with the initial epoch. It can be noted a general improvement of the situation, especially in the crowded critical regions around 900 and 1400 km, due to the increased number of satellites de-orbited at the end-of-life. Nonetheless, looking carefully at the higher end of the plots, around 2000 km of altitude, an opposite behavior, with a growth of the density in the mitigation scenario, can be noticed. This is due to the following reason: in the software, whenever an object has to be disposed at the end-of-life, the best solution, in terms of the Δv required for de-orbiting is selected, choosing between the de-orbiting to a lower elliptical orbit with a defined residual lifetime and a re-orbiting in a circular "graveyard" orbit above the LEO protected zone (i.e., above 2000 km of altitude). In Fig. 4 we are starting to see not only the simple effect of the accumulation of the disposed satellites but also the growth of fragments generated by the mutual collisions between the uncontrolled disposed spacecraft (unable to perform avoidance maneuvers).

It is worth stressing here that, in SDM, the objects disposed in the super-LEO graveyard are properly dispersed on a range of altitudes to avoid concentration of objects at exactly the same altitude. This result reinforces the conclusion that novel disposal means should be devised also to lower the energetic requests of de-orbiting maneuvers, thus minimizing the recourse to the LEO graveyard zones. The mapping of the phase space performed in work package 2, with the search for the "de-orbiting highways" is devoted exactly to this purpose.

Therefore, in conclusion, for the LEO region we can state that:

- in accordance with a number of previous studies (e.g., within the IADC Working Group 2 joint simulation efforts), the LEO environment appears "unstable", with the population growing notwithstanding the currently adopted mitigation measures.
- More aggressive mitigation measures can slow down the growth pace, but not stop or revert it.
- The use of super-LEO storage zone should be "handled with care", to avoid accumulation of uncontrolled objects possible leading to unavoidable collisions on the long term.
- The simulation of appendages and the related collision dynamics should be taken properly into account

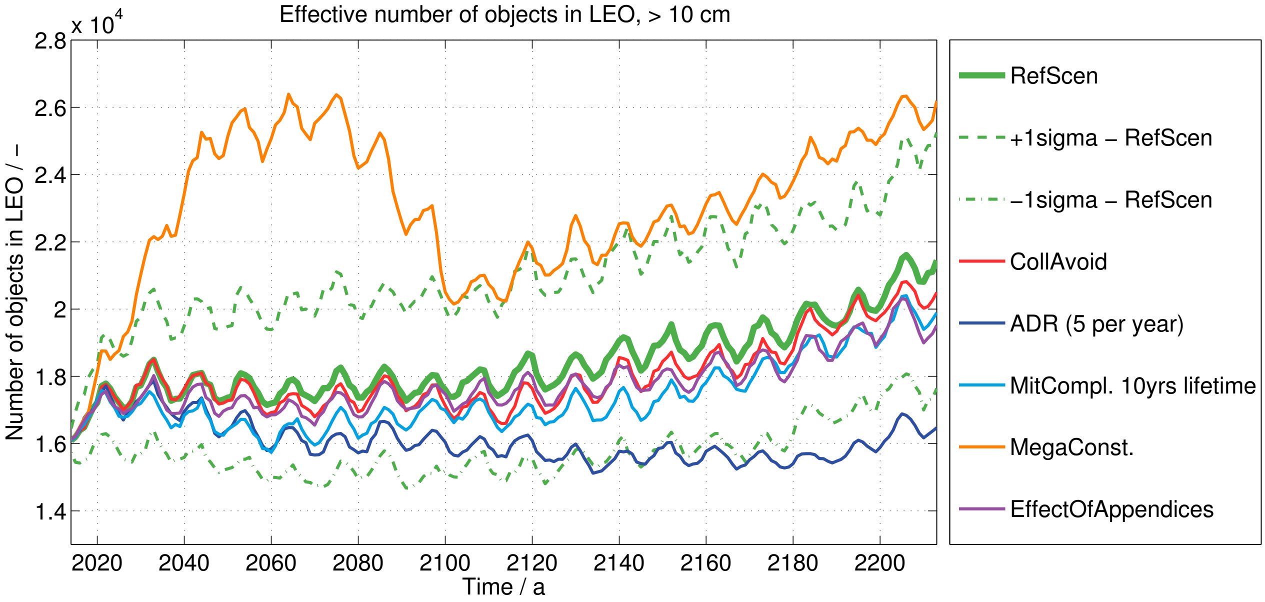

Figure 2. Number of objects in LEO for different scenarios. The plot compares the results of 5 variations of parameters against the baseline scenario (solid green, with $\pm 1\sigma$ standard deviation in dash-dotted and dashed green line). The increased collision avoidance (100 % success rate) is shown in red; mitigation compliance to 10 years lifetime orbit is shown in light blue; The effect of appendices is shown in purple, ADR (5 missions per year) in dark blue, and the mega-constellation in orange.

