INTRODUCING MEDEE – A NEW ORBITAL DEBRIS EVOLUTIONARY MODEL

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ABSTRACT

In early 2012, CNES decided to focus some of its efforts on the development of an orbital debris evolutionary model in order to have a better insight on the issues concerning the long-term sustainability of space activities. As a consequence of this decision, since May 2012 CNES has started the development of MEDEE (Modelling the Evolution of Debris in the Earth's Environment).

This paper is intended to give a first insight on MEDEE after almost a year of development. A description of the general structure of the model, the algorithms that have been implemented and those to be implemented shortly as well as the validation of the model by comparison with reference space debris evolutionary models will be presented on this paper.

1 INTRODUCTION

Long term space debris evolution and the sustainability of space activities constitutes a major concern for space faring nations as well as for any individual or government aware about the tremendous importance of space activities for human beings. Even though the study of the long term evolution of space debris have known a raising interest over the last years, the first studies on this topic are due to Kessler and Cour-Palais back in 1978 [1].

In this context, the French space agency has been working on its own projection model since 2012: MEDEE, for Modelling the Evolution of Debris in the Earth Environment. MEDEE uses a highly efficient and accurate semi-analytical propagator and the last publicly available NASA Break-up Model. It has been designed to be highly flexible and therefore to be able to re-run any simulation by changing the propagator's force model (solar activity, geopotential degree/order, atmospheric model), or the different models acting on space environment (launch rate, explosion rate, mitigation laws, break up model etc.). The motivation for such flexibility comes from the need to study the model sensibility to initial conditions but also to computation hypothesis. MEDEE outputs the projected space debris population at user-defined frequency, allowing to track through the years the origin of each fragment with its orbital parameters. Through the post processing of such output, we are able to model the spatial density evolution at any location in space. The collision risk computation module is able to track the collision probability with time of any space object present in the population, and therefore to build a list of suitable objects to be removed from the space environment.

The reason that has motivated the development of MEDEE is to dispose of a high fidelity space debris evolutionary model that can be used to analyse the measures either of mitigation or remediation, that have to be applied to the environment to guarantee the sustainability of space activities for the next centuries.

2 MEDEE'S GENERAL STRUCTURE

The highly flexible structure of MEDEE has been made possible by the development of the model using a module-based architecture. Each constituting module of MEDEE, is responsible for a specific function involved on the modelling of the evolution of a given space debris population (e.g. orbital propagation, probability of collision computation, etc…). Consequently the modification of the computation hypothesis or even the algorithms defining one of these functions can be made independently of the rest of the functions.

As shown on Fig. 1 the initial population, representing the space environment at a specific date, can be built from a series of external sources or directly given as a model input. The dashed lines on this figure means that a given module is under development and that it is not yet connected to the overall model.

As one of the more time consuming operations of our model deals with the orbital propagation of the sixth orbital elements for each objects of the population, the code of MEDEE has been designed to take advantage of massively parallel, computer system available at CNES. This means that the orbital propagation module has been parallelized, in order to propagate the population at each time-step over all available cores.

The computer system in which MEDEE is executed is formed by 360 cores summing a total RAM of 24 Go and an overall computing power of 4 Tflops/second.

