THE IMPACT OF THE INCREASE IN SMALL SATELLITE LAUNCH TRAFFIC ON THE LONG-TERM EVOLUTION OF THE SPACE DEBRIS ENVIRONMENT

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ABSTRACT

In recent years, the launch traffic to low Earth orbits (LEO) has undergone a significant change: while in the beginning of this century the launch rates dropped to their lowest level since the beginning of the space age, the yearly number of launches performed has now recovered to 20th century levels. Although absolute launch numbers are now comparable to historic levels, fundamental space activity has changed dramatically: instead of launching few, complex, large and expensive spacecraft, as done typically by governments, the trend is now towards the deployment of space systems that are much smaller, less complex and of lower cost. A major factor in this change of philosophy has been the shift from institutional operators towards those from private industries. Current market analyses furthermore assume that these recent changes in launch traffic are only the beginning of a continuing change in the use of LEO.

When considering this shift towards increasing numbers of smaller satellites, the question arises what impact will these objects have on the long-term evolution of the space debris environment? A general concern exists that small satellites might pose a major threat to classical missions, as many of them are not equipped with propulsion systems and thus cannot perform any collision avoidance or end-of-life disposal manoeuvres. To assess the role of these small satellite missions in the evolution of the space debris environment, long-term projections of the space debris environment for different assumptions of small satellites' launch rates, release orbits and capabilities have been performed and their results are presented in this paper. For these projections, the Institute of Space System's tool LUCA (Long Term Utility for Collision Analysis) has been used.

In this paper, the current trends in launch traffic are first summarized, focusing on describing the characteristics of small satellites. Following this, an approach to project future launch traffic scenarios using knowledge from currently launched small satellites is described. This approach is based on deriving distributions that capture the characteristics of current small satellites missions, such as their mass, shape, release orbit, launcher, etc. Depending on the scenario to be simulated, these distributions are manipulated and to-be-launched objects drawn from them during the simulations. This method is applied to different parametric variations of the small satellite launch traffic, including the number of objects to be launched, their orbital distribution, their potential to perform post-mission disposal and collision avoidance manoeuvres, and their launch as swarms of satellites.

Key words: Long-term evolution; small satellites; new space; LUCA;.

1. INTRODUCTION

In recent years, launch traffic to low Earth orbits (LEO) has undergone enormous changes. Alongside a general recovery of the launch rate, which dropped to an all-time low in the beginning of this century (cf. Figure 1), the number of launched small satellites and their share in all launched objects has increased significantly. In this paper, the term small satellites is used for all payloads with masses below 100 kg. The reason for this change is probably a combination of several factors, such as the general miniaturization of satellite parts and their standardization, new, and supposably cheaper launch opportunities such as the Indian PSLV or upcoming launchers such as Virign's LauncherOne or Rocket Lab's Electron, alongside with America's legalization of private spaceflight in 2004 [1]. These factors are furthermore enhanced by newly emerging markets from increased worldwide connectivity and computation capabilities, allowing easy and automated processing of the vast amounts of data collected by the small satellites. While the underlying reasons of this shift shall not be discussed in detail in this paper, questions of "'if"' and "'how"' the increase of launched payloads, although small and of low masses, might affect the long-term evolution of the space debris environment are important. This is vital to be able to judge on the applicability of existing space debris mitigation guidelines and standards for small satellites.

Some work on this topic has already been published [2], [3], [4], [5]. In these studies, different projections for possible future CubeSat or small satellite traffic were designed and the impact of this traffic on the space debris environment analysed. All publications agree that, if current trends in small satellite traffic continue or are even surpassed, small satellites will pose a possible threat to the space debris environment. This paper complements the previous work by designing different small satellite traffic scenarios, and additionally varying characteristics, and capabilities of small satellites in a parametric manner. All performed variations are summarized in Table 1. Some early results on small satellites' impact on the space debris environment from the same study were already published in [5].

2. TRENDS IN CURRENT LAUNCH TRAFFIC

The evolution of both the number of launched objects as well as their relative share in all launches for different mass classes of satellites is shown in Figure 1. From this figure, two trends become apparent: first of all, the total number of launched objects has been increasing since the very low numbers encountered in the first decade of the 21^{st} century, which is valid for all masses of objects. Second, both in terms of total number of objects but also their relative share in all objects, small satellites with masses below 100 kg have encountered the largest increase, leading to at least 100 objects launched per year since 2012 and a share well above 50%.

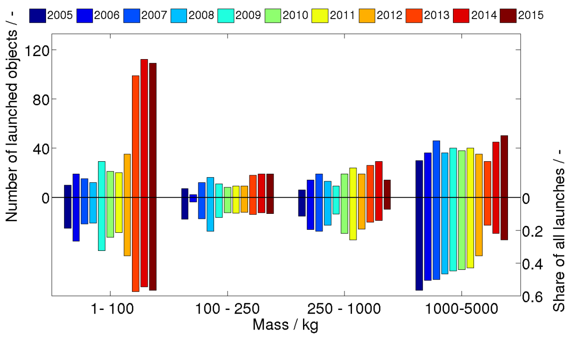

Figure 1. Histogram of number of launches per mass bin for years 2005 to 2015 and share of small satellites in overall launch rates. Data from Discos.

Besides the number of objects, their distributions of orbital parameters, mass, area-to-mass ratios etc. are also of high interest for a launch traffic creation. To gather this information, a compilation of databases from the University of Southampton [2] and TU Berlin [6] was used, and partially updated when information on objects was missing. Due to availability of the data at the time the analyses were performed, only small satellites launched between January 2012 and May 2015 were considered.

3. LONG-TERM SCENARIOS

To be able to estimate the impact of the increasing number of small satellites, a set of future launch traffic scenario was defined, on which basis characteristics and capabilities of small satellite launches were varied parametrically. These scenarios were then used to project the long-term evolution of the space debris environment. Simulations shown in this paper were performed using the long-term evolution tool LUCA (Long term utility for collision analysis) [7]. The results of the simulations were then compared against a reference scenario, in which no additional small satellite launches were considered. In the following, the different scenarios are generally described, a detailed description of the small satellite launch traffic is given in Section 4.

The **reference scenario** was chosen to be in-line with current simulations performed by the Inter-Agency Space Debris Coordination Committee (IADC) and those for other publications, such as those in [9]. The initial population used for the simulations included all LEO-crossing objects $\geq$ 10 cm on January 1^{st} 2013, derived from ESA's Meteoroid and Space Debris Terrestrial Environment Reference Model (MASTER) [10], [11]. The traffic was created by repeating all LEO and geostationary transfer orbit (GTO) launches between 2005 and 2012. It was assumed that no further explosions occur and that 90% of all spacecraft and rocket bodies perform a disposal to an eccentric 25-year orbit at the end of their active mission, if their orbital lifetime exceeds this limit. Note that this assumption for post-mission disposal is rather optimistic compared to results from recent studies, which show that only about 20% of all space systems, which are not naturally compliant, meet a 25-year disposal rule [12], [13]. For the future solar activity, five different random-cycles were created. All simulations were performed for simulation time frames of 200 years, performing 50 Monte-Carlo runs per scenario.

Atop this reference scenario, different assumptions for future small satellite traffic were assumed. The complete simulation plan is shown in Table 1. For the sake of clarity, scenario 1.a.2 is from hereon denoted as **small satellite baseline scenario**. If not stated otherwise, all variations are performed in reference to this scenario.

