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Aims and Scope

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SENSITIVITY ANALYSIS OF THE LONG-TERM EVOLUTION OF THE SPACE DEBRIS POPULATION IN LEO

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ABSTRACT
Since the launch of Sputnik-1 in 1957, the amount of space debris in Earth’s orbit has steadily increased. Historically, the primary sources of space debris in Earth’s orbit were (a) accidental and intentional break-ups which produce long-lasting debris and (b) debris released intentionally during the operation of launch vehicle orbital stages and spacecraft. In the future, fragments generated by collisions are expected to be a significant source of space debris.

As described by Kessler and Cour-Palais in their 1978 seminal paper “Collision Frequency of Artificial Satellites: The Creation of a Debris Belt”, the amount of space debris in Earth’s orbit may reach a tipping point in which the future space debris population may be dominated by fragments produced by the mutual collisions between the objects already present in the population. This cascade effect is commonly known as “the Kessler Syndrome”.

In recent years, much of the work done to model the long-term evolution of the space debris population aimed to understand the effectiveness of mitigation measures in constraining the growth of the space debris population. Such work have highlighted the potential ineffectiveness of the mitigation measures alone to stabilise the growth of the space debris population in Low Earth Orbit (LEO), and has therefore suggested the need to investigate more aggressive measures, such as the active removal of space debris from the environment, that may be used to reach such stabilisation.

The objective of the work that we present in this paper is to assess the effect of four sources of uncertainties (i.e. solar and geomagnetic activity, break-up model, collision prediction algorithm and post mission disposal compliance rate) on the long term evolution of the space debris population. This study has been done via sensitivity analysis, where uncertainties affecting the considered uncertainty sources have been defined. Through comparative analysis of each of the studied scenarios, in terms of population growth and long-term dynamics of the effective number of LEO objects, we want to characterize and quantify the effect of such uncertainty sources on the long term projections of the space debris population performed with up to date evolutionary models. This characterization and quantification is a first necessary step to be able to study the robustness of mitigation and remediation measures to uncertainties affecting the long term evolution of the space debris population.

1. INTRODUCTION
Since the launch of Sputnik-1 in 1957, human activities in space have led to the production and release of thousands of objects of various sizes, from particles smaller than 1 mm to non-operational spacecraft measuring several square metres. While in the past the primary sources of space debris were accidental and intentional break-ups as well as the intentional release of debris, the growing amount of space debris makes the risk of collision among space objects increasingly likely.

The fear that future environment growth may be dominated by collisions, rather than by launches and explosions, was already expressed decades ago. In order to avoid such a situation, several responses outlining mitigation procedures, including the Inter-Agency Space Debris Coordination Committee (IADC) Space Debris Mitigation Guidelines, the United Nations Committee on the Peaceful Uses of Outer Space Mitigation Guidelines, the International Organization for Standardization Space Debris Mitigation Standards, and a multitude of other national and international documents have been and continue to be developed, to limit the expected growth of the debris population.

Whilst mid-term and long-term projections of the Earth’s satellite population rely on our ability to predict and model a series of exogenous (e.g. future solar activity, the nature and magnitude of space traffic activities, etc.) and endogenous (e.g. the number of fragments generated after each collision, number of future collisions among orbiting objects, etc.) variables, many of which are completely out of the control of the modeller. In the last decade, space debris modelling has suggested that the long-term Low Earth Orbit (LEO) debris population may continue to grow, even with the widespread adoption of mitigation measures. Since the publication of the Inter-Agency Space Debris Coordination Committee (IADC) study on the Stability of the future Low Earth Orbit
(LEO) environment\(^5\), which suggested the need to investigate more aggressive measures to stabilize the environment in LEO, much work has been done on the study of how remediation techniques, as Active Debris Removal (ADR), could be used to reach such stabilisation.

In the study presented in this paper, we analyse the effect that four uncertainty sources have on the long term projections performed with up to date evolutionary models. Such analysis is the first necessary step to identify the sources of uncertainties to which the environment is the most sensitive, and to characterize the many possible futures of the space debris population. In a further work these variables will be used to study the robustness of mitigation and remediation measures in a wide range of possible futures.