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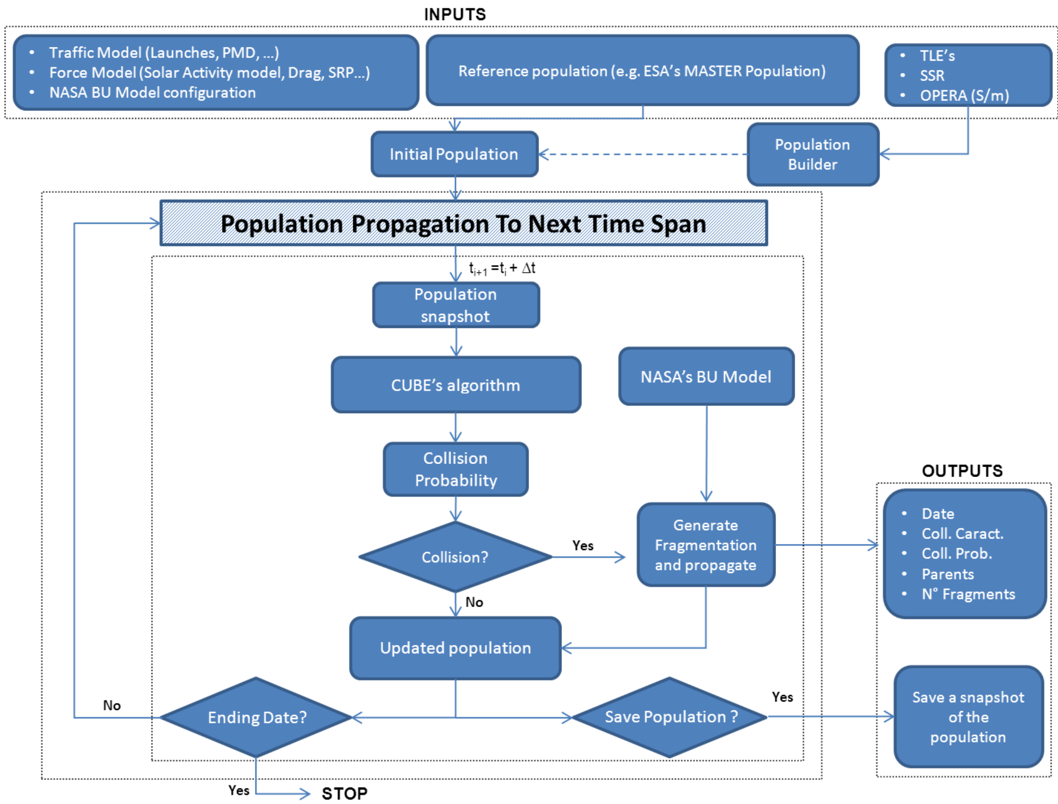

Figure 1- Top level model structure of MEDEE

3 ORBITAL PROPAGATOR

As far as we intend to model the long-term evolution of space debris population around the Earth, we need to dispose of an eccentricity / inclination singularity-free orbital propagator, with a high degree of computational efficiency. The orbital propagator that we have implemented in our algorithm, is a semi-analytic orbital propagator known as STELA [2]. STELA, which is a CNES reference tool, has been primarily developed in order to validate the compliance of satellite's operators with the French Space Act, prior to the delivery of authorizations by the ministry in charge of space activities.

As the verification of the French Space Act's rules and criteria requires long-term orbital propagation, to evaluate orbit parameters evolution (up to 100 years), a semi-analytical method much better suited for long-term extrapolation than numerical propagation, with non-singular equations in eccentricity and inclination, has been developed in cooperation between CNES and IMCCE. In order to ensure a reasonable CPU integration time, the long time scale analysis is based on the numerical integration of equations of motion, where the short period terms have been removed by means of an analytical averaging. This allows the use of a very large integration step size, reducing significantly the computation time. The orbital modelling, which depends on the orbital regime of the object to be propagated, accounts for all significant perturbations (cf. Tab. 1).

As it can be seen on Fig. 2, STELA propagator shows a very good coherence with numerical propagators implementing the full dynamic equation. On Fig. 3, a comparison of a STELA simulation, done by the propagation with STELA of the TLE set released at the epoch t_0, and real data is shown. The coherence of STELA, regarding the real data, as well as its ability to model the Luni-Solar resonances is to be highlighted.

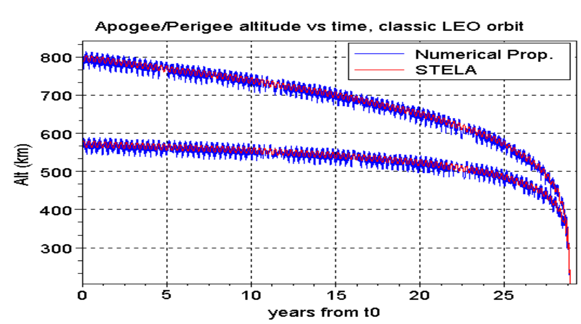

Figure 2 - STELA vs. Numerical propagation apogee/perigee evolution of a classic LEO [2]

Perturbation	LEO type orbits	GEO type orbits	GTO type orbits
Earth's gravity field	J2, J3, J4, J2² zonal model	Complete 4x4 model	J2, J3, J4, J2²,J5, J6, J7 zonal model + some dedicated tesseral terms for resonant orbits
Solar and Lunar gravity	Yes	yes	Yes
Atmospheric drag	Yes	no	Yes
Solar radiation pressure (SRP)	yes (including Earth shadow)	yes (including Earth shadow)	yes (including Earth shadow)

Table 1 - STELA Dynamical model [2]