Table 1. *Simulation plan of long-term scenarios including small satellites. SMA stands for semimajor axis, PMD for post-mission disposal.*

Scen. Number	Short description	Variation
Ref	Reference scenario	-
1.a.1	Low small sat. traffic	Assume a low, constant small sat. launch rate
1.a.2	Medium small sat. traffic	Assume a medium small sat. launch rate
1.a.3	High small sat. traffic	Assume a high small sat. launch rate
1.b.1	Increase CubeSat form factor	1U to 3U, 3U to 6U
1.b.2	Increase CubeSat form factor	1U to 6U, 3U to 12U
1.b.3	Increase CubeSat form factor	1U to 12U, 3U to 24U
1.c.1	Assume low small sat. launch altitude	Launch small satellites 50\50 to SMA bins 2 and 3 from Table 3
1.c.2	As 1.c.1, increase piggy back rate	As 1.c.1, 80% piggy back launched
1.c.3	Assume high small sat. launch altitude	Launch small satellites to SMA bins 3 (25%), 4 (50%), and 5 (25%) from Table 3
1.c.4	As 1.c.3, increase piggy back rate	As 1.c.3, 80% piggy back launched
1.d.1.i-iii	Some small sats. are launched in swarms	launch 20% of small sats in swarms of [10 - 30; 30 - 50; 50 - 80] sats.
1.d.1.iv-vi	Half of all small sats. are launched in swarms	launch 50% of small sats in swarms of [10 - 30; 30 - 50; 50 - 80] sats.
1.d.1.vii-ix	Most small sats. are launched in swarms	launch 80% of small sats in swarms of [10 - 30; 30 - 50; 50 - 80] sats.
2.a.1.i-iii*	Small sats perform PMD to 25 year orbits	[30%; 60%; 90%] PMD success; eccentric 25 year PMD orbits.
2.a.1.iv-vi*	Small sats perform PMD to 10 year orbits	[30%; 60%; 90%] PMD success; eccentric 10 year PMD orbits.
2.a.1.vii-ix*	Small sats perform PMD to 5 year orbits	[30%; 60%; 90%] PMD success; eccentric 5 year PMD orbits.
2.a.2.i-iv*	Small satellites perform collision avoidance	[30%; 70%; 90%; 100%] collision avoidance success.

*Small satellites are assumed to have active lifetimes of five years.

4. CREATION OF FUTURE LAUNCH TRAFFIC

To perform the long-term simulations, most crucial is the creation of traffic for future launches. As the scenarios shall be comparable against each other, and especially also against the reference scenario, the underlying assumptions for launched objects need to be consistent. Therefore, the launch traffic creation is based on deriving distribution functions from prior launched small satellites and randomly drawing objects from these distributions. For background objects, random objects were drawn from the repeating launch cycle. To launch objects during the simulations, the following parameters are needed:

- total number of payloads to be launched,
- orbital parameters,
- satellite characteristics such as mass and cross-section,
- number of objects included in a single launch,
- used launcher system,
- insertion of mission related objects (MRO) during the launch,
- capabilities of the launched objects such as post-mission disposal and collision avoidance.

4.1. Number of payloads to be launched

The numbers of launched background objects and small satellites were derived differently. To be in-line with the reference scenario, the number of launched background objects is a repeating cycle, based on launches performed between 2005 and 2012. For the small satellite launch rates, three different scenarios were assumed: One constant scenario, one medium launch rate scenario, and one high launch rate scenario. For the constant launch rate scenario, it was assumed that the number of small satellites stays about the same as in 2013, thus 100 objects per year were included. Similar to [2], the number of small satellites launched per year during the other scenarios were estimated using different Gompertz Logistic curves:

$$L = \lfloor ae^{-be^{c(t-t_0)}} + 0.5 \rfloor. \quad (1)$$

The coefficients used for the different scenarios are shown in Table 2; Figure 2 shows the numbers of payloads launched during the different scenarios, including the historical rate for small satellites..

Table 2. Gompertz coefficients used in the logistic functions to determine number of launched small satellites during long-term simulations.

Coefficient	Medium	High
a	270	540
b	5	21.5
c	0.15	0.235
t_0	2003	2003

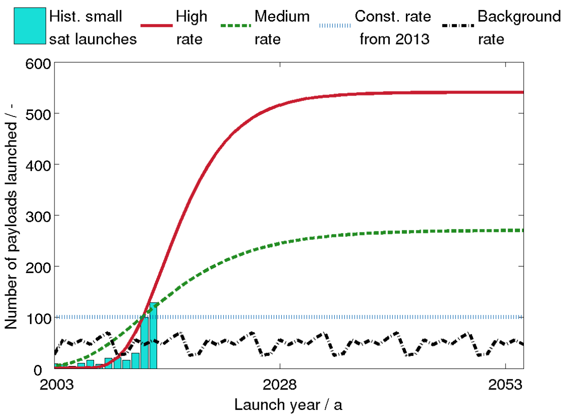

Figure 2. Launch rate of small satellites and background payloads for different future scenarios.

4.2. Orbital parameters of payloads

Second, the orbital parameters for each launch including small satellites needed to be determined. To achieve this, orbital parameters of past launches have been analysed, from which distributions of the orbital parameters were derived. To create the launch traffic scenarios, the orbital parameters were then drawn from these distributions. The distributions have only been derived for small satellites, background objects were randomly drawn from the objects in the repeating launch cycle.

The basis for the small satellite launches is the semimajor axis. From the distribution of past small satellite launches, a Gaussian mixture with five components was derived. It was decided to use a Gaussian mixture for three reasons: First of all, it was assumed that small satellites will be launched in the futures to similar regions of interest as today, but not to identical orbits. Using a parametric distributions offers an easy solution to add a spread to the orbital parameters. Secondly, from analysis of past launches, different altitude regions of interest were identified: launches directly from the ISS, two peaks in semimajor axes around 7000 km and 7200 km, some launches between the ISS orbit and 7000 km, and last very some launches to high orbits above 7200 km. Third, in the progress of the study, variations of the launch altitudes were to be performed. Using the derived distributions, this aim can simply be achieved by adopting the mixing coefficients. The resulting distributions together with the histogram of launched small satellites are shown in Figure 3. The expected values, standard deviations and mixing coefficients for the distributions are shown in Table 3.

Table 3. Components of the Gaussian mixture distribution to draw the semimajor axis for small satellite payloads. For scenarios 1.c.x, the mixing coefficients have been varied accordingly.

Class	Mix. Coeff.	μ / km	σ / km
SMA 1	0.3075	6547.5	20.47
SMA 2	0.1139	6751.7	63.14
SMA 3	0.4191	7045.8	45.57
SMA 4	0.1503	7171.9	39.69
SMA 5	0.0091	7787.4	141.85

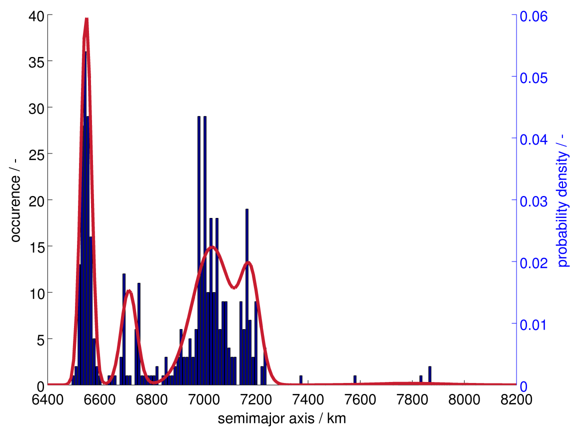

Figure 3. Gaussian mixture distribution to determine future small satellite launches together with the histogram of semimajor axis from launched small satellites. For the histogram, 120 bins have been used.

The second orbital parameter needed is the eccentricity. Here it was found that so far, all small satellites were placed on near-circular orbits, random values from a log-normal distribution with a mean of -6.39 and a standard deviation of 1.3 were drawn. In accordance with the available data, only eccentricities above 0 and below 0.08 were accepted.