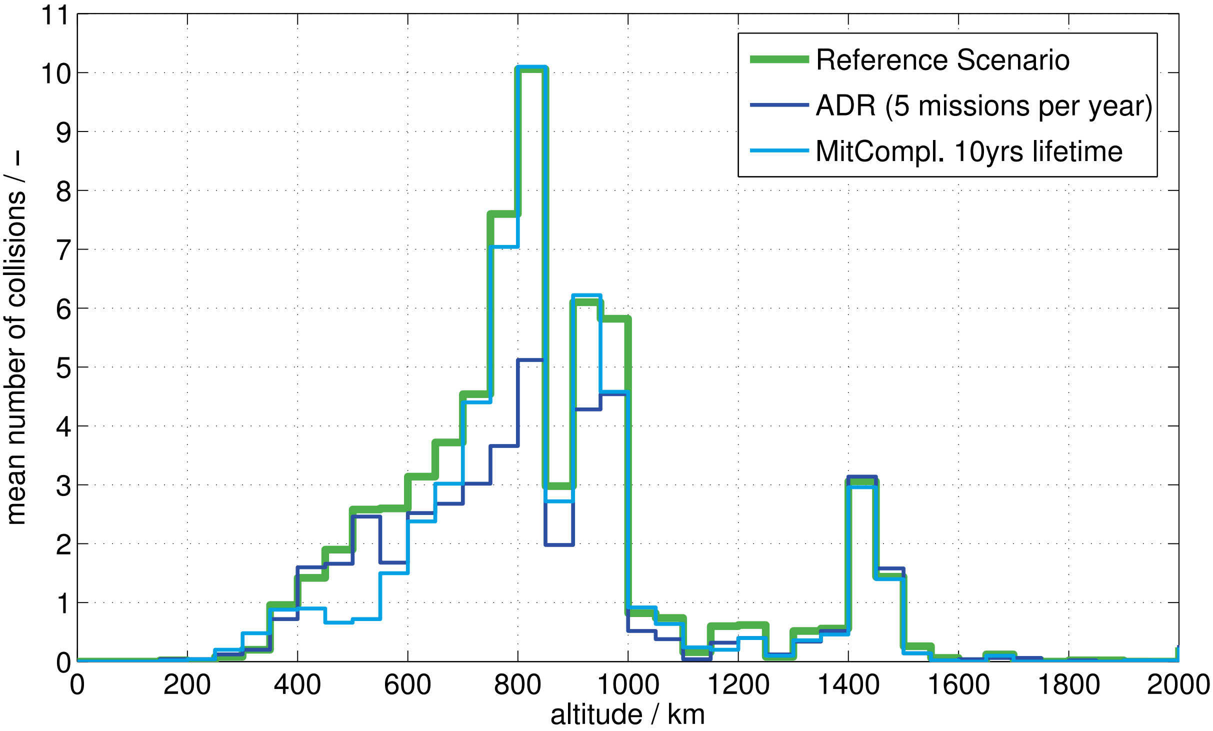

Figure 3. Number of catastrophic and non-catastrophic collisions over altitude. The plot compares only the tightened mitigation compliance (to 10-year lifetime) scenario in light blue and the ADR (5 missions per year) scenario against the baseline in green.