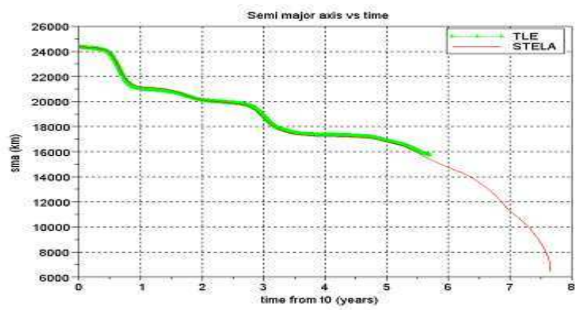

Figure 3 -*Mean Semi-major axis evolution with time, directly extracted from the TLEs, in comparison with STELA simulation for a GTO type orbit [2]*

4 COLLISION PROBABILITY EVALUATION

The collision probability algorithm implemented in MEDEE is CUBE, developed at NASA/JSC [3]. It estimates the long-term collision probabilities by means of uniform sampling of the system in time and can be applied to any kind of orbit.

As implemented in the model, probabilities of collision among the orbiting objects are evaluated every 5 days (user defined value).

At each time step the earth's close environment is discretized, in Cartesian space, in 10 km wide cubes. The probability of collision of objects falling within the same cube is computed following the formalism presented in [3].

5 FRAGMENTATION MODELING

The NASA's standard break up model (EVOLVE 4.0) has been implemented as an independent module within MEDEE's architecture to simulate the generation of debris clouds produced by on-orbit explosions and collisions.

The implementation of the NASA's BU model has been done using the paper of Johnson et al. [6] [7] as reference.

Even if other fragmentation models has been published, and could have been implemented in MEDEE, the NASA's BU Model is the one that is mainly implemented in the reference evolutionary models as LEGEND [8] or SDM [9]. By hence and in order to ease the comparison of MEDEE's results with already published results, at least during the early phases of development, the use of such model has been privileged with respect to other fragmentations models.

6 TRAFFIC MODELING

The ability to predict the mid-term and long-term evolution of the space debris evolution relies, in part, on our ability to predict the space activities.

Predicting space activities means being able to properly model:

- The nature and magnitude of future space launch activities.
- The scenarios of application of post mission disposal (PMD) techniques, as the 25 years rule or the passivation of upper stages and payloads.
- The potential development of new mitigation or remediation measures, as the extensive use of de-orbitation kits on newly launched payloads, or the development of active debris removal (ADR) techniques.

6.1 Space Launch Activities

MEDEE is actually able to simulate either a time varying launch traffic or to repeat a given launch traffic cycle at a user's defined frequency.

In both cases the users must prepare in advance a launch traffic file that will implement, either a time varying launch traffic and by hence that will cover the overall simulation's time span, or a launch traffic file mapping the launch traffic performed during the last N years, and that will be repeated during the overall simulation time.

6.2 Explosions

For the moment only a constant rate explosion model has been implemented in MEDEE. The explosion model takes as inputs the frequency of explosions (i.e. the number of explosions by unit of time) and the minimal weight and nature of objects that can explode.

Once these inputs has been defined by the user, the model will randomly chose, the identity of the objects that will explode as well as the date of the explosion.

The standard NASA's BU model is used to generate the fragments and the semi-analytical orbital propagator STELA, will be used to propagate all the generated fragments to the next snapshot, where they will be added to the rest of the space debris population.

6.3 De/Re-Orbitation

Two End Of Life (EOL) operations models have been implemented in MEDEE for the moment. On one side the de-orbitation model ensures the elimination of some space objects of the population caused by re-entry into the Earth's atmosphere. On the other side, the re-orbitation model places some of the space-objects in less populated regions of space in order to minimise the probability of collision between those objects and the rest of the population.

The de-orbitation model takes as inputs the type of objects that will perform EOL operations, the operational lifetime, the residual lifetime after EOL operations, the date of the beginning and end of the application of the de-orbitation scenario, as well as the success rate of such operations.

The de-orbitation models allows the splitting of the population in sub-sets as a function of the type of space object (e.g. Payload, R/B) in order to apply a different de-orbitation model to each sub-set. This model allows to model from direct re-entry scenarios to the N years rule scenario, as for example the 25 years scenario.

The re-orbitation model takes as inputs the type of objects that will perform EOL operations, the operational lifetime, the semi-major axis increment after EOL operations, the date of the beginning and end of the application of the re-orbitation scenario, as well as the success rate of such operations.