The third orbital parameter used is the inclination. Again, a Gaussian mixture model was derived for their distribution, but as the inclinations used depend on the semimajor axes, one model was derived for each semimajor axis class. The resulting components are shown in Table 4, the distribution together with a histogram of the inclinations from small satellites launches are shown exemplary for semimajor axis class three in Figure 4. For those classes of the mixture functions that were identified to represent sun-synchronous objects, the inclinations were not determined by a random draw from the distribution, but using

Table 4. Components of the Gaussian mixture distributions to draw the inclination for small satellite payloads.

Class	Mix. Coeff.	μ / °	σ / °
1, 1	0.2593	37.0466	7.3585
1, 2	0.6074	51.6151	0.0235
1, 3	0.1111	67.0353	2.2870
1, 4	0.0222	SSO	-
2, 1	0.44	39.2659	1.5364
2, 2	0.4	51.638	0.0041
2, 3	0.16	SSO	-
3, 1	0.1196	65.2630	1.8182
3, 2	0.8151	SSO	-
3, 3	0.0652	120.4981	0.0001
4, 1	0.0455	19.9633	0.0058
4, 2	0.3636	45.0158	0.0132
4, 3	0.1667	76.46	5.4026
4, 4	0.4242	SSO	-
5, 1	0.5	82.485	0.0212
5, 2	0.5	SSO	-

the simplified formulation for sun-synchronous inclinations:

$$i_{sso} = \text{acos}\left(-0.09896 \cdot \frac{a}{R_E} \cdot \left(1 - e^2\right)\right). \quad (2)$$

Here, a is the semimajor axis of the orbits, R_E the Earth's radius and e the eccentricity.

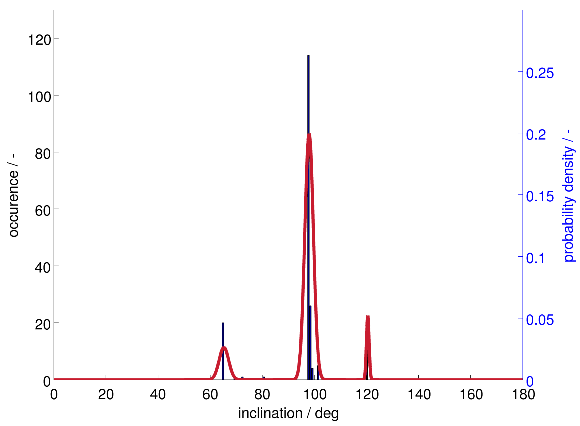

Figure 4. Gaussian mixture distribution to determine future small satellite launches together with the histogram of inclinations from launched small satellites of semimajor axis class 3. For the histogram, 75 bins have been used.

Figure 5 shows the orbits of 10000 small satellites drawn from the distribution functions together with those from the underlying databases. It can be seen that the "hot spots" are well reproduced using the distributions. Due to using normal distribution functions and the large number of objects, the spread around these areas are enlarged.

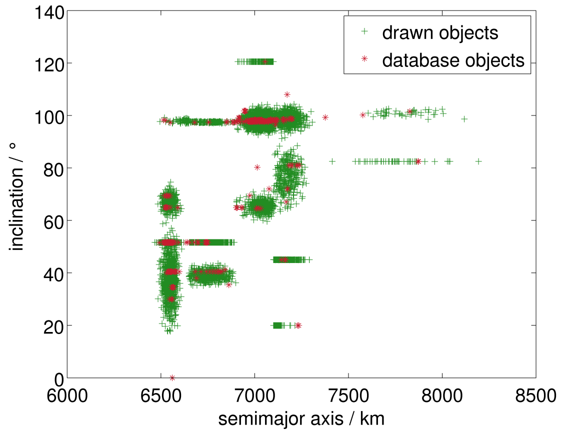

Figure 5. Inclination over semimajor axis for small satellites from databases (red) and drawn from derived distributions (green). 10000 random draws.

As all objects were placed on near-circular orbits, the argument of perigee is of less interest, so it was set on a random value between 0° and 360°. Furthermore, the right ascension of ascending node (RAAN) and mean anomaly are randomized during the collision rate determination algorithms used. Therefore, these two values are randomly set between 0° and 360°. Note that this procedure was different for those scenarios in which a subset of the small satellites was launched within swarms (refer to Section 4.7).

4.3. Satellite characteristics

For the long-term simulations, the satellites' characteristics are described using the mass and diameter. For the launch traffic creation it was decided to use the mass as independent variable and a double-logarithmic fit to determine the diameter based on the mass. For CubeSats, a different approach was used.

The mass of the to-be-launched small satellite was simply determined by randomly drawing from all satellites within the used databases. Then, based on the mass, a fit over all available satellite masses and diameters was used to determine the diameter:

$$d = 10^{-0.8877} \cdot m^{0.4523}. \quad (3)$$

To account for variations within the densities of typical satellites, a random variation of $\pm 50\%$ of the diameter was allowed. To determine the cross sections (and thus the area-to-mass ratios important for the propagation), all small satellites were assumed to be spherical. As this estimation does not work out well for very light-weight satellites, which typically are CubeSats. In the database, CubeSats are mostly 1U, 2U or 3U satellites. Therefore, objects with masses according to the CubeSat standard were assumed to be CubeSats. The cross sections of these CubeSats were determined using the tool CROC from

Table 5. characteristics of CubeSats during the simulations. Note that CubeSats larger than 3U were only considered during simulations 1.b.x.

Type	Mass / kg	Diameter / m	Cross-Section / m^2
1U	1.333	0.1377	0.0149
2U	2.666	0.1884	0.0279
3U	4.0	0.2224	0.0388
6U	12.0	0.2642	0.0548
12U	24.0	0.3186	0.0797
24U	48.0	0.4061	0.1295

ESA's DRAMA Tool Suite [8]. Their values are stated in Table 5. Note that CubeSats larger than 3U were only used in simulations 1.b.x.

4.4. Number of objects per launch

Next to payloads, the number of rocket bodies injected also have a large impact on the long-term evolution of the space debris environment, so the number of objects that are launched together need to be considered. To determine this number, the launches are distinguished between background launches, piggy-back and dedicated small satellite launches. In case of piggy-back launches, the small satellites are released into orbit together with a generally larger background object.

For the number of background objects per launch, the repeating launch cycle was used. The launches included in there could be fitted using a log-normal distribution with $\mu = 0.4171$ and $\sigma = 0.67$. A maximum number of eight background objects per launch were allowed.

To determine the number of piggy-back objects in one launch, the number of small satellites per launch vehicle launched between 2012 and 2015 have been used. These move between 1 and 12 objects per launch, with the exception of US military missions with more than 25 objects per launch. Additionally, almost 80 small satellites were launched from the ISS. For the launch traffic creation, the latter ones have been assumed to be exceptional events, and a normal logarithmic distribution function has been used to describe the number of small satellite in piggy-back launches with $\mu = 0.8869$ and $\sigma = 1.0346$.

To determine the number of small satellites in dedicated launches, a log-normal distribution with $\mu = 1.2653$ and $\sigma = 1.10551$ was used.

If not stated otherwise, it was assumed that 50% of the small satellites were launched as piggy back objects with background objects.

4.5. Used launcher system

For the launch system used, all launches included in the repeating launch cycle were analysed in regards to their mass delivered to orbit. Based on the mass to be delivered to orbit in the long-term simulation, an appropriate system was randomly chosen from those used in the repeating launch cycle.

In addition to the rocket bodies from launch to LEO, also rocket bodies to GTOs were also considered in the simulations. As these are not correlated with any mission within this study, the GTO rocket bodies were included based on the launches in the repeating background launch cycle.