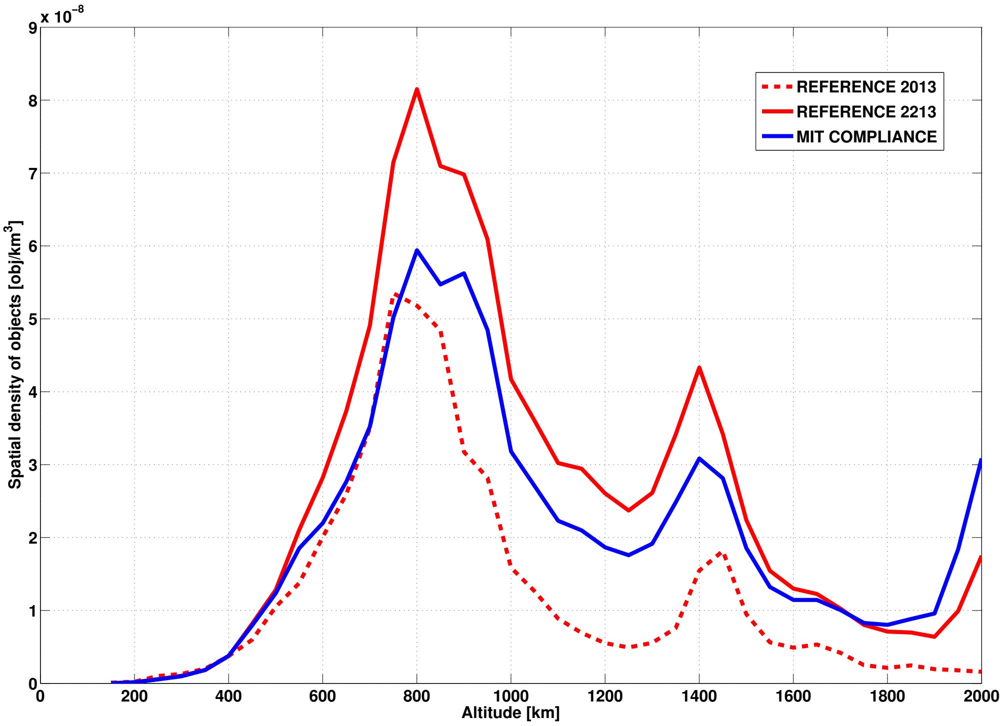

Figure 4. Spatial density of objects in LEO in the Reference (red: epoch 2013 dashed line, 2213 solid line) and the improved mitigation cases (blue, epoch 2213)

to avoid over-estimation of the collisional activity in LEO.

- The planned mega constellations might represent a big issue in the future of the LEO environment, hence a careful look should be kept on them and on the way their operations are handled.

The ReDSHIFT project is aiming at a number of possible mitigation solutions to the above points, e.g., by proposing the use of the “de-orbiting highways” as mentioned above or by evaluating the performances of area augmentation devices in helping the de-orbiting of spacecraft in LEO.

4. REENTRY CONDITIONS

This section presents results which were derived from the reference simulations and act as input for an ambition of the ReDSHIFT project: Spacecraft design for end-of-life demise. In order to optimize the design for demisability on re-entry, it is necessary to learn more about how the objects come back and start their descent into Earth’s atmosphere. Important information in this regards are the orbital elements during their last revolution, the point in time when we know the object about to re-enter. In a first attempt we recorded the orbital elements just before the long-term simulations mark them as re-entered. A threshold of 100 km or below in altitude was chosen as criteria to determine whether an object is about to re-enter. The reason herefore is that typically the main structural breakup event of a satellite during reentry takes place at altitudes between 84-72 km [10]. A value of 78 km is used in several reentry models which is derived from analysis of reentering spacecraft [11]. Therefore, both SDM and LUCA were adapted to output this information for each simulation run.

Regarding LUCA, the implementation was made inside the orbit propagator FLORA [12]. Here, there was already a sanity check on the orbital elements. It assures that the input variables for the implemented equations are within the allowed limits. The check prevents that results become invalid and sets the orbital elements of the re-entering object to the last sensible state. The threshold was set to the above mentioned 100 km altitude. If the propagator manages to calculate a sensible orbit below the 100 km, that information is used as output. If the state below 100 km is invalid, the previous step, just above the 100 km is returned. Please note that FLORA uses geodetic altitude equations. Looking at the first simulation results, we found that in a rather high number of cases, the altitude reached values from 120-200 km; in rare cases even above the 200 km mark. We considered this spread as too big. The intention was to know the orbital conditions very close to the threshold of 100 km. We decided to re-propagate the recorded re-entry conditions in order to bring them closer down to the 100 km. We tuned the parameters of the propagator, most importantly the time step size was reduced. Special care was taken to re-propagate each object with the correct environment information as it was at that exact time step during the reference simulations. For instance, the solar activity had been randomly predicted in all the reference simulations based on historical Sun cycles. In order to achieve consistent results, the re-propagation was initialized at the proper time step and with the correct physical environment settings. Especially important in this case is the correct solar activity from the correct Monte-Carlo run and at the correct time, since the atmospheric drag is the dominant perturbance at these altitudes and it is directly related to Sun’s intensity.

