DELTA (DEBRIS ENVIRONMENT LONG-TERM ANALYSIS)

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ABSTRACT

In this paper, we present the ESA Debris Environment Long Term Analysis (DELTA) tool, used to analyse the long term propagation and evolution of the future debris environment. DELTA is one of the models that contribute to the IADC studies on long term evolution, which have already been used to derive the mitigation guidelines and have also underlined the need for Active Debris Removal (ADR). DELTA is a three-dimensional, semi-deterministic model, which allows a user to investigate the evolution of the space debris environment and the associated mission collision risks in the low, medium and geosynchronous Earth orbit regions over user defined timespans. DELTA is able to examine the long-term effects of different future traffic profiles and debris mitigation measures, such as passivation and disposal at end-of-life, and also to take into account remediation measures, with the possibility to perform active debris removal in a variety of scenarios with different criteria.

DELTA uses an initial space object population as input and forecasts the evolution of all objects larger than a user-defined size. The population is described by representative objects, evolved with a fast analytical orbit propagator which takes into account the main perturbations. The initial population is usually extracted from ESA's MASTER-2009 (Meteoroid and Space Debris Terrestrial Environment Reference) model at a given epoch, and can consider objects down to 1 mm in size. DELTA uses a set of detailed future traffic models for launch, explosion and solid rocket motor firing activity. They are each based on the historical activity of the preceding years. The collision event prediction is done by using a target centred approach, developed to stochastically predict impacts between all objects within the DELTA population. The fragmentation, or break-up, model used is based on the EVOLVE 4.0 (NASA) break-up model.

In this paper, we show in detail the architecture of DELTA. Furthermore, we explain its singular way of computing the probability of collision, which is flux-based, different to the majority of the long term evolution tools which use a CUBE method. Finally, some sample results of simulations performed with DELTA are shown in order to display the large range of possible scenarios and applications that such a tool has.

Index Terms— Space debris, long-term analysis, space environment

1. INTRODUCTION

The number of human made objects in space has undergone a steady increase since the beginning of spaceflight. The fear that the future environment growth might be dominated by collisions, rather than by launches and explosions, was expressed already decades ago. In response to this, the IADC (Inter-Agency Space Debris Coordination Committee) formulated a set of mitigation requirements that were issued in 2002 [1]. These requirements aimed at a limitation of the growth rate rather than at a reduction of the object population below the current numbers. These IADC guidelines recommend the spacecraft to perform collision avoidance maneuvers while operational, and to be passivated and perform a re-orbit or de-orbit maneuver in order to be outside from the LEO protected regions in less than 25 years at the end of their operational life.

Tools had to be developed in order to support the IADC studies, capable of analyzing the long term effects of the different measures and model the evolution of the environment. DELTA is the ESA tool contributing to the IADC studies. Nowadays, many different environment models exist from different space agencies (MEDEE for CNES, DAMAGE for UKSA, LUCA for DLR, LEGEND for NASA,…)[2,3,4], and the results of studies performed within the Inter-Agency Space Debris Coordination Committee (IADC) were used to derive their mitigation guidelines[1], and also to analyse the necessity of active debris removal[5] with the aim to avoid the long-term proliferation of space debris due to collisional cascading (Kessler syndrome)[6].

2. OVERVIEW OF DELTA (Debris Environment Long-Term Analysis)

DELTA is a sophisticated simulation and analysis tool used to investigate the space debris environment, developed by QinetiQ and modified by ESA to add the active debris removal capabilities. DELTA is a three-dimensional, semi-deterministic model, which in its entirety allows a user to investigate the evolution of the space debris environment and the associated mission collision risks in the low, medium and geosynchronous Earth orbit regions over the years. DELTA is able to examine the long-term effects of different future traffic profiles and debris mitigation measures, such as passivation and disposal at end-of-life.

DELTA is an integral part of the MASTER model, and necessarily shows a high degree of harmonization with the historical and reference population model POEM. In particular, POEM provides DELTA with an initial reference population and both tools use the same source models for fragmentations and solid rocket motor firing. In the context of the MASTER model, DELTA provides the underlying population data for the debris flux analysis at future epochs.