2. REVIEW OF SOURCES OF UNCERTAINTY

As clearly presented in Ref. 6 and 7, mid-term and long-term projections of the Earth’s satellite population are affected by several important sources of uncertainty which are, most of the time, completely outside the control of modellers. As long-term evolutionary models are not aimed to predict what the future will be but to study the relative effect that different assumptions (e.g. launch traffic, explosion rate, …) will have on the long term evolution of the space debris population, the uncertainties affecting such long term evolution may be taken into account in order to widen the envelope of the many possible futures of the space debris population on which this relative effect can be studied.

One way to take into account sources of uncertainty in the long-term projections of the Earth’s satellite population is via sensitivity analysis. Sensitivity analysis aims to characterise the sources of uncertainty, together with their domain of variation and, if possible, the statistical nature of such variations, in order to study the effect of the considered sources of uncertainty on the output. Through such analysis we are able to identify critical parameters that have a major effect on the model’s result, discard the uncertainty of parameters that have a minor effect on the output and study the reliability and robustness of the conclusions that may be made with the model.

In our study, four major sources of uncertainty have been considered and analysed.

- solar activity
- break-up model (number of fragments)
- collision prediction algorithm
- compliance level with the 25 years rule

This list is far from being exhaustive, and many more sources of uncertainty exist, such as, for example\(^5\):

- break-up model (area, mass and velocity distribution of fragments)
- atmospheric density models
- energy dissipation in a given collision
- energy to mass ratio leading to a catastrophic fragmentation
- initial debris environment considered for the simulation
- future launch traffic
- quality of mitigation measures adopted and levels of compliance
- target Selection and Ranking for ADR
- Future deliberate or accidental fragmentations
- evolution of earth’s upper atmosphere
- space technology evolution

3. METHOD

A future projection from 1 May 2009 to 1 May 2200 for the Low Earth Orbit (LEO) debris population \(\geq 10\) cm has been performed using MEDEE, our model presented below. The common assumptions made within the study, and shared by all the studied scenarios that are presented in table 2 and described in section 3.2, are given in table 1.

Together with these common assumptions, a series of “BASE” scenarios have been defined in order to perform the sensitivity analysis. The study of the sensitivity of the model to one given parameter is carried out through the analysis of the deviation of the results on each “BASE” scenario when one and only one parameter is varied (i.e. the studied variable). In doing so, the individual effect of each studied variable on the mid-term and long-term projections of the Earth’s satellite population can be properly assessed.
Table 1: Summary of common assumptions considered within the study

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Population</td>
<td>ESA’s MASTER-2009 reference population ≥ 10 cm residing in or passing through the LEO regime (altitude ≤ 2000 Km) on 1 May ’09</td>
</tr>
<tr>
<td>Launch Traffic</td>
<td>The observed 2001 – 2009 launch traffic cycle is repeated throughout the simulation</td>
</tr>
<tr>
<td>Satellite properties</td>
<td>Operational lifetime of satellites is set to 8 years. No station-keeping or collision avoidance manoeuvres are considered.</td>
</tr>
<tr>
<td>Post-Mission Disposal</td>
<td>Satellites and Rocket bodies (R/B) were moved to orbits that decay within 25 years.</td>
</tr>
<tr>
<td>MC Simulations</td>
<td>Each studied scenario, if not explicitly stated otherwise, is comprised of 40 future projections.</td>
</tr>
<tr>
<td>In-Orbit Explosions</td>
<td>No future explosions were assumed</td>
</tr>
</tbody>
</table>

Table 2: Summary of “BASE” scenarios considered within the study as a function of the analysed variable

<table>
<thead>
<tr>
<th>Studied Variable</th>
<th>“BASE” Scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Activity</td>
<td>Common assumptions + 10 km side cube + 90% PMD + standard implementation of the NASA BU Model</td>
</tr>
<tr>
<td>NASA Break Up (BU) Model</td>
<td>Common assumptions + 10 km side cube + 90% PMD + Mean F10.7 Flux and Ap=15</td>
</tr>
<tr>
<td>Collision Prediction</td>
<td>Common assumptions + 90% PMD + standard implementation of the NASA BU Model + Mean F10.7 Flux and Ap=15</td>
</tr>
<tr>
<td>Algorithm</td>
<td>Common assumptions + 10 km side cube + standard implementation of the NASA BU Model + Mean F10.7 Flux and Ap=15</td>
</tr>
<tr>
<td>Post-Mission Disposal</td>
<td>Common assumptions + 10 km side cube + standard implementation of the NASA BU Model + Mean F10.7 Flux and Ap=15</td>
</tr>
</tbody>
</table>

3.1 The MEDEE Model

CNES’s tool to Model the Evolution of Debris in the Earth’s Environment (MEDEE)\(^8\), is one of the models that has contributed since 2013 to IADC studies on space debris’ long-term evolution. The development of MEDEE began in mid-2012, with the objective of improving CNES’s knowledge on the mechanisms driving the mid-term and long-term evolution of the Earth’s satellite population.