The data on the re-entry conditions was collected in all the simulations described in Section 3. This data contains all objects returning including also smaller fragments from collisions and explosions. The list was filtered in a first step so that it just contains intact defunc satellites and rocket bodies which cannot perform any maneuver. Over the 200 years simulation time, LUCA recorded an average of well above 12000 such re-entries in all the 50 Monte-Carlo runs of the baseline scenario.

Those objects ultimately face an uncontrolled re-entry and imply a potential on-ground casualty risk if parts of the satellites survive the re-entry. Design for demisability is a term in this context which wants to minimize the amount of mass that survives re-entry. Ideally, the whole satellite or rocket-body should burn-up during re-entry, so that no remaining parts hit the ground. ReDSHIFT addresses this topic in the next phase of the project. The general idea is to introduce special failure modes or break-up lines in the structural design of a spacecraft. This would cause the re-entering craft to break-up in smaller pieces which either burn-up completely or impact on the ground with much less mass and severity. The downside of this approach is that it increases the dispersion and the elliptical footprint indicating the possible impact of objects from the re-entry is enlarged. Since we deal with uncontrolled re-entry, there is no way to move this predicted impact corridor to an unpopulated area (as it is done on controlled re-entry).

Figure 5 shows inclination and eccentricity over the semi-major axis. The data points mark the re-propagated orbital elements with a perigee at altitudes of 100 km or below. The points are taken from one single Monte-Carlo run of the baseline scenario; in total more than 12500 entries. The inclination plot at the top shows an accumulation of entries at smaller values for the semi-major axis. This is of course expected since most spacecraft are in LEO. At the very low end, the data points almost cover the full range of inclinations. At higher semi-major axis values some preferred inclination bands are visible, e.g. at around 60 degrees or at 20 degrees. The color code is an indication for the mass-to-area ratio of the re-entering objects, an important factor besides the drag coefficient of the spacecraft itself, which determines the re-entry. The majority of the objects have a ratio between 50-200 kg/m^2. The lower part of Figure 5 shows the eccentricity over semi-major axis. The points are distributed along a

Table 1. Number of recorded objects before and after re-propagation of a single Monte-Carlo run. The table lists the number of objects with an eccentricity less than 0.1, 0.01 and 0.001. Additionally, it gives the share of the total number of entries of 12691 in percent.

condition	before re-prop.	after re-prop.
$e \leq 0.1$	11511 (90.7%)	12021 (94.7%)
$e \leq 0.01$	10714 (84.4%)	11507 (90.7%)
$e \leq 0.001$	9912 (78.1%)	10860 (85.6%)

distinct curve. It matches very well to the theoretical results of orbits with a perigee r_p at the mean radius of the Earth plus 100 km following the equation for the eccentricity e as a function of semi-major axis a: $e(a) = 1-\frac{r_p}{a}$. This makes us confident that we have recorded the orbital elements which are relevant for further re-entry calculations, e.g. the heat flux, the duration of the re-entry and temperatures. Same as in the above plot, the color code gives the mass-to-area ratio. It can be seen that towards larger values of the semi-major axis, the mass-to-area of the objects increases. For the lower values of the semi-major axis the mass-to-area range is between 50 to 200 kg/m^2. For higher values of the semi-major axis, we can also see higher mass-to-area ratios, e.g. around 200 kg/m^2 and above. This tells us that objects coming back on high elliptical orbits tend to have larger values for mass-to-area ratio.

Figure 6 shows the same information as in the previous plot, inclination and eccentricity over semi-major axis. However, the semi-major axis ranges only until 8000 km. It is basically a zoomed in view on the LEO region. The vast majority of the re-entry orbits we recorded have very low values for the eccentricity (are circular). This again is an important information for the further development of the re-entry. The more circular the orbit, the smaller the flight path angle and the more shallow the objects re-enter into the lower layers of the atmosphere.

From a design for demisability point of view, it is interesting to know how much circularization is happening before the final orbit and the actual decay. In order to examine this, we looked at two data sets. The first one containing the re-entry conditions before they were re-propagated closer to the 100 km altitude, and the second one after the re-propagation.

Table 1 gives an insight into the data before and after the re-propagation step. It lists the number of entries in the recorded simulation files below a certain eccentricity threshold. The numbers show a clear shift from higher values of the eccentricity to more circular orbits. The percentages of the objects with low values for the eccentricity are relatively high, which indicates that the majority of trajectories just before re-entry are near-circular.