The current version of DELTA uses an initial space object population as input (extracted from ESA's MASTER-2009 (Meteoroid and Space Debris Terrestrial Environment Reference) model) and allows the forecasting of all major sources of space debris (launch and mission-related objects, explosion fragments, collision fragments, sodium potassium (NaK) droplets and solid rocket motor slag particles) larger than one millimeter in size. Within the model the population is described by representative objects, each object having a set of physical and orbital properties and a weighting factor specifying how many 'actual' objects are represented. Additionally, the individual representative objects have full classification information, including their origin, enabling the user of DELTA to examine population histories for any simulated satellite constellation, cloud of fragmentation debris or solid rocket motor firing. A fast, analytical orbit propagator is used to evolve the orbits of the representative object population with respect to geopotential, atmospheric drag luni-solar gravitational effects and solar radiation pressure. The future solar flux evolution has a strong effect on the results, as the atmospheric drag is the main factor for the natural decay of objects and is correlated to it. ESA has its own solar and geomagnetic activity prediction model (SOLMAG), which uses data from past solar cycles to predict the future ones. Different solar activity predictions can been used within DELTA.

The debris flux environment is represented at a given epoch with a user-defined three-dimensional spatial resolution (altitude, declination and right ascension) for the different debris source types and size thresholds.

The high fidelity of the DELTA model is ensured by using a set of detailed future traffic models for launch, explosion and solid rocket motor firing activity. These are each based on historical activity (the eight years preceding the simulation epoch) and represent the known orbital and mass distribution of these events. This is one of the main causes for uncertainties in the results, as varying the future traffic models has a big impact, and there is no certainty on the actual evolution of the space activity in the future.
The final source of space debris in DELTA are collision events. The collision event prediction is done by using a target centered approach, developed to stochastically predict impacts between all objects within the DELTA population [7, 8, 9]. The target and chaser orbits and mass information are fed into the fragmentation (break-up) model to generate the debris produced by each predicted catastrophic or non-catastrophic collision event. The fragmentation model used is based on the EVOLVE 4.0 (NASA) break-up model [10].

To complement the above sources of space debris, the DELTA model simulates the implementation of the following mitigation measures, with differences possible between the type of objects:

- Mission-related object limitation
- Explosion prevention (passivation)
- Solid rocket motor firing prevention
- Disposal of objects at the end of their useful lives
  - De-orbiting objects so that they re-enter the Earth's atmosphere within a limited number of years
  - Re-orbiting objects so that they remain outside the protected regions defined at LEO and GEO altitudes.

Active debris removal is also implemented and the selection of the objects to be removed can be based on different criteria (mass, area, probability of collision, type of object,…).

A graphical user interface (GUI) is provided to support the operation of the DELTA model (although it does not preclude directly editing the input fi required by the underlying code, if the user prefers). A snapshot of some of the GUI screens is shown in Figure 1 and Figure 2.