4.6. Insertion of mission related objects

From the launches performed between 2005 and 2012 it was found that 28% of all LEO missions released at least one mission related object (MRO) into orbit that lasted at least three months. Furthermore 73% of all GTO rocket bodies released at least one, in general very large, mission related object. Therefore, for both types of launches, randomly chosen mission related objects were released into close vicinity of the launch orbit.

4.7. Launching swarms of satellites

In one of the scenarios, different shares of all small satellites were assumed to be launched in swarms of satellites of different sizes. As swarms of satellites, three different types were assumed possible: strings of pearl, Walker-Delta constellations, and Walker-Star constellations.

In the process, at first the number of objects in the swarm to be created is determined by a random draw from an uniform distribution of even numbers. Second, it is decided if the swarm was a string of pearl or any type of constellation. No data is available to indicate a correlation between number of objects in a swarm of satellites and type of swarm, as the underlying assumption is that strings of pearls tend to be smaller than other types of constellations. To apply this assumption, a normal distribution of the shape

$$p_c = \frac{1}{2}\left(1 + \text{erf}\left(\frac{n_{sats} - \mu}{\sqrt{2\sigma^2}}\right)\right) \qquad (4)$$

is used. Here, the mean value is decribed by $\mu = 25$ and the standard deviation with $\sigma = 10$. For a swarm consisting of n_{sats} members, the probability of being a constellation p_c is determined. Then, this probability is compared against a random number z from a uniform distribution in the interval $[0, 1[$. If $z \leq p_c$, the swarm is assumed to be a constellation, else it is considered as a string of pearls. Furthermore is decided if the constellation is Walker-Star or Walker-Delta. Again, no data is available to support this decision, therefore it was assumed that highly inclined constellations are generally Walker-Star, others are Walker-Delta. To decide between those two types, again a normal distribution was used, with the inclination being the independent variable, $\mu = 80°$ and $\sigma = 2°$. If the inclination exceeds 90°, $180° - i$ is used. The resulting value is used as probability, if a constellation is a Walker-Star constellation.

Next, the distribution of the objects along their orbital planes is determined. For strings of pearls, the approach is straight forward, as all object are on a single orbital plane. This plane is randomly drawn, the objects are then evenly distributed in slots along this plane. For the constellations, first the number of planes are determined, which are randomly chosen to be between three and eight. Second, the nodes of the single planes are set. For Walker-Delta constellations, they are evenly distributed along 360°, for Walker-Star constellations along 180°. Last, the objects are evenly distributed in slots along each plane. For Walker-Delta constellations, the offset between slots in neighbouring planes is defined by the Walker factor as:

$$w = \frac{2\pi}{n_{sats,plane}} \cdot \frac{1}{n_{planes}}. \quad (5)$$

For Walker-Star constellations, the slots are also evenly distributed along the orbital planes, with the offset between neighboring planes being half the difference of objects in a single plane.

5. RESULTS OF THE LONG-TERM SIMULATIONS

5.1. Reference and baseline scenarios

All simulations were analysed in comparison to a reference scenario, in which no extra small satellites were included (only those included in the repeating launch cycle were considered). The main results of this simulation are shown in Figure 6. The simulation projects a constant median number of objects, with the worst case being an increase of about 65% and a best case a decrease to about 73% of the initial number of objects in orbit. On the median, during the first half of the simulation, 0.17 catastrophic collisions are triggered per year, afterwards the collision rate decreases to 0.13 per year. In between, the collision rate undergoes a subtle change. Considering these numbers it has to be kept in mind that the chosen scenario has, compared with most periods of spaceflight, a very low launch traffic. Furthermore, the results are highly sensitive to implementations of underlying models and assumptions such as future solar activity.

The scenario in which a medium launch rate of small satellites is superimposed to the traffic of background objects is chosen as the small satellite baseline scenario. The results of this scenario are also shown in Figure 6. In this scenario, the additional launch traffic leads to a direct increase of the number of objects in LEO by about 70% during the first half of the simulation. From then, only a low further increase by less than 10% on the median over the rest of simulation time frame can be observed. The number of catastrophic collisions evolves similar to that of the reference scenario, but at different rates. Again, after about half of the simulation time frame, the rate decreases again. Until then, 0.31 collisions are trigged per year. For the rest of the simulation time, on the median 0.25 collision occur per year. Both rates behave very linear over the stated time frames (with correlation coefficients of $R^2 = 0.99$ between the correlation rates and their linear trends).

To determine the statistical significance of the difference in the median of two long-term simulations, the results in terms of numbers of objects in the environment have been analysed using a Wilcoxon rank sum test [14]. This is a non-parametric hypothesis test using as null-hypothesis that the medians of the tested samples from independent populations are identical at an assumed significance level (α). As result, the test returns a p-value, which describes the probability that the tested samples come from distributions which fulfill the null-hypothesis. If $p < \alpha$, the null-hypothesis is rejected, indicating a significant difference in the medians of the tested simulations. The standard significance level for this test is $\alpha = 0.05$, which has also been used in the context of the paper. With this test, always two long-term scenarios, which differ in one parameter of the simulation set-up were compared. If the null-hypothesis hypothesis is rejected with this test, the influence of the changed parameter had a significant impact on the median results.

While the difference between reference and baseline scenario appears obvious already from the graphical comparison, differences were less obvious when considering other scenarios. Comparing these two scenario, using the Wilcoxon rank sum test, the null-hypothesis is rejected at the 5% significance level over the complete simulation time frame.

5.2. Variation of the small satellite launch traffic rate (scenarios 1.a.x)

The first variation of the small satellite launch traffic was with respect to the number of objects included into the population. The results of the variations are shown together with the reference and baseline scenarios in Figure 7. Note that the spread in the simulation results of the baseline and high launch traffic scenario are omitted for clarity, but exist in all results in similar extent.

Scenario 1.a.1 has the lowest number of added small

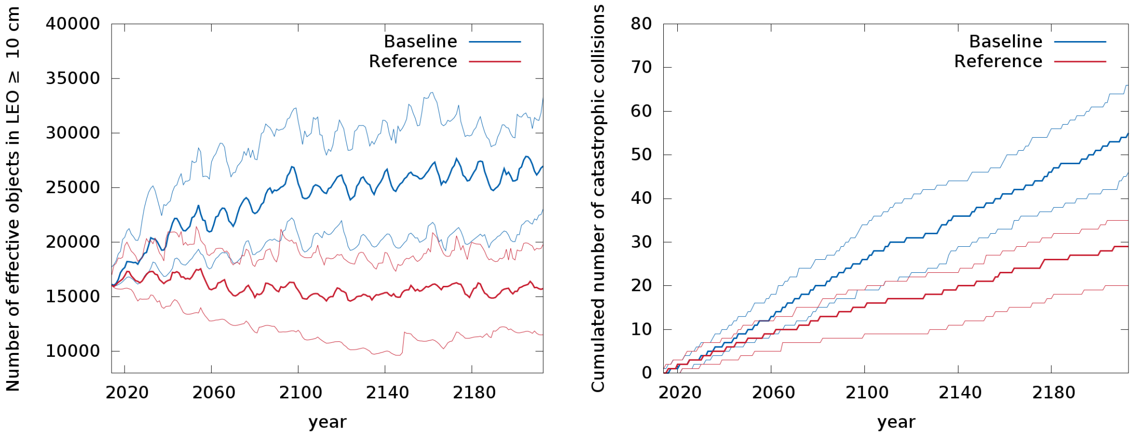

Figure 6. Results of the baseline scenario considering a medium small satellite launch rate. Shown are median (thick line) and 10% and 90% quantiles (thin lines). ***Left:*** *Effective number of objects in LEO over time,* ***right:*** *Cumulated number of catastrophic collisions. Computed from 50 Monte-Carlo runs.*

satellites. The median number of objects increases by 26% and behaves in an almost linear fashion. The number of catastrophic collisions increases strongly during the first half of the simulation with 0.22 median collisions per year, followed by 0.18 collisions per year. Again, the cumulative number of collisions behaves linear during both time frames ($R^2 = 0.99$). In the scenario with a high small satellite traffic, the median number of objects increases by about 80% until the year 2060, followed by a less strong increase over the remaining 150 years of simulations leading to a total increase of 135%. In contrast to the other scenarios, the number of catastrophic collision increases almost linearly with 0.43 collisions per year ($R^2 = 0.99$) over the complete simulation time frame.