MEDEE\(^8\) is a three-dimensional, semi-deterministic model, allowing the user to examine the long-term effects of different future traffic profiles, debris mitigation measures and solar activity projections.

MEDEE uses an initial space object population as input and forecasts the evolution of all objects larger than a given threshold, as a function of a given set of assumptions. Until now, mid-term and long-term projections made with MEDEE have only considered objects ≥ 10 cm. The orbital evolution of the population is described by a fast semi-analytical propagator, developed under the French Space Act and known as STELA (Semi-analytic Tool for End of Life Analysis)\(^9\). The force model includes the orbital perturbations due to Earth’s gravity harmonics J2, J3, J4, J2\(^2\), J5, J6, J7 and some dedicated tesseral terms for resonant orbits, the luni-solar gravitational perturbations, the solar radiation pressure including Earth’s shadow and atmospheric drag. The implementation of the semi-analytical orbital propagator on MEDEE has been carried out in order to guarantee relative error of less than 5% when compared with a fully numerical orbital propagator implementing our best available dynamical model.

![Fig. 1: Relative error map between STELA and the fully numerical orbital propagator, as a function of the inclination of the orbit to propagate and the integration time step.](image)

As shown in Fig. 1, and in order to guarantee relative error of less than 5% when compared to a fully numerical orbital propagator, we adapt the integration step size as a function of the orbit to be propagated.
Collisions are predicted using the “Cube” approach\textsuperscript{10}. The generation of fragments when explosions are considered and/or collisions detected is performed using the NASA standard break-up model\textsuperscript{11}.

### 3.2 Considered Scenarios

A total of 14 different scenarios have been defined in order to study, via a sensitivity analysis, the effect of sources of uncertainty on the mid-term and long-term projections of the Earth’s satellite population. The variables that have been considered for the study, together with the considered domain of variation are presented hereafter.

- **NASA break-up Model\textsuperscript{11}:** According to the NASA standard break-up model, the number of fragments of a given size and larger (\(N(Lc)\)), in the case of a collision, is given by the following power law, where \(M\) is the mass parameter that is defined differently in the case of a catastrophic and of a non-catastrophic collision, and \(Lc\) the characteristic length of the fragments.

\[
N(Lc) = 0.1M^{0.75}L_c^{-1.71}
\]  

[1]

Most of the previous sensitivity analyses performed on the NASA break-up model concentrate on the Energy to Mass Ratio (EMR) parameter, which is used as a threshold to differentiate between a catastrophic and a non-catastrophic collision (EMR < 40 J/gr). Such analysis shows that this threshold has little influence when dealing with ≥ 10 cm populations\textsuperscript{12} as the mean EMR of considered collisions is several orders of magnitude higher than the 40 J/gr threshold. In our study, we analyse the sensitivity of the model to an over/under generation of the number of fragments after each fragmentation.

\[
N(Lc) = K \times (0.1M^{0.75}L_c^{-1.71})
\]  

[2]

The factor \(K\) in Eq. 2 represents an over/under generation factor of the number of fragments for all the regimes of sizes.

- \(K = 1.2\) and 1.3 corresponding to a 20% and 30% over estimation factor
- \(K = 0.8\) and 0.7 corresponding to a 20% and 30% under estimation factor

- **Collision Prediction Algorithm:** Collisions are predicted using a fast pairwise collision prediction algorithm, based on the “Cube” approach\textsuperscript{10}. The implementation of the “Cube” algorithm in MEDEE consists of the following steps:

  o At the beginning of each time-step (\(t_i\)) we propagate the full population, using the STELA\textsuperscript{9} propagator, up to \(t_i + \Delta t\) days. Where \(\Delta t\) is typically 5 days.
  o At \(t_i + \Delta t\) days we randomise the mean anomaly of all the objects on the population, and we consider that each object is at one and only one position on its orbit.
  o The space environment is discretised in cubes of size \(L\) (10 km by default), and objects falling on the same cells of the space are detected.
  o Probability of collision between the objects sharing the same cells is computed in a pairwise manner accordingly to formalism described in Ref. 10.