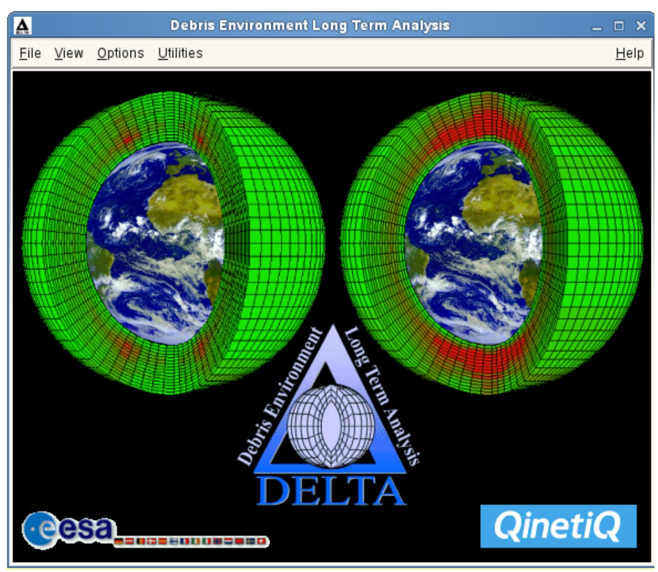

Figure 1. DELTA GUI main window

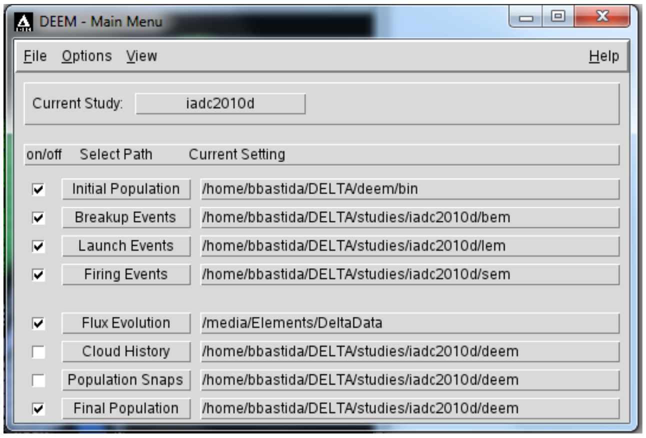

Figure 2. DELTA DEEM GUI main menu window

3. MODEL IMPLEMENTATION

The DELTA model has an integrated three-stage approach to the complex problem of debris environment modeling. It combines debris source event pre-processing with the evolution dynamics of the simulation of the future environment and the subsequent analysis of the results. This approach can be visualized in the top-level functional decomposition of DELTA, presented in Figure 3.

Three separate pre-processing programs - Launch Event Model (LEM), Break-up Event Model (BEM), Solid Rocket Motor Event Model (SEM) - have been designed to randomly predict future launch, explosion and SRM firing events, based upon the average event rates of pre-determined families (or classes) of objects. The future event data is stored, in chronological order, in event files for later access by the future environment simulation. Given the random prediction of these future events, and likewise the prediction of on-orbit collisions, the full DELTA simulation must be performed a number of times in a Monte Carlo approach, with each run having different random conditions. Accordingly, the LEM, BEM and SEM programs each produce multiple data files, one for each Monte Carlo run.

In addition to the generic launch traffic database, constellation deployments can be defined in the DELTA software. A constellation pre-processor, known as the Constellation Deployment Model (CDM), takes each constellation design in the database and produces data for individual satellites by assuming Walker constellations when deriving the orbital parameters. It also considers the objects associated with the deployment of each constellation, for example launch vehicle upper stages or mission related objects.

The simulation of the evolution of the debris environment is performed by the main DEEM (Debris Environment Evolution Model) program.