Again, the difference of the scenarios with respect to the reference scenario, but also against one another has been tested using the rank sum test. Even though the spreads within the simulation results overlap, especially for the reference scenario and case 1.a.1 (constant launch rate), the null-hypothesis is rejected over the complete simulation time frame for all scenarios when compared against the reference case. Comparing the small satellite scenarios against one another, a significant difference is achieved after 15 years when comparing the baseline scenario and scenario 1.a.1 (constant launch rate) and already after five years when comparing either of the scenarios against scenario 1.a.3 (high launch rate). While this result is not surprising for the small satellite baseline case and scenario 1.a.3 (high launch rate), it shows that already the small satellite launch traffic as performed today, which is represented by scenario 1.a.1 (constant launch rate), has already a significant impact on the long term evolution of the space debris environment.

5.3. Variation of the small satellite form factor (scenarios 1.b.x)

The second variation was a change in the form factor of all launched CubeSats. The variation has been performed under the assumption that CubeSat sizes will increase in the future to enable more capable payloads for commercial missions. Three variations as shown in Table 1 were performed with CubeSat characteristics (mass and cross section) as stated in Table 5. The results of these simulations are shown in Figure 8.

In terms of the median number of objects in the environment, during the first about eighty years, all simulations behave similarly, leading to an increase in the number of objects between about 60% (for the baseline scenario and scenario 1.b.1) and 75% (for scenarios 1.b.2 and 1.b.3). Over the time, the results start to differ and the increase relaxes in all cases, but while for the baseline case the number of objects stays almost constant for the remaining simulation time frame, it further increases for the scenarios with the variations. This leads to a total increase of about 75% in scenario 1.b.1, 100% in scenario 1.b.2, and even 110% in scenario 1.b.3. A similar behaviour is shown for the number of catastrophic collisions: while during the first half of the simulation all small satellite scenario show a median of about 0.31 collisions per year, the numbers start differing between scenarios afterwards. For the baseline scenario, the rate decreases to 0.25 collisions per year, for scenario 1.b.1 it stays around 0.31, and for scenarios 1.b.2 and 1.b.3 it increases to 0.34, and even 0.47 during the last 50 years of the simulation time frame. Therefore, in terms of collisions, the scenarios in which the CubeSats sizes are increased, an acceleration in the collision activities can be observed.

In terms of the statistical significance of the results, the null-hypothesis is rejected when comparing the variations against the baseline scenario at the end of the simulation time frame. For the first 40 years nev-

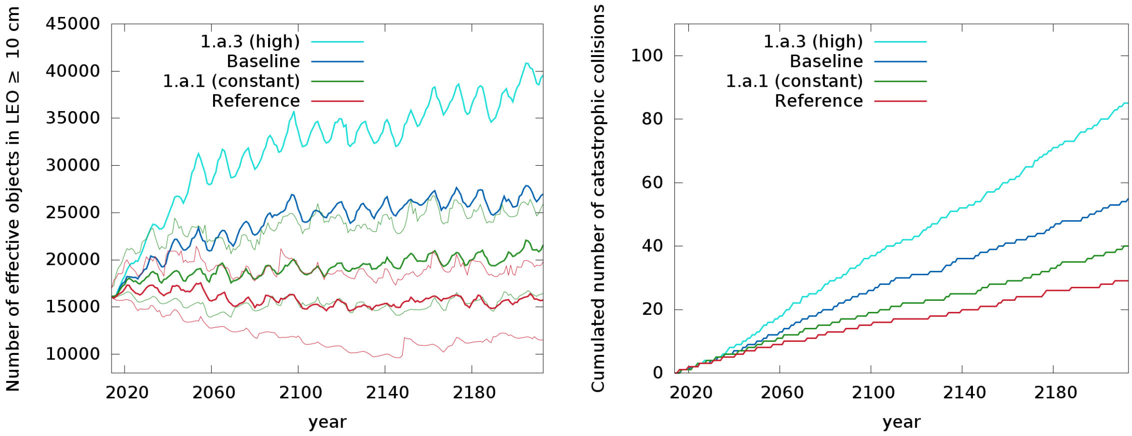

Figure 7. Results of the scenarios varying the small satellite launch rate in comparison with the reference scenario. Note that the quantiles for scenario 1.a.1 and 1.a.3 have been omitted for clarity but exist in similar extend as for other scenarios shown. ***Left:*** *Effective number of objects in LEO over time,* ***right:*** *Cumulated number of catastrophic collisions. Computed from 50 Monte-Carlo runs.*

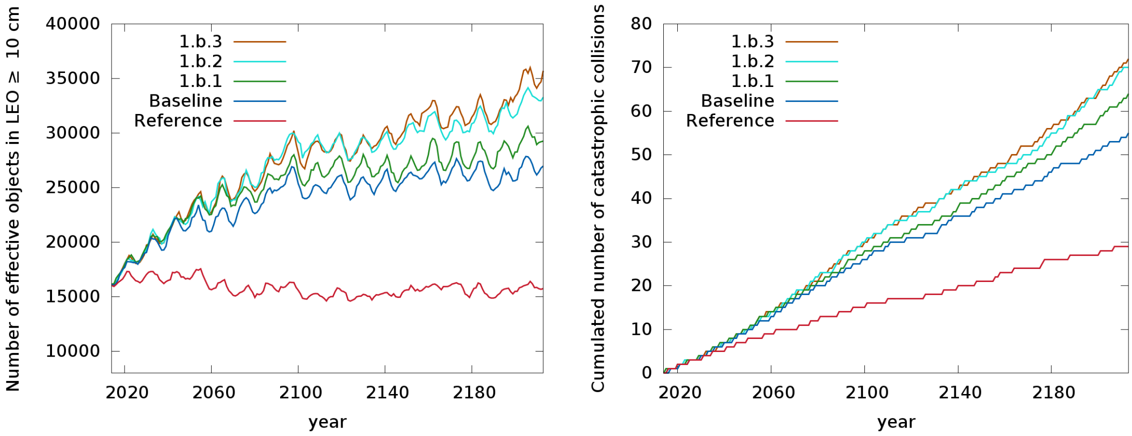

Figure 8. Results of the scenarios varying the small satellite form factor in comparison with the reference scenario. In scenario 1.b.1, all CubeSats are increased to 3U to 6U, in scenario 1.b.2, all CubeSats are increased to 6U to 12U and in Scenario 1.b.3, all CubeSats are increased to 12U to 24U. Note that the quantiles have been omitted for clarity. ***Left:*** *Effective number of objects in LEO over time,* ***right:*** *Cumulated number of catastrophic collisions. Computed from 50 Monte-Carlo runs.*

ertheless, the assumed significance level for rejection is not achieved, which means the impact is only weak in all scenarios (cf. Figure 15). Comparing the variation scenarios against each other shows that scenario 1.b.1 the significance in the differences increases over time, after sixty years, it crosses the set confidence threshold of 5%. The difference between scenarios 1.b.2 and 1.b.3 stays low over most of the simulation time frame, becoming significant only towards the end. From these simulations it can be deduced that the impact from small satellites increases with the size of small satellites.