Similarly to the de-orbitation scenario, the re-orbitation one allows for the splitting of the space population in order to apply a different re-orbitation model to each sub-set.

Considering starting and ending dates of the re/de-orbitation scenarios, allows realistic PMD scenarios, where the effectiveness of such EOL operations can evolve with time.

Active Debris RemovalFor more than a decade, worldwide studies have highlighted the instability of the space debris population, most of all for LEO regime. The main conclusion of those studies is that even with a good implementation of the mitigation measures, the LEO population is going to continue to grow through the next decades [12]. In order to control the evolution of space debris population, studies like [13] highlight the necessity to remove mass from orbit.

Consequently, MEDEE implements the possibility to take into account ADR missions, for the modelling of the long-term evolution of space debris environment.

Some of the MEDEE ADR model inputs are the ADR starting date, the number of objects to remove per unit of time, and a group of metrics adapted for selecting and ordering ADR targets. [14].

7 OUTPUTS

As shown in Fig. 1 MEDEE has been designed to provide the user with an extensive amount of data, concerning the evolution of the space debris population.

To this extent, MEDEE provides snapshots of the overall population (i.e. 5 orbital elements (i.e. the argument of latitude is considered as randomly distributed), id, type of object, mass and surface of all the objects) at a user defined frequency. It also provides a detailed description of the events that have occurred between each snapshot.

Consequently the user will have access, with the temporal resolution allowed by the snapshot frequency, to the following dated information:

- Objects launched
- Natural re-entries
- Objects that have exploded, region of explosion and generated fragments (i.e. Id, type of object, surface, mass and 5 orbital elements)
- Pairs of objects within the same cell, with the associated probability of collision, and the orbital elements of the objects.
- Catastrophic and non-catastrophic collision events, with the description of the objects involved in the collision and the description of the fragments generated.
- Objects targeted by mitigation measures (i.e. planned re-entries)

8 POST PROCESSING

As an external module of MEDEE, a post-processing module is under development in order to process all the information given by the model and present it to the user in an easily comprehensible format. Among the different results given by the post-processing module, we can quote the following outputs:

- Cumulated number of events (launches, re-entries, catastrophic and non-catastrophic collisions) as a function of time
- Total number of objects in the population as a function of time and as a function of object's nature for a given minimal particle size

- Mean collision probability and mean number of collisions as a function of altitude and/orinclination
- Density of objects as a function of altitude

Those post-processing results are not exhaustive, and will be completed depending on future study needs. Nevertheless it gives to the user the necessary information to understand how the space debris population will evolve in the future and which phenomena are driving such evolution.

9 PRELIMINARY RESULTS AND VALIDATION

The purpose of this section is to present an overview of the type of analysis that can be performed with MEDEE as well as to evaluate the coherence between MEDEE and other reference evolutionary models, by comparing our results with the results of such models (e.g. LEGEND or DELTA).

Due to the existence of an extensive amount of literature analysing the long term evolution of the space debris environment as a function of different initial populations, different hypothesis concerning the traffic model, the minimal size of objects to be consider, we have decided to take the work presented in [12] as a reference to validate our model.

Indeed Ref. [12] presents an excellent source of information to validate our model, as the many degrees of freedom involved in the simulation of the long term evolution of the space debris environment are constraint by the clear statement of the hypothesis that have been taken into account to perform the analysis. In addition to this, the results of six space debris evolutionary models are compared, which serves to evaluate the coherence between those models and the predictions obtained using MEDEE.

The initial population used for this study, is considered sufficiently similar to the Ref. [12] reference population, as to being in measure to compare MEDEE's results with the predictions presented in Ref. [12].

9.1 Assumptions

The assumptions that have been considered to perform the simulations presented in Ref. [12] and that we have consequently considered to perform our analysis and validate our model are:

- Future launch traffic represented by the repetition of the historic 2001 to 2009 space traffic.
- The commonly-adopted mitigation measures are well-implemented. In particular, a compliance of 90% with the post-mission disposal "25-year" rule.
- 100% success for passivation (i.e., no future explosions).
- Catastrophic collision was defined as one characterized by an impactor kinetic energy to target mass ratio of 40 J/g.

9.2 Population Prediction Results

The first goal of an evolutionary model as MEDEE, is to be able to forecast the evolution of the space debris population for an user defined time span.