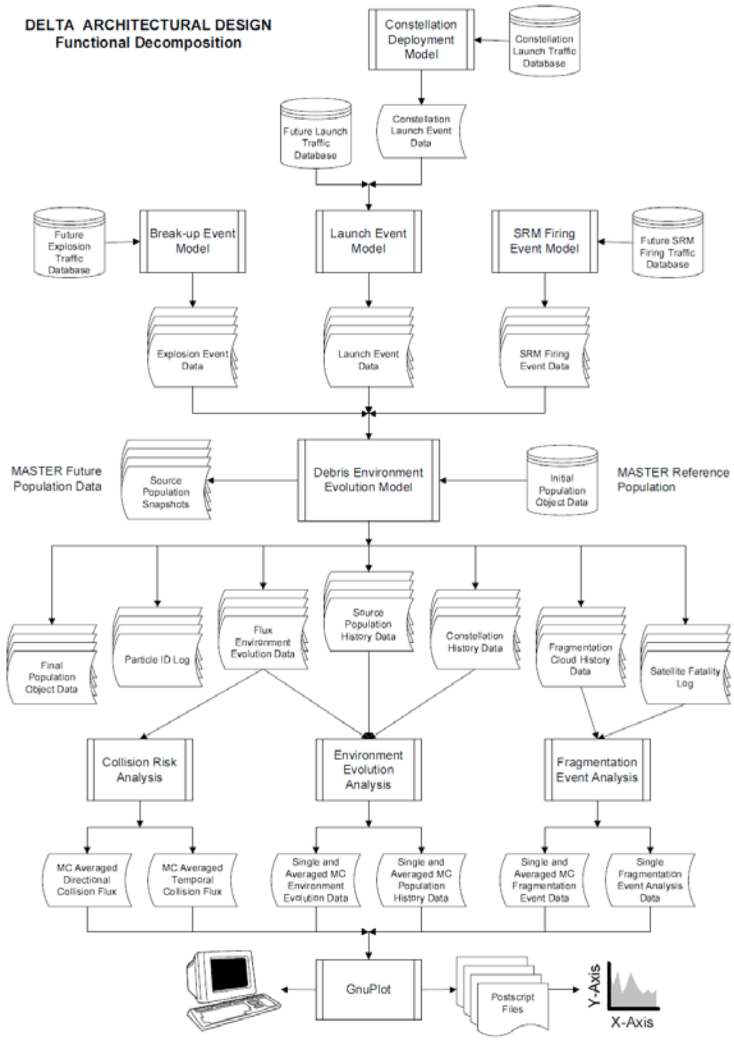

Figure 3. Top-level System Design of the DELTA Software

In addition to the data files containing the future events, the DEEM program also takes the reference population (extracted from MASTER) as input, to form the DELTA initial population. The main concept of the environment evolution engine is based upon a time increment method, where all source and sink mechanisms are processed in a cyclic manner over successive time steps. Thus at each epoch launch, explosion and SRM firing events are executed, possible collisions are assessed, the object population is propagated forward and any required debris mitigation is performed. During each Monte Carlo run the DEEM program generates a number of data files that can be accessed by the four post-processing programs known as Collision Risk Analysis (CRA), Environment Evolution Analysis (EEA), Fragmentation Event Analysis (FEA) and Collision Event Analysis (CEA). Using these programs the

DEEM output may be analyzed in a flexible manner. The results can also be plotted via the GnuPlot package.

The debris flux environment in the LEO, MEO and GEO regions is determined by DEEM at regular time intervals and output to the flux environment evolution data files. The full set of these files produced by a number of Monte Carlo runs, are used by the CRA program to produce statistically-averaged directional and temporal impact flux data to a user-specific target orbit. They are also input to the EEA program to produce environment evolution data, e.g. spatial density over altitude and time. The various population history data files written by DEEM, are also used by EEA to derive projections of the number of debris objects from a given source over time. These EEA results may be produced for a single Monte Carlo run or as an average across all of the Monte Carlo simulations.

The FEA program reads the Monte Carlo set of satellite fatality logs, which detail the explosions and collisions that were simulated during each run of DEEM. It uses these files to determine the distributions of explosions and collisions over time, altitude and inclination. As in EEA, these results can be produced for one run, or as an average across all Monte Carlo runs. Additionally, a single Monte Carlo fragmentation cloud history data file can be analyzed by FEA to examine the evolution of the number of fragments for any simulated fragmentation event. The CEA program analyses in more detail the collision events and characterizes both target and chaser involved on a collision, as well as producing statistics for the set of Monte Carlo runs.

The DEEM program also produces complete source population data at regular time intervals throughout the simulation, producing one file per source at each epoch. These files are then processed to generate the averaged future population input files for the MASTER model.

3.1. Collision prediction

The determination of debris flux for discrete spatial sectors of the Earth orbit regime is an essential component of the DELTA model. The techniques used provide snapshots of the debris flux environment, enabling the statistical prediction of collisions and the directional collision risk analysis of a single target mission. The debris flux environment is represented by three, three-dimensional control volumes — LEO, MEO and GEO — defined in terms of radius, declination and right ascension (Figure 4). The Klinkrad collision risk theory [7] is used extensively in DELTA to determine the debris flux environment [8]. To increase the fidelity of environment predictions made with the DELTA model, the debris flux is also categorized by object size and source type. This has the advantage of enabling feedback collisions, i.e. those collisions caused by a fragment from a previous collision, to be tracked by the model.

Collision event prediction is treated in DELTA using a target-centered approach, allowing the collision risk assessment of objects in the population relative to the size and source-dependent flux environment. The target objects encounter an orbit-integrated mean flux from debris of each size bin and source type. In each case the probability of collision is:

$$P_c = F_t \sqrt{\sigma_t^2 + \sigma_p^2} \Delta t$$

where F_t is the orbit-integrated mean flux to the target, σ_t is the cross-sectional area of the target, σ_p is a representative cross-sectional area of the population objects in the size bin and Δt is the time interval.