5.4. Variation of the small satellite launch altitude (scenarios 1.c.x)

Next, the launch altitudes of small satellites were varied. The reason for this variation is that higher orbits in general allow longer mission lifetimes, whereas launches to lower orbits in general comes with lower launch costs. To achieve the desired variations, the mixing coefficients of the distribution functions stated in Table 3 were changed. The coefficients used for the varied scenario are given in Table 6 and shown in Figure 9. Additionally, it was tested in this scenario if launching more small satellites (80%) using piggy back launchers has an impact on the environment evolution. The results of this variation are shown in Figure 10.

In terms of the median number of objects in the LEO

Table 6. Components of the Gaussian mixture distribution to draw the semimajor axis for small satellite payloads for scenarios 1.c.x. 1.c.1 and 1.c.2 launched to low altitudes, 1.c.3 and 1.c.4 launched to high altitudes.

Class	Low altitude	High altitude
SMA 1	0	0
SMA 2	0.5	0
SMA 3	0.5	0.25
SMA 4	0	0.5
SMA 5	0	0.25

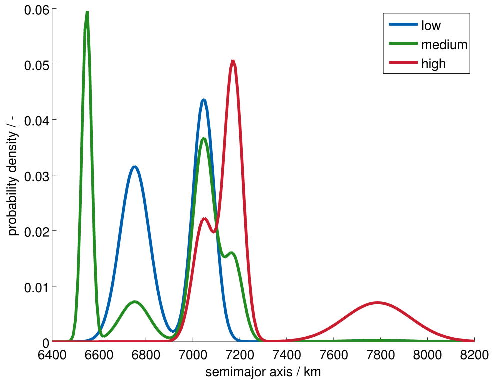

Figure 9. Semimajor axis distributions used during scenario 1.c.x, 1.c.1 and 1.c.2 used the low distribution, 1.c.3 and 1.c.4 used the high distribution, the baseline scenario used the medium distribution.

environment, launching to higher altitudes (scenarios 1.c.3 and 1.c.40 leads to an increase in the number of objects by 160%. Again, the increase is higher until the year 2100. Launching to generally low orbits, as done in scenarios 1.c.1 and 1.c.2, still leads to an increase in the number of objects by 47%, compared to the baseline scenario; nevertheless this difference is very low. Similar evolutions can be found for the cumulative number of catastrophic collisions: scenarios 1.c.1 and 1.c.2 have yearly collision rates very similar to that of the baseline scenario, thus on the median 0.31 until 2100 and 0.25 afterwards. Scenario 1.c.3 and 1.c.4 nevertheless clearly show a different trend. Here, over the complete simulation time frame the median collision rate is 0.38 collisions per year, which increases to 0.47 collisions per year during the last 50 years of the simulation.

Looking at the statistical significance of the difference in the simulations, first of all it can be found that launching more small satellites using dedicated launchers did not lead to a significant change in the simulation results (only in some years was the null-hypothesis rejected when comparing scenario 1.c.1 against scenario 1.c.2 or scenario 1.c.3 against 1.c.4 respectively). The reason for this is probably that the orbital distributions of small satellites and background objects are generally too similar to show a very clear effect. This should be further investigated though. Comparing the general change of the launch altitude for small satellites shows a significant impact though (cf. Figure 16). This is especially the case for the scenario in which small satellites were launched to higher altitudes than today. Although the altitudes chosen for the simulations might appear unrealistically high, it leads to an assumption that also less drastic changes in the launch altitudes might lead to both more objects in the environment and more collisions.

5.5. Small satellites launched in swarms of satellites (scenarios 1.d.x)

In the following variation, it was assumed that a set of small satellites was launched as swarms of satellites. The process to achieve this is described in Section 4.7. The rationale for this scenario was to test if releasing large numbers of satellites on very similar orbits changes the collision rates between these objects. Two different effects were expected: firstly, the small satellites were released on identical semimajor axes, which for a certain time should reduce the collision rate between the satellites of one swarm as the orbital motion is phased. Secondly, launching large numbers of small satellites into identical orbits leads to a local increase in the spatial densities, which furthermore might increase collision rates, once the first effect has vanished and after a certain time of propagation. The results of some of the simulated scenarios are shown in Figure 11.

In the figure, it becomes obvious that the impact of launching large numbers of the small satellites showed only a very limited impact on the long-term evolution. In terms of number of objects, only the case in which many swarms with many small satellites were launched, demonstrated a clear separation from other scenarios. Similar behaviour is found in the evolution of the cumulative number of catastrophic collisions.

The rank sum test for the swarm satellite scenario support the observations from the shown results (cf. Figure 17). Nevertheless, as there appears to be a significant difference when launching many large swarms of small satellites, it should be studied more closely: how this difference is achieved, and if and how this effect might be beneficial for the future evolution of the debris environment.

5.6. Small satellites perform end of life manoeuvres (scenarios 2.a.1.x)

In the next variation, it was assumed that different fractions of the small satellites were equipped with propulsion systems and capable of performing post-mission disposal manoeuvres to different remaining

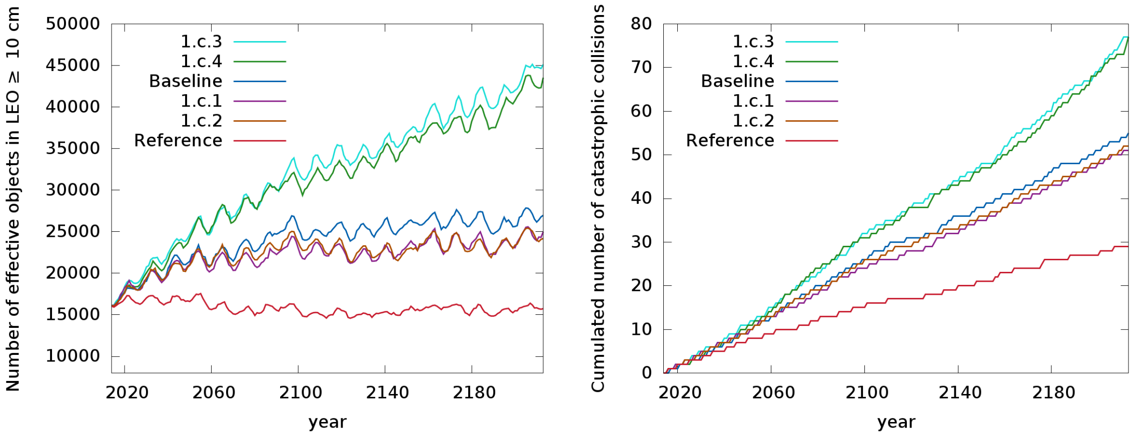

Figure 10. Results of the scenarios varying the small satellite launch altitude in comparison with the reference scenario. Note that the quantiles have been omitted for clarity. ***Left:*** *Effective number of objects in LEO over time,* ***right:*** *Cumulated number of catastrophic collisions. Computed from 50 Monte-Carlo runs.*