The evolution of the population, in which we are interested in, can be defined either as a function of the minimal size of the objects contained in the population, and/or as a function of the nature of the objects constituting this one (e.g. Debris, S/C, …).

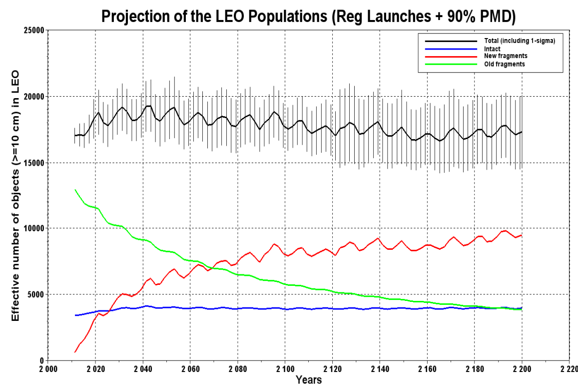

Figure 4 – *MEDEE space debris population forecasting for the next 200 years (60 MC simulations).*

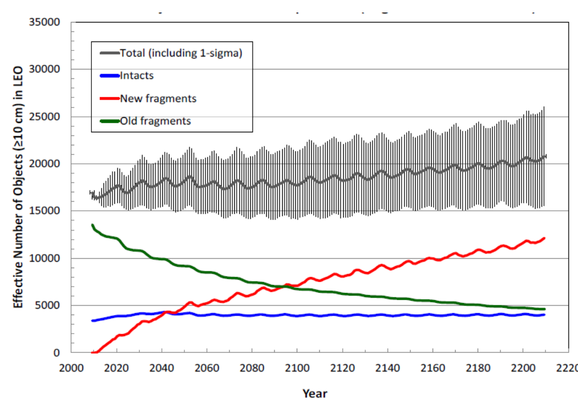

Figure 5 – DELTA *space population forecasting for the next 200 years [12]*.

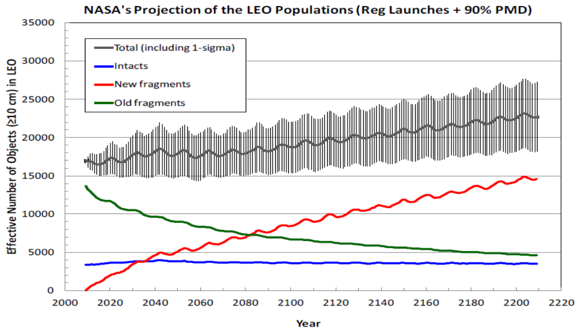

Figure 6 – LEGEND space population forecasting for the next 200 years [12].

Comparing Fig. 4 to Fig. 5 we can see that MEDEE's results, even if they mostly fall in the 1-σ uncertainty region of DELTA simulation (Fig. 5), do not predict a significant increase of the space debris population after 200 years. When comparing MEDEE with LEGEND, a clear difference in the number of new fragments can be seen. This difference makes MEDEE's prediction to be outside the 1- σ uncertainty region of LEGEND. Comparing MEDEE with both models, a difference is identified in the decreasing rate curve of old fragments. After 200 years simulation, we predict about 1000 less old fragments than reference evolutionary models. This highlights the possibility that the difference in the evolution results comes from the orbital propagator. In our case, the orbital propagator could predict a shorter lifetime for the objects that the orbital propagators used by NASA and ESA.

9.3 Rate of Catastrophic Collisions

As far as catastrophic collision rate forecasting is concerned, by the comparison of Fig. 7 and Fig. 8; we observe that the cumulated number of catastrophic collision predicted by MEDEE is in coherence with the results of reference evolutionary models. This is, MEDEE predicts one catastrophic collision every 7 years while reference models predict one catastrophic collision every 5 to 9 years [12].