In this study, we analyse the robustness of the algorithm by modifying the size of the cube. The stability of the algorithm can be assessed if the dependency of the results to the size of the cube is low.

- **Post-Mission Disposal:** Sensitivity to post-mission disposal is also analysed by varying the percentage of satellites and rocket bodies that will be compliant with the 25 years rule, thanks to a de/re-orbitation manoeuvre. Thus, the percentage of Post-Mission Disposal (PMD) compliance considered for the study concerns only the satellites and rocket bodies that will have natural orbital lifetimes greater than 25 years.

  o 30% PMD compliance
  o 60% PMD compliance
  o 90% PMD compliance

- **Solar Activity:** The following solar activities (F10.7 and Ap proxies) have been considered for the simulations:

  o **Deterministic Solar Flux Projections:** Equivalent to consider that the future solar activity will be identical to one of the studied scenarios. The three studied scenarios have variations in amplitude and in phase, as seen in Fig. 2. Concerning the geomagnetic indexes, and given their relatively important short term variations (cf. Fig. 3), in the frame of this study it has been decided to consider two different values for the Ap proxies

    - Ap = 15, which is equivalent to the mean observed value of Ap since 1957
    - Ap = 8, which is equivalent to the median observed value of Ap since 1957
The list of exogenous and endogenous variables considered in our study, and described above, is far from being exhaustive, and a more complete list of variables that may be considered for future sensitivity analysis is given in Section 2. and in Ref. 6.

Fig. 2: Deterministic Solar Flux Projections considered for some of the studied scenarios. The F10.7 proxy is given in sfu [10^{-22}WM^{-2}Hz^{-1}] units.

Fig. 3: Daily AP variation of geomagnetic-Index during the 23rd Solar Cycle.

4. RESULTS AND DISCUSSION

4.1 Validating the Number of Monte Carlo Projections

To determine the number of projections needed to establish a reliable picture of the trends and standard deviations of the results, a sub-sampling technique was applied. A detailed description of this technique, applied also to the long term evolution of the space debris population, can be found on Ref. 13.

In this analysis, the evolution of the first and second moments of the distribution as a function of the number of projections is compared with the mean and standard deviation of the population for 100 projections. Figs. 4 and 5 illustrate this process for the 90% PMD scenario. The analysis here focuses on the 10 cm and larger LEO population at the end of the projection period.

From the analysis of Figs. 4 and 5, we can conclude that a total of 10 MC runs allows a mean within 10% of the 100 MC mean to be achieved approximately 9 out of 10 times, and a standard deviation within 20% of the 100 MC standard deviation approximately 7 out of 10 times. In order to improve the representativeness of the standard deviation, we have adopted 40 MC simulations for our study. Such number of simulations will allow a mean within 5% of the 100 MC mean to be achieved approximately 9 out of 10 times, and a standard deviation within 20% of the 100 MC standard deviation approximately 9 out of 10 times and within 10% of the MC standard deviation approximately 8 out of 10 times.

Fig. 4: Sub-sampled means from the pool of 100 MC projections of the 10 cm and larger LEO debris population in 2200. Each point represents the mean from a random, no duplication selection of N samples. A total of 100 selections is repeated for each N. The 5% and 10% boundaries of the 100 MC mean are shown as the dashed green and thin red lines respectively.

Fig. 5: Sub-sampled standard deviations from the pool of 100 MC projections of the 10 cm and larger LEO debris population in 2200. Each point represents the standard deviation from a random, no duplication selection of N samples. A total of 100 selections is repeated for each N. The 10% and 20% boundaries of the 100 MC mean are shown as the dashed green and thin lines red respectively.
We believe that it is important to highlight the fact that the sub-sampling technique used to define the minimum number of projections to reach a representative first and second moment values, does not allow to determine either the nature of the probability density function describing the number of objects on the environment at a given time or the evolution of this probability density function with time. Consequently, the mean and standard deviation values given on this paper must not be used to compute the likelihood that the space debris population reaches a given value at a given time, assuming for example a Gaussian probability density function, but rather to relatively compare the effect of each uncertainty source on the long term evolution of the space debris population.