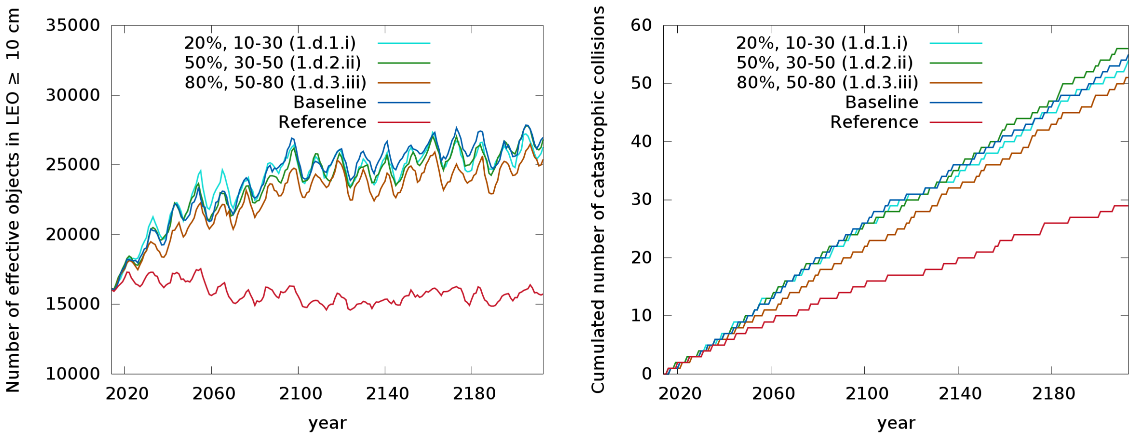

Figure 11. Results of the scenarios launching different shares of all small satellites as swarms of satellites consisting of varying numbers of objects. Note that the quantiles have been omitted for clarity. ***Left:*** *Effective number of objects in LEO over time,* ***right:*** *Cumulated number of catastrophic collisions. Computed from 50 Monte-Carlo runs.*

lifetime orbits. The stated success rates where applied per object. When comparing these scenarios against the others it has to be considered that in here, small satellites have an active lifetime of 5 years (compared to 0 in all other cases). Therefore, to allow a first order comparison, the number of objects on orbit has to be increased in the baseline scenario by at least 1350 (which accounts for the small satellites launched during the 5 years). This number neglects possible collisions involving active small satellites. Similarly, when considering the number of collisions over time, it needs to be considered that all small satellites spend five years longer on-orbit and can collide during this time. Note that no collision avoidance is performed in this scenario. Therefore, the number of catastrophic collisions is naturally a little bit higher.

The results of a section of these simulations are shown in Figure 12. In these figures, clearly a positive effect from performing post-mission disposal can be observed, both in terms of the median number of objects on orbit as well as cumulative number of catastrophic collisions. In particular the case in which 90% of all small satellites are disposed to 5-year orbits benefits. After an increase in the median by 18% during the first 50 years, the number of objects stays on a constant level over the rest of the simulation time frame. The median number of collisions is 0.2 over the complete time frame, which is reduced to 0.18 during the last 50 years of simulation.

The findings from the direct results are again supported by the rank sum analysis. After the first few years, all scenarios showed significantly lower median numbers of objects in the environment. For the case, in which 30% of the objects were disposed to 25 year orbits, the null-hypothesis is rejected from the year 2137. Nevertheless, the difference in the simulation assumptions should be considered. Therefore, a clear statement can be made that performing post-mission disposal for small satellites is highly beneficial for the long-term environment evolution. Taking the additional simulations

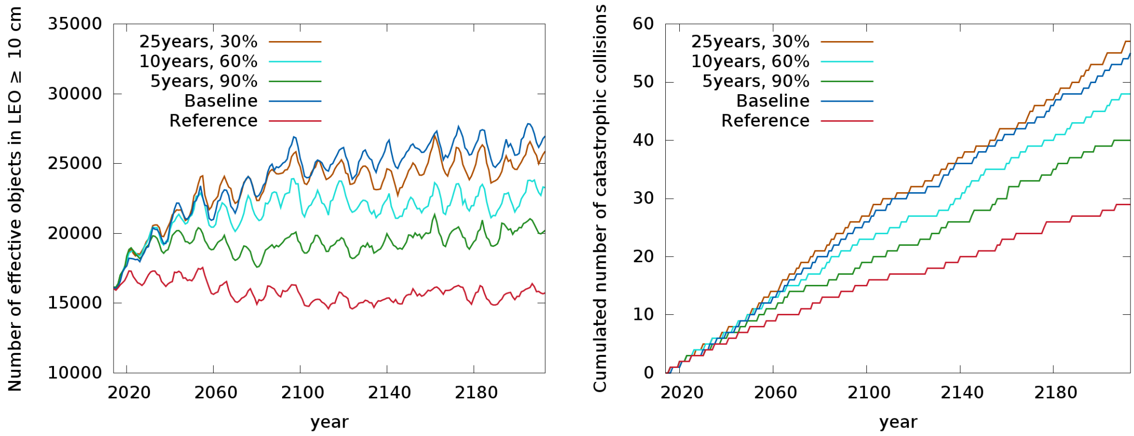

Figure 12. Results of the scenarios assuming different post-mission disposal strategies and success rates for small satellites. The success rate is used as 'per satellite' for those satellites that do not comply naturally. Note that the quantiles have been omitted for clarity. ***Left:*** *Effective number of objects in LEO over time,* ***right:*** *Cumulated number of catastrophic collisions. Computed from 50 Monte-Carlo runs.*

of this case into account (compare Table 1), it could be shown that most benefit is achieved by a high PMD success rate, with the remaining orbital lifetime to be of secondary value (in the limits analysed in this study). Nevertheless, it needs to be considered that even with a very strict disposal to short-living orbits, the impact of small satellites on the space debris environment is still significant, leading to 11 extra collision on the median.

5.7. Small satellites perform collision avoidance (scenarios 2.a.2.x)

Last, the possible impact from small satellites performing collision avoidance was analysed. Alongside the collision avoidance capabilities it was assumed that 30% of all small satellites perform an end-of-life manoeuvre to a 25 year disposal orbit after their active mission lifetime of five years (during which collisions could be avoided). Four variations were performed, in which the collision avoidance success rate was set to 30%, 70%, 90% and 100%. This success rate is used per encounter per active small satellite. The results of these scenarios are shown in Figure 13. Note that in this case, instead of the baseline scenario, scenario 2.a.1.i (in which 30% of the small satellites perform a 25 year disposal) is used for the comparison.

Looking at the results, the effect of collision avoidance of small satellites shows a rather low impact: the median number of objects in orbit can be lowered in comparison to scenario 2.a.1.i, but the differences are almost indistinguishable. The reason for this might be that collisions involving small satellites lead to a generally low number of fragments. In terms of the number of collisions, the effect is more clearly visible. On the median, 5 collisions can be avoided when small satellites have collision avoidance capabilities. Nevertheless, the differences between the success rate of the collision avoidance remain small.

For those scenarios in which collision avoidance is performed with either 30% or 60% success, the impact on the number of object is insignificant at most times (cf. Figure 18). For cases, in which collision avoidance is 90% or higher, the null-hypothesis can be rejected most of the times, however, leaving the conclusion that collision avoidance, if enough small satellites participate, can support the reduction of the number of objects on orbit.

To further understand the impact on the number of catastrophic collisions over time, the collision partners for small satellites have been investigated. They are shown in Figure 14. It becomes evident that most avoided collisions are against payloads, which explains the lowered number of objects on orbit during the collision avoidance scenarios, followed by those against small satellites. For other types of collision partners, the reduction in collisions is not as clear, especially against rocket bodies. Here the assumption is that collisions with rocket bodies occur mostly after the active lifetime of small satellites. Therefore, although the median number of collisions cannot significantly be reduced in scenarios with collisions avoidance for small satellites, it leads to a decreasing number of collisions involving small satellites themselves as well as collisions against other payloads. Thus, it can be used to support mitigating the overall impact of small satellites.