This probability is used in conjunction with a Poisson distribution to statistically predict the number of collision events for each target in the time interval. If a collision is predicted for the target object, the lethality of the encounter is assessed using the energy-to-mass ratio (EMR). If the EMR is greater than the lethality threshold of the target (typically 40 J/g) a catastrophic collision break-up is simulated using the fragmentation model, setting the anomaly of the break-up position as the point in the target's orbit where it encountered the peak flux. In case the EMR is below the threshold, a non-catastrophic collision break-up is simulated, where only a fraction of the mass of the target is released in the fragmentation. In any case, once a collision is predicted, a real chaser is selected from the list of objects based on the orbital properties and on the size and source type, and then the two objects are put through the fragmentation process (generating two clouds in case of a catastrophic collision).

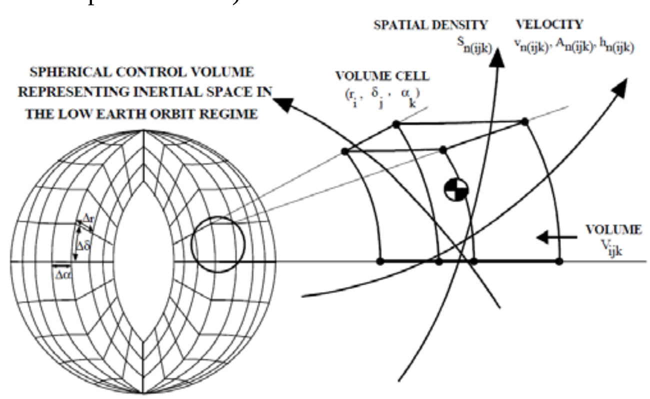

Figure 4. Spherical control volumes representing inertial space in DELTA

4. DELTA SIMULATION RESULTS

4.1. Influence of solar activity on long-term evolution[11]

When performing DELTA simulations, it has become evident that the solar flux had a major effect on the results obtained. In general, the results could vary quite dramatically, showing a regular or exponential increase of the space debris population in the environment implying a need for active debris removal. Or on the other side, not showing any increase at all, meaning that the current situation would remain stable. All depends on the selected scenario (which traffic launch is used, to which extent passivation or mitigation is taking place,…). Nevertheless, within the same scenario there could also occur big differences just using different solar fluxes.

In the following, we can observe these differences in two different scenarios of space debris environment evolution in low-Earth orbit (LEO), both using as background the population of objects bigger than 10cm at 1st January 2013. The first one (30% post-mission disposal (30%PMD)) is a scenario which considers that the new launches reproduce a similar traffic as for the last 8 years (between 2005 and 2013), that no new explosions occur in orbit (all objects are passivated after end of operations), and that there is a compliance of 30% with the post-mission disposal mitigation guideline (which requires all satellites in LEO to abandon the LEO region in less than 25 years after the end of the operational lifetime). This case is quite close to reality, as some studies[12] have observed that the current compliance to the guidelines is around 30% (including the natural compliances). Still, this scenario has a large uncertainty, which is driven by the launch traffic modelling (as it is difficult to predict how it will evolve in the future). In addition, as many new objects are inserted in the environment through launches and collisions, the individual effect of the solar activity can be slightly hidden.

In order to have a scenario free of additional uncertainties and to focus only on the solar activity influence, the second one is based on a no-further-release case (NFR). It supposes that no additional objects are inserted to the population after the beginning of the simulation (so there are no new launches and no explosions), thus the only source for new objects in the environment are collisions between objects already in space. This scenario is far away from reality, since there will almost surely be launches in the years to come. However, it has two advantages: it is free from uncertainties other than the one we want to check (the solar activity influence) and, in addition, it is the best case for the evolution of the environment (any added object can only make the situation worse). We have performed 50 MC runs for each of the 2 scenarios, using different solar fluxes (SF), only taking into account the monthly F10.7 index, with a fixed Ap value of 9. The “default SF” is based on predictions with data from cycle 12 onwards. The “low SF” is based on data from cycle 1 onwards. This means that all historical cycles are used for the fit and prediction, and the prediction provides lower values because there was a period of low solar activity comprising cycles from 5 to 7 (called the Dalton Minimum). The “high SF” is based on data from cycle 19 onwards for the fit and prediction, where the activity was in average higher than in previous cycles, therefore also the prediction values are also higher. In addition, for the NFR scenario we have performed simulations adding/subtracting the standard deviation of the mean to the “default SF”. It has to be remarked that those two cases are the complete extremes, as they suppose that for every month in the predictions the flux would be at the 1-σ level, which is extremely unlikely. These five different F10.7 indices are plotted in Figure 5.