4.2 Sensitivity Analysis

As described in paragraph 3.2, the sensitivity of the MEDEE model has been studied regarding some of the main sources of uncertainty, such as future solar activity, the break-up model, etc.

For the sake of clarity, only some of the long-term projections of the ≥ 10 cm population scenarios, together with their 1-sigma dispersions, will be presented in a graphical manner. If more than 3 scenarios exist, figures will only present the reference scenario as well as the two extreme scenarios.

Sensitivity concerning all the scenarios, as far as the LEO effective number of objects ≥ 10 cm is concerned, will be presented in tables. The variation of the number and frequency of catastrophic and non-catastrophic collisions will not be presented in order to not overload this article with figures or tables.

4.2.1 Sensitivity to the Break-up Model

Several parameters can be considered for a sensitivity analysis concerning the NASA BU model. They include the collision energetic threshold for catastrophic break-up, area, mass and velocity distributions of the generated fragments.

As described in paragraph 3.2, in our sensitivity analysis we have studied the effect of varying the number of fragments generated in a collision, on the long-term projection of the Earth’s ≥ 10 cm satellite population.

Figure 6 presents the reference scenario (K=1), when the number of generated fragments is as described by the NASA BU Model (cf. Eq. 2), and the two extreme scenarios (i.e. those presenting the largest differences when compared with the reference scenario) corresponding to K=1.2 and K=0.7.

Table 3 presents the percentage of variation of the effective number of objects ≥ 10 cm in LEO in 2200, with respect to the initial population, together with their 1-σ dispersion for all the considered K.

<table>
<thead>
<tr>
<th>K</th>
<th>% of Variation wrt initial population after 200 years [mean +/- 1 σ Dispersion]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.3</td>
<td>25 % +/- 26%</td>
</tr>
<tr>
<td>1.2</td>
<td>29% +/- 26%</td>
</tr>
<tr>
<td>1.0</td>
<td>10% +/- 20%</td>
</tr>
<tr>
<td>0.8</td>
<td>0.7% +/- 17%</td>
</tr>
<tr>
<td>0.7</td>
<td>-8% +/- 16%</td>
</tr>
</tbody>
</table>

From Table 3, it can be seen that the K factor introduces an important variability, which is in the order of 20% with respect to the nominal K = 1 scenario.

4.2.2 Sensitivity to the Collision Prediction Algorithm

For the reader’s convenience, Fig. 7 schematically presents the Cartesian space discretisation performed in MEDEE, taking as the only variable the size of the cube’s “L”.

Fig. 6: MEDEE simulated LEO debris population (objects 10 cm and larger) as a function of K factor (cf. Eq. 2). The solid curves are the arithmetic means from 40 MC projections. The dotted curves represent the 1-σ standard deviation.
From Fig. 7 and considering the implementation within MEDEE of the formalisms presented in Ref. 10, it seems intuitive what the sensitivity of the model will be to the parameter $L$. This is, the smaller the size of the cubes, the higher the number of samples needed to have two objects within the same cube. Once two objects fall within the same “small” cube, the higher their spatial densities in the cube, with respect to a bigger cube, and therefore the higher their probability of collision.

The same reasoning can easily be done backwards, if we increase the size of the cubes. Nevertheless something that is not as intuitive as it may seem is the dependence of the number of collision risks with the size of the cube (cf. Fig. 9 and Fig. 10). This is, when the size of the cube decreases we will have less probability to have a close approach (i.e. two objects falling within the same cube) but once that a close approach is detected the probability that the collision really happens will be high (cf. Fig. 11 and Fig. 12).

On the contrary, when the size of the cube increases, each close approach will have a lower probability to really become a collision (cf. Fig. 11 and Fig. 12), but we will detect a greater number of close approaches than in the previous case (cf. Fig. 9 and Fig. 10).

This complementary dependence of the number of close approaches and of the probability of collision on the cube’s size, is why the percentage of variation with respect to the initial population for the 10 Km cube size and for the 50 km cube size are on average comparable (cf. Fig. 8).

Table 4 presents the percentage of variation of the effective number of objects $\geq 10$ cm in LEO in 2200, with respect to the initial population, together with their 1-σ dispersion, for all the considered sizes $L$.