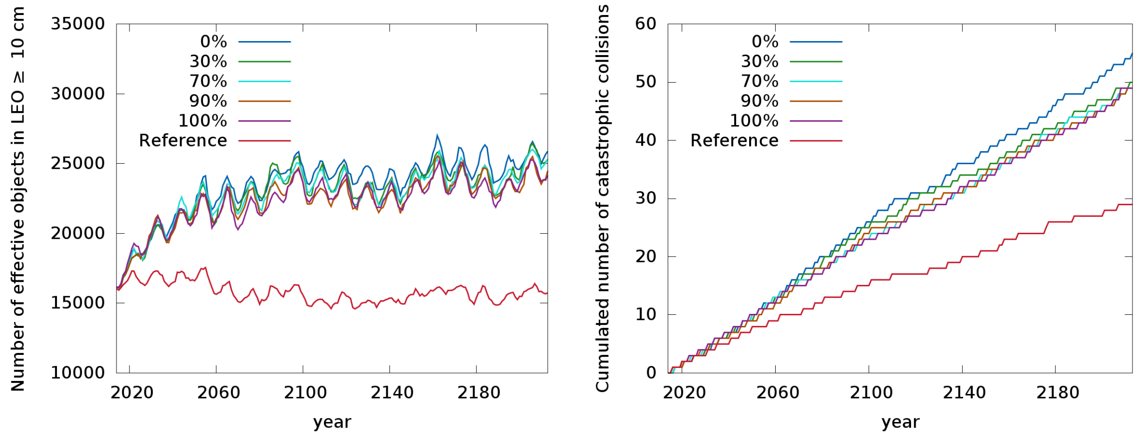

Figure 13. Results of the scenarios assuming different collision avoidance success rates for small satellites, alongside the assumption that 30% of all small satellites perform an end-of-life manoeuvre to an eccentric 25-year disposal orbit. The success rate is used as 'per satellite' for those that do not comply naturally.. Note that the quantiles have been omitted for clarity. ***Left:*** *Effective number of objects in LEO over time,* ***right:*** *Cumulated number of catastrophic collisions. Computed from 50 Monte-Carlo runs.*

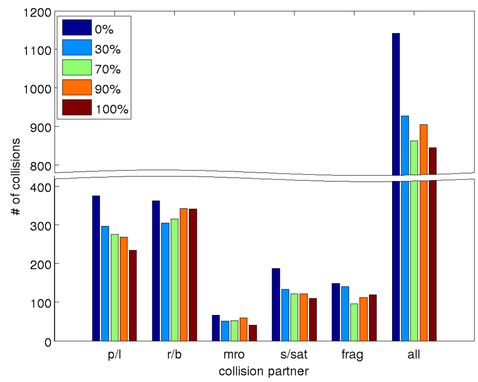

Figure 14. Collision partners (payloads (p/l), rocket bodies (r/b), mission related objects (MRO), small satellites (s/sat) and fragments (frag)) for catastrophic collisions involving small satellites in all Monte-Carlo runs in the collision avoidance scenarios. Numbers stated in the figure refer to the collision avoidance success rates.

6. CONCLUSION AND OUTLOOK

A large number of long-term simulations including different scenarios of future small satellite traffic have been performed. From these simulations, several conclusions can be drawn:

- In all performed simulations, small satellites had a significant impact on the long-term space debris environment. In fact, no single Monte-Carlo run was performed that resembled a Monte-Carlo run from the reference scenario in terms of the number of objects on orbit or number of catastrophic collisions.
- It was furthermore shown that the long-term evolution is highly sensitive to changes in small satellite numbers, characteristics and capabilities. Increased sizes or higher launch altitudes of small satellites compared to today's values will lead to an amplification of the overall impact.
- Performing post-mission disposal nevertheless helps mitigating the impact of small satellites. For this, focus should be set on performing end-of-life manoeuvres with as many objects as possible, followed by the selection of the remaining lifetime of the disposal orbit. Collision avoidance capabilities help to reduce the risk for both active small satellites themselves as well as other payloads, but is only of secondary importance.
- Therefore, it is important that small satellites adhere to available guidelines, standards, and regulations.

Although these conclusions can be drawn from the simulations results as presented, more work needs to be performed to fully understand the impact of small satellites on the long-term evolution of the space debris environment. This includes on the one hand understanding better the variations presented in this paper, especially the impact of collision avoidance and the release of small satellites as swarms. On the other hand, important influences were not studied in the frame of this paper, such as possible changes in the behaviour of the background population. Furthermore, the analysis presented here was based on describing the direct simulation outputs. Follow-up analyses need to go one step further and investigate the importance of the different variations to be able to provide guidelines, on how to most effectively reduce the impact of small satellites, without restricting the emerging small satellites market.

Last, for all shown results it should be kept in mind that the simulations were performed using 50 Monte-Carlo runs only. Although the statistical significance when comparing the runs was tested many more runs would be needed, especially in cases which showed only slight differences.

7. ACKNOWLEDGEMENTS

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A. RANKSUM TESTS

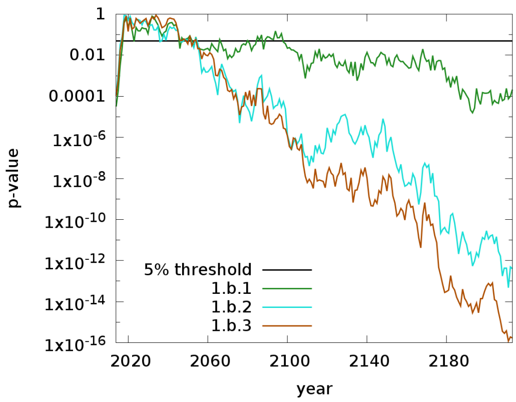

Figure 15. Results of the rank sum test when comparing scenarios 1.b.x against the small satellite baseline scenario.

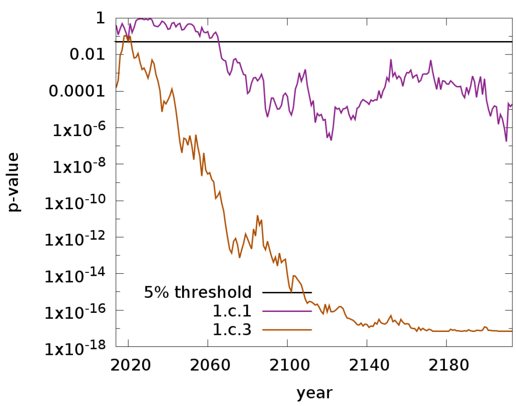

Figure 16. Results of the rank sum test when comparing scenarios 1.c.x against the small satellite baseline scenario.

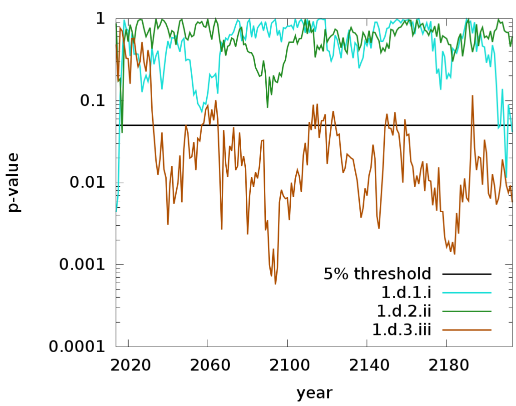

Figure 17. Results of the rank sum test when comparing scenarios 1.d.x against the small satellite baseline scenario.

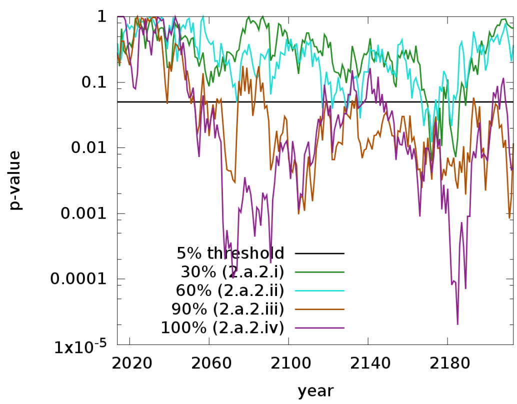

Figure 18. Results of the rank sum test when comparing scenarios 2.a.2.x against the scenario 2.a.1.i (30% of all small satellites perform post mission disposal to an eccentric 25 year orbit.