This is just a first attempt to analyze the data. Further analysis will be part of ReDSHIFT throughout the next phase of the project. But we can already state that most of the defunc satellites and rocket bodies on uncontrolled re-entry trajectories are expected to come back from almost circular orbits and perform a very shallow re-entry.

5. CONCLUSION AND OUTLOOK

The paper presents results from long-term simulations of the space debris environment. It validates the results of two tools, SDM and LUCA, on the basis of simple scenarios. The tools agree very well in their results and in the more elaborate scenarios, different mitigation effects are varied and a mega-constellation is added. From the results, we can see that in the densely populated LEO region, all simulations show an increase of the effective number of objects. Collisions are likely to become the dominant source of new debris. Modeling the satellites in more detail with a main body and appendices prevents an overestimation of collisions, and should be incorporated further. Mega-constellation might pose a big issue on the LEO environment and should be carefully considered in the near future. Moving LEO satellites above the altitude of 2000 km for a graveyard orbit should be handled with care, because eventually objects will accumulate and the collision risk in that regime will rise. The re-entry conditions recorded in the simulations suggest that orbits from uncontrolled intact satellites and rocket bodies circularize before their final decay, ultimately leading, to shallow flight path angles. The data can be examined further and should be cross-validated with the orbital evolution of observed re-entries.

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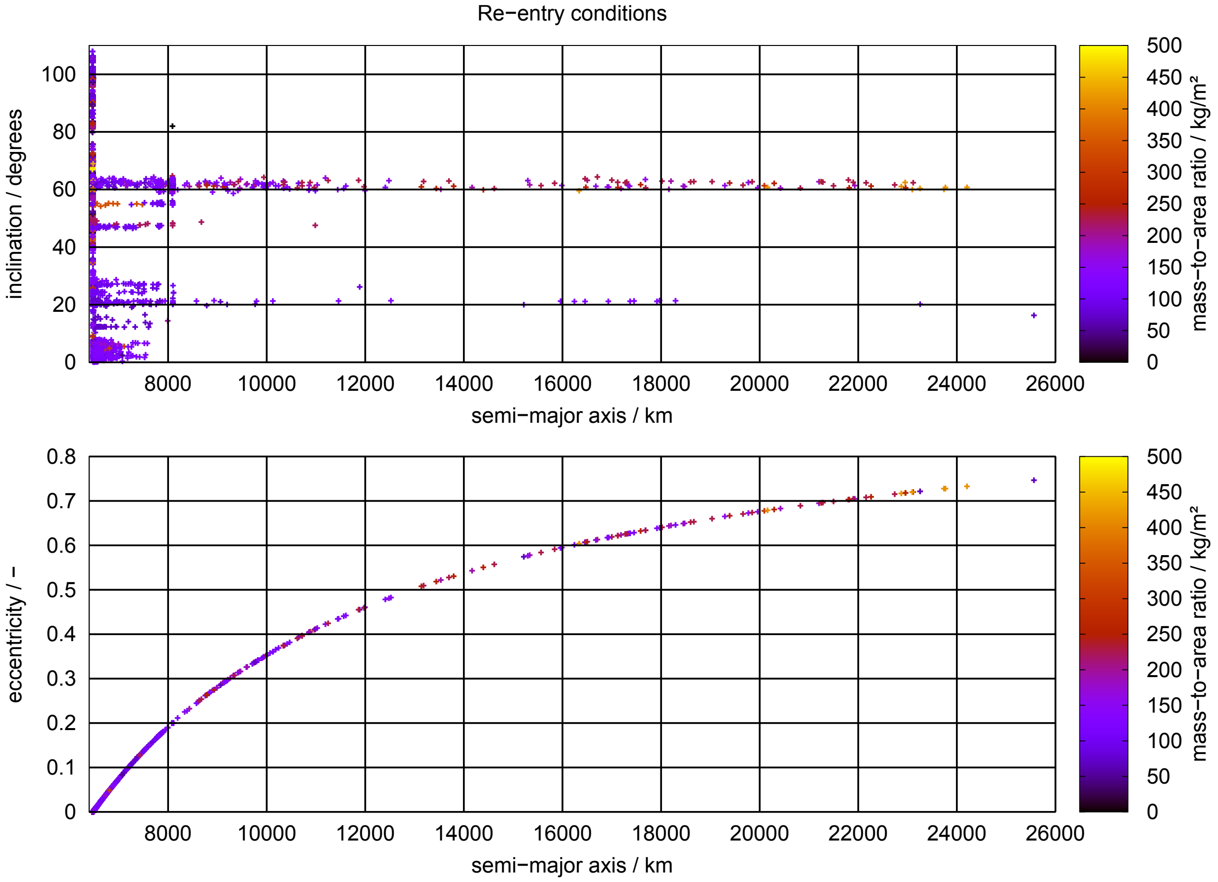