<table>
<thead>
<tr>
<th>% of Variation wrt initial population after 200 years</th>
<th>mean +/- 1 σ Dispersion</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L=5$ km</td>
<td>-13% +/- 12%</td>
</tr>
<tr>
<td>$L=10$ km</td>
<td>2% +/- 16%</td>
</tr>
<tr>
<td>$L=50$ km</td>
<td>-5.3% +/- 14%</td>
</tr>
</tbody>
</table>

An additional study has been performed to better understand the complementary dependence of the number of close approaches and of the collision probability on the cube’s size. On this analysis we have examined the collisional process on the most dense regions of the space (i.e. between 700 and 900 km), as a function of both the cube’s size ($1, 5, 10$ and $50$ km) and the discretisation time-step ($1/2, 1$ and $5$ days) during 200 years and with the dynamical model introduced in Section 3.1. As on this study we only focus on the analysis of the collisional process among the objects of a given population, the generation of new debris has not been modelled.

The first conclusion of this analysis concerns the number of times where two objects are going to be collocated on the same cube, which corresponds to the number of close approaches between orbiting objects. This number is directly proportional to the cube’s size and inversely
proportional to the discretization time-step. This proportion, as can be seen on Fig. 9 and 10, can be modelled by a power law.

![Fig. 9: Mean Number of Collocated pairs, for the 700 – 900 km population (objects 10 cm and larger), as a function of the Cube’s size and for different discretization time-steps.](image1)

![Fig. 10: Mean Number of Collocated pairs, for the 700 – 900 km population (objects 10 cm and larger), as a function of the discretization time-step and for different Cube’s size.](image2)

Figure 11 and 12 presents the mean probability of collision (i.e. the mean number of collocated pairs divided by the mean number of collisions) as a function of the discretization time-step and of the cube’s size. From these figures we observe that contrary to the number of collocated pairs, the probability of collision will be directly proportional to the discretization time-step and inversely proportional to the cube’s size. This proportion may be understood as the weight given by our collision prediction algorithm to a given close approach, either via the spatial density (i.e. cube’s size) or via the integration variable (i.e. time). The direct dependence of the probability of collision with the time-step is not surprising, as the collision probability algorithm depends directly on the time-step. On Fig. 11 and 12 it is important to highlight that the 1 km – 5 days scenario did not allow to identify any real collision and therefore the mean probability of collision for this scenario could not be computed. This very important result which is justified by the very low number of close approaches detected among the objects of the population (cf. Fig. 9 and Fig. 10), shows very well the coupling that exists between the cube size and the sampling period (i.e. time-step) and the effect that this may have on the simulation outputs.

![Fig. 11: Mean Probability of Collision of Collocated pairs, for the 700 – 900 km population (objects 10 cm and larger), as a function of the Cube’s size and for different discretization time-steps.](image3)

![Fig. 12: Mean Probability of Collision of Collocated pairs, for the 700 – 900 km population (objects 10 cm and larger), as a function of the discretization time-step and for different Cube’s size. (The 1 km – 5 days scenario has been removed from the graph as not statistically representative)](image4)

4.2.3 Sensitivity to Future Solar Activity

Solar and geomagnetic activity are of key importance when modelling the long-term evolution of the Earth’s satellite population in Low Earth Orbit (LEO), as satellites’ lifetimes in orbit, and therefore their probability to collide with other objects, will be highly dependent on these solar activity proxies. As can be observed from Fig. 13, and as could be a priori predicted, a variation in the solar activity proxies, either F10.7 and/or Ap (cf. Tab 5), will induce an equivalent variation in the number of objects of the population. What is interesting to remark is that the dynamic of the population remains considerably

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similar for the Low, Medium and High solar activity cases. This is probably due to the fact that these three scenarios share a very similar solar activity pattern.

Fig. 13: MEDEE simulated LEO debris population (objects 10 cm and larger) as a function of solar activity proxies. The thick curves are the arithmetic means from 40 MC projections. The dotted curves represent the 1-σ standard deviation.