In Figure 6 and Figure 7, we show the evolution of the number of objects in LEO for these DELTA simulations. We can observe a big variation of the results in both scenarios due to the use of different solar fluxes, which go from a clear increase of the population to a clear decrease. It is even possible to see that for the NFR scenario in the low extreme (default -1σ) the population is at all times higher than that in the 30% PMD and high SF scenario, which points out the big influence of the solar activity in the long term simulations. Within the NFR scenario, the default+1σ and the default-1σ cases provide the boundaries of the evolutions of the population, and give a clear indication that our lack of knowledge on the Sun’s evolution (too much variability in the observed cycles to justify simple cyclic regression statistics, little understanding of the Sun physics,…) can make the results of long term analysis very unreliable. But we want to stress again that the two cases using the standard deviation are very unlikely, and more realistic bounds are the ones defined by the low SF and the high SF simulations.

In Figure 6 we give the standard deviations to the average of the 50MC runs for the evolution of the population in the default SF case. It shows a big spread around the mean, which even encloses the high SF case mean. This uncertainty is often not considered when presenting the results, but it should be taken into account as it has an important effect and it could affect the results from the long-term environment simulation.

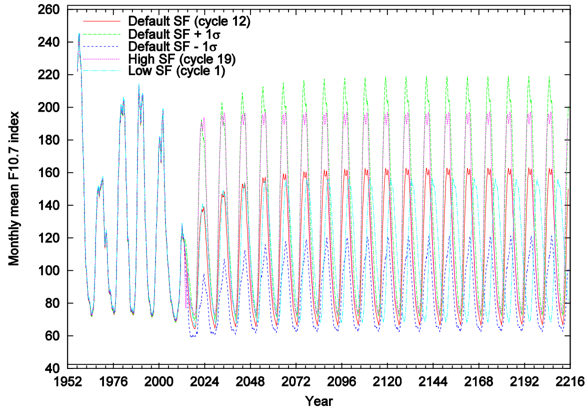

Figure 5. Monthly mean F10.7 values for the different solar fluxes used for the DELTA simulations.

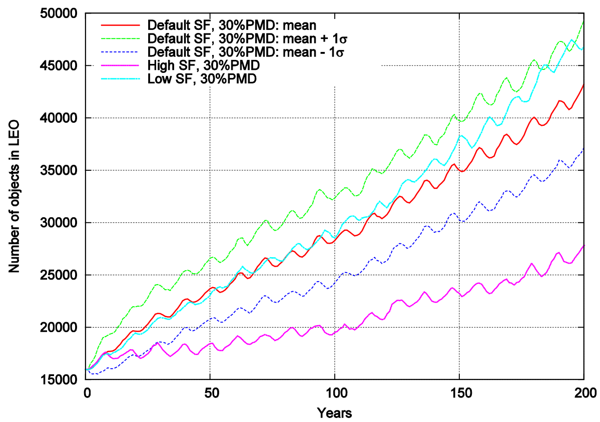

Figure 6. Evolution of population above 10 cm in LEO for the 30% PMD scenario in three different solar flux environments (default, high and low). The mean of the 50MC runs is provided, plus the +/-1σ in the default SF.

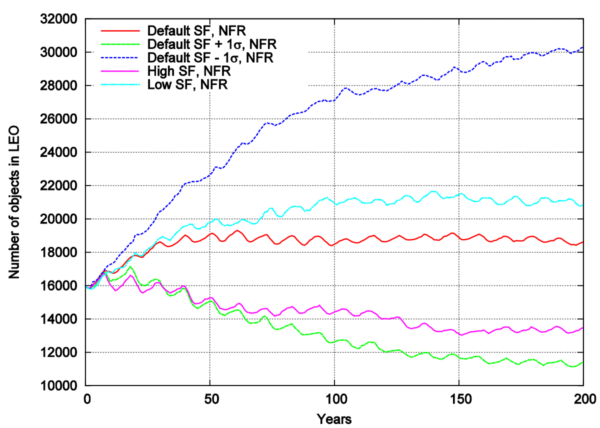

Figure 7. Evolution of population above 10 cm in LEO for the NFR scenario in five different solar flux environments (default, default + 1σ, default – 1σ, high and low).