Figure 5. Eccentricity and inclination plotted over semi-major axis up to 26000 km. The color bar indicates the mass-to-area ratio.

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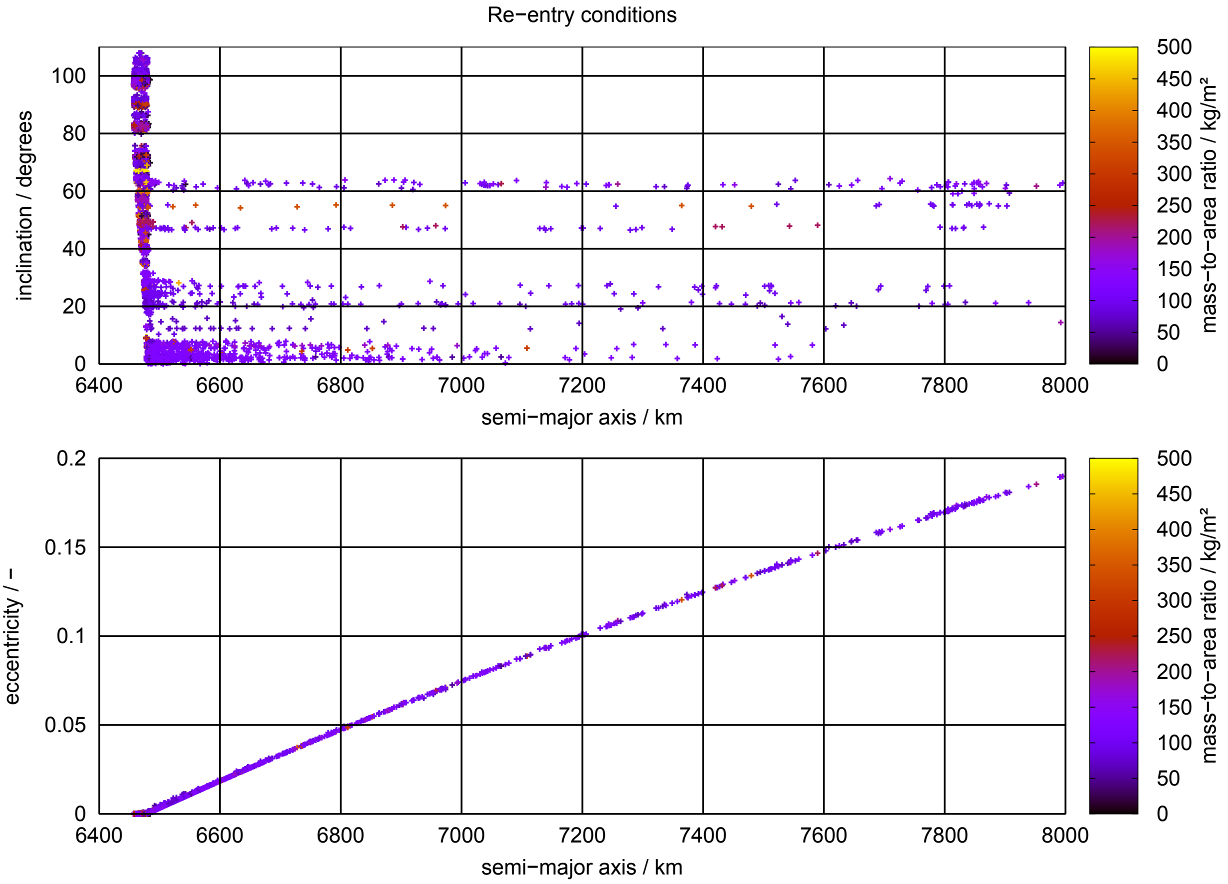

Figure 6. Eccentricity and inclination plotted over semi-major axis up to 8000 km. The color bar indicates the mass-to-area ratio.