Table 5: Percentage of Variation of the Effective number of LEO objects > 10 cm in 2200, with respect to the initial population, as a function of solar activity projections

<table>
<thead>
<tr>
<th>% of Variation w.r.t. Initial population after 200 years [mean +/- 1 σ Dispersion]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low F10.7, Ap=15</td>
</tr>
<tr>
<td>Medium F10.7, Ap=15</td>
</tr>
<tr>
<td>Medium F10.7, Ap=8</td>
</tr>
<tr>
<td>High F10.7, Ap=15</td>
</tr>
</tbody>
</table>

As presented in Tab. 5, not only the solar flux (i.e. F10.7) but also the geomagnetic indexes (i.e. Ap), have an important effect on the long term evolution of the Earth’s satellite population. In contrast to the solar flux, the geomagnetic indexes proxies have not a clear periodic evolution (cf. Fig. 3) and making long term predictions on these proxies becomes a very complicated task. One way to take into account realistic evolutions of geomagnetic indexes could be to build the future solar activity projections from the past observed solar cycles.

4.2.4 Sensitivity to Post-Mission Disposal Compliance

All the scenarios presented previously, and as described in Tab. 2, consider a Post-Mission Disposal (PMD) success rate of 90%. This means that 9 out of 10 objects not re-entering the Earth’s atmosphere naturally in less than 25 years are placed into disposal orbits with a residual lifetime of 25 years. This hypothesis concerning the PMD compliance rate, even if it is not representative of the situation today, has been chosen to be in coherence with the study on the Stability of the future Low Earth Orbit (LEO) environment, released by the Inter-Agency Space Debris Coordination Committee (IADC). Today, based on early data analysis, it is estimated than around 10% of the spacecraft and rocket bodies reaching their end of life between 600 – 1400 km performed a re/de-orbitation manoeuvre.

Fig. 14: MEDEE simulated LEO debris population (objects 10 cm and larger) as a function of Post-Mission Disposal (PMD) compliance Rate. The thick curves are the arithmetic means from 40 MC projections. The dotted curves represent the 1-σ standard deviation.

Table 6: Percentage of Variation of the Effective number of LEO objects > 10cm in 2200, with respect to the initial population, as a function of the Post-Mission Disposal (PMD) compliance rate

<table>
<thead>
<tr>
<th>% of Variation w.r.t. Initial population after 200 years [mean +/- 1 σ Dispersion]</th>
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<tbody>
<tr>
<td>30% PMD</td>
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<tr>
<td>60% PMD</td>
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<tr>
<td>90% PMD</td>
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</table>
5. CONCLUSION AND FUTURE WORK

As presented in previous chapters, the models used to study the long term evolution of the space debris population are conditioned to a great number of exogenous and endogenous variables which, in most of the cases, are partially or totally out of the control of modellers. Consequently, the predictions performed with such models, in particular beyond a few decades, are affected by a considerable uncertainty. Such uncertainty, which is unavoidable given the uncertainty of each of the physical and nonphysical variables taken into account to model the long term evolution of the space debris population, will just contribute to widen the envelope of the possible futures of the space debris environment. Furthermore, being aware of such uncertainty is of particular importance as long term evolutionary models are not conceived to predict the future, but to study the relative effect of different assumptions on the long term evolution of the space debris population.

With that in mind, the objective of this paper was to study the effect that two endogenous (i.e. break-up model and collision probability algorithm parameters) and two exogenous variables (i.e. solar and geomagnetic activity and rate of compliance with post mission disposal) had on the long term evolution of the space debris population.

Concerning the collision probability algorithm, besides the analysis of the influence of its parameters on the long term evolution of the space debris population, this study has allowed us to understand the complementary dependence of the number of close approaches and of the collision probability on the cube’s size.

Concerning the other three studied variables; we can conclude that the solar activity and the break-up model parameters are two major sources of uncertainties affecting the long term evolution of the space debris population. Nevertheless, the long term evolution of the space debris population shows the highest sensitivity, as far as the four studied variables are concerned, to the rate of compliance with post-mission disposal.

Given the results of this study, future work will be focused on the analysis of the robustness of mitigation (i.e. post mission disposal compliance rate) and remediation (i.e. active debris removal) to uncertainties coming from the break-up model and from the solar and geomagnetic activity.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

5. Inter-Agency Space Debris Coordination Committee, Stability of the future LEO environment, IADC-12.08.


Progress in space safety lies in the acceptance of safety design and engineering as an integral part of the design and implementation process for new space systems. Safety must be seen as the principle design driver of utmost importance from the outset of the design process, which is only achieved through a culture change that moves all stakeholders toward front-end loaded safety concepts. Superb quality information for engineers, programme managers, suppliers and aerospace technologists.

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