4.2. ADR for LEO missions [13]

We have simulated ADR scenarios by selecting the objects from a list according to their likelihood of being involved in collisions in previous DELTA analysis. We have chosen as reference scenario the one that has been used for the IADC comparison study [5]. It means a propagation of 200 years, starting with the MASTER-2009 population on 1st May 2009 above 10 cm, a high solar flux prediction, the implementation of the lifetime limitation of 25 years with 90% of success, no new explosions on orbit, a launch traffic based on that of 2001-2009, and an operational life for new payloads of 8 years. In this scenario, based on 100 MC runs, ESA results predicted 35 collisions to happen, an average increase of 22% of the population after 200 years, and 75% of the runs having a final population above the initial one (in number of objects). This is an optimistic scenario because studies [12] show that for the past years the compliance rate with the mitigation guidelines is around 30%, and there are still explosions in orbit every year. However, we have selected this scenario as it is the one used for the IADC study and as it has international recognition.

For the ADR scenarios, we have simulated the removal of 1 or 5 objects per year (ADR1 or ADR5), and starting the ADR missions 15 years after the epoch of the population (i.e. in 2024) because the technology is not yet ready to perform ADR missions and we expect that we will have to wait at least 10 more years before a real ADR mission is launched. We have also considered removing the same quantity of objects as in the 1 object per year scenario, but condensed in 35 years with 5 objects removed per year (ADR5L). For each of the cases, we have performed 40 MC runs.

The evolution of the population for the three scenarios as well as for the reference case can be seen in Figure 8, whereas the cumulative number of catastrophic collisions is shown in Figure 9. We can observe that in all the cases the population evolves below the reference case, as do the collisions. The feature that the number of objects is slightly above the reference for the first 25 years is an artifact of the averaging and not significant. However, once the ADR missions start, we see a decrease on the number of objects compared to the reference.

In addition, in ADR1, the final population is above the initial one, but with a smaller increase than the reference. In this case we also observe that the number of collisions is almost the same as for the reference during the first 120 years and only afterwards decreases. However, the collisions which occur produce fewer objects, thus being not so critical for the environment.

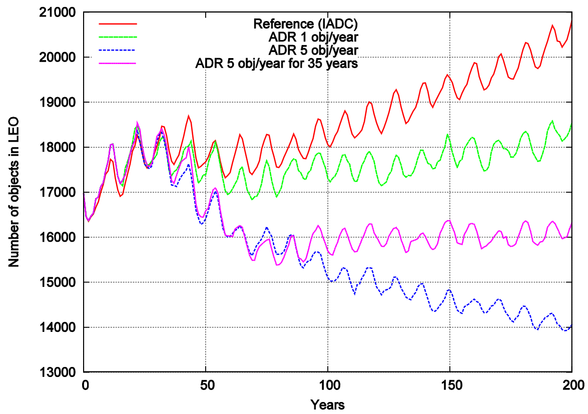

Figure 8. Evolution of population above 10 cm in LEO for the reference scenario and for the ADR scenarios selecting 1 and 5 objects per year starting in 2024 (15 years after the simulation start) from the ranking, with no end date for the ADR (ADR1, ADR5) or with only 35 years of ADR missions (ADR5L).

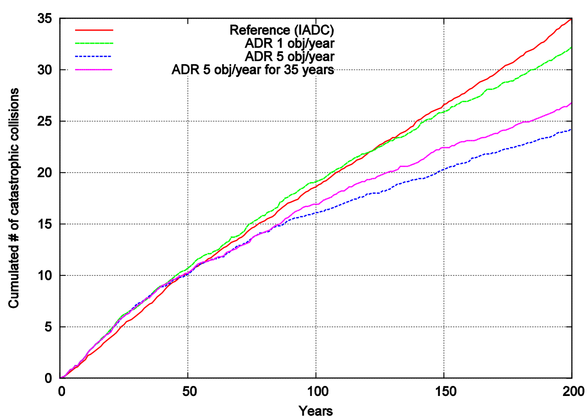

Figure 9. Cumulative number of catastrophic collisions for the reference scenario and for the ADR scenarios selecting 1 and 5 objects per year starting in 2024 (15 years after the simulation start) from the ranking, with no end date for the ADR (ADR1, ADR5) or with only 35 years of ADR missions (ADR5L).

4.2. Level of compliance for mega-constellation [14]

We have simulated a synthetic mega-constellation and analyzed the effect of the percentage of satellites in the constellation which correctly perform a deorbit maneuver at the end of the operational life. We simulated 3 scenario, one with the ISO required 90% compliance, versus a perfect one where no satellite fails (100% compliance), while the last one considers that only half are able to perform the deorbit maneuver (50% compliance). In Figure 10 and Figure 11 we show the evolution of the number of objects and of collisions respectively for these scenarios. As a reference, a case without the mega-constellation is simulated.

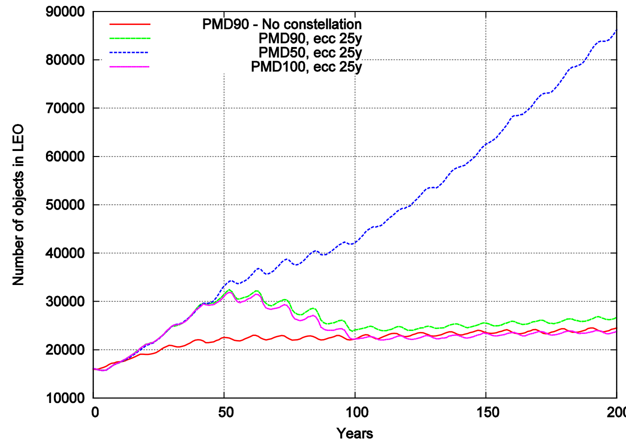

Figure 10. Evolution of the population above 10 cm in LEO for a 90% PMD scenario without constellation, or with the constellation deorbiting in eccentric orbit in 25 years, with 90%, 50% or 100% success rate on PMD.

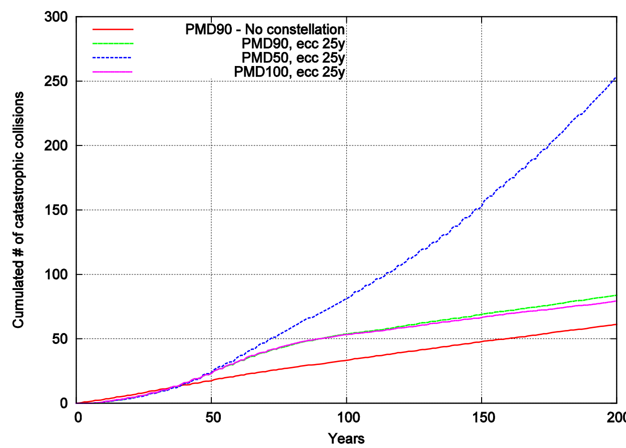

Figure 11. Cumulative number of catastrophic collisions for a 90% PMD scenario without constellation, or with the constellation deorbiting in eccentric orbit in 25 years, with 90%, 50% or 100% success rate on PMD.

The results show that if all the satellites (100%) of the constellation comply with the mitigation guidelines and deorbit, in the long term, once the operational phase is over, there is no difference to not having the constellation. However, if only half (50%) comply, which means that the other half stays in the operational orbit of the constellation, we observe an exponential increase of the number of objects and of collisions, which is the result of the Kessler syndrome. Most of the collisions and the fragments remain in an orbit close to the orbit of the constellation, but with the energy imparted with the collisions there are fragments which will attain objects on other orbits and create even further debris. In addition, having so many objects failing in the constellation orbit will also exponentially increase the need for collision avoidance maneuvers for the operational satellites in the constellation. In the own interest of the constellation operator, and for the rest of the environment, constellation satellites should strictly comply with the mitigation guidelines and perform a deorbit.

5. CONCLUSION

DELTA is a very powerful tool developed and maintained by ESA allowing to simulate the long-term evolution of the space environment under a large variety of conditions. It has been used for many studies under international collaboration (IADC). It has been also used to further analyze the main space debris topics at the time these are detected, in order to anticipate ESA and international response to stress situations for the space debris environment.

The structure and modular design of DELTA has been explained, with a special focus on the algorithm for collision detection and fragment generation.

Some of the past results of studies performed in DELTA have also been displayed to exemplify the wide range of possibilities that the tool offers.

DELTA is under constant improvement and revision process, and currently the efforts are centered in developing the possibility of using different collision detection algorithms, as well as improving the atmospheric model usage without losing performance.

6. REFERENCES

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