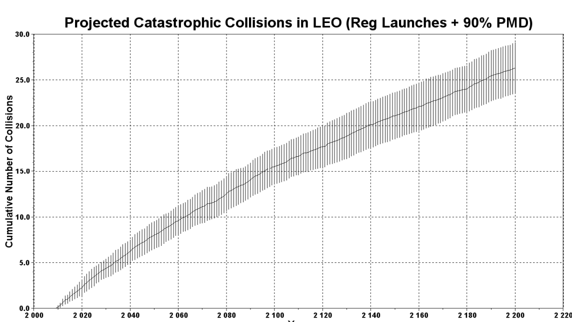

Figure 7 – MEDEE projected number of catastrophic collision in LEO

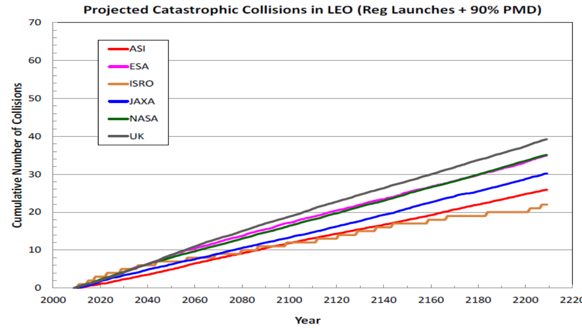

Figure 8 – Projected number of catastrophic collision in LEO [12]

9.4 Regions of Catastrophic Collisions

Once that we have verified that the number of catastrophic collisions predicted by MEDEE is coherent with the results presented in Ref. [12], the origin of the differences could also come from the fact that the collisions predicted by MEDEE are not taking place at the same regions of the space that the collision predicted by reference evolutionary models.

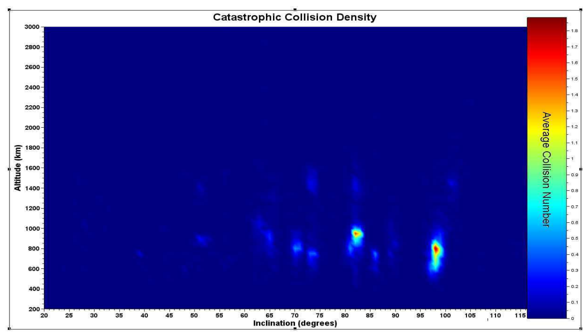

Figure 9 – Projected number of catastrophic collision as a function of altitude and inclination in LEO (MEDEE)

From the observation of Fig. 9, we observe that three regions appears to be the ones where most of the catastrophic collisions take place. The first region is between [97, 100] degrees in inclination and [600, 900] km in altitude. The second region is between [81, 84] degrees in inclination and [800, 1000] km in altitude. The third region is between [70, 74] degrees in inclination and [700, 900] km in altitude.

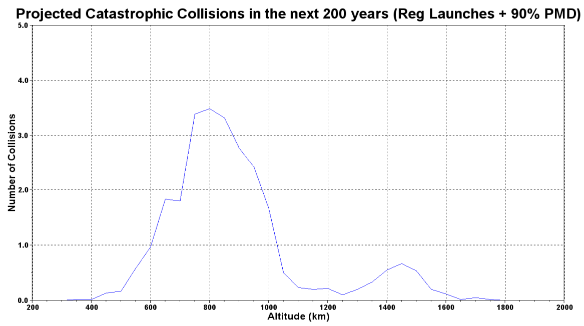

Figure 10 – Projected number of catastrophic collision as a function of altitude in LEO (MEDEE)

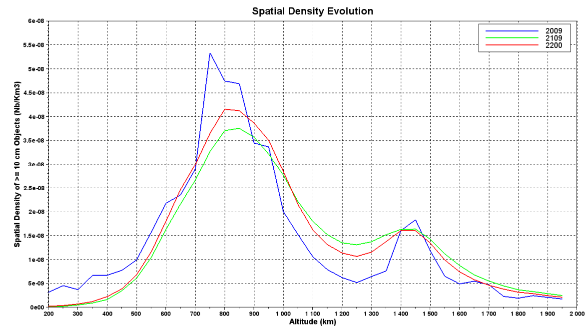

Figure 11 – Spatial density as a function of altitude and for different simulation dates (MEDEE).

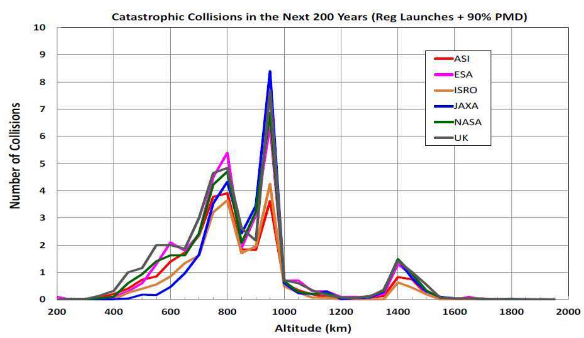

Figure 11 – Projected number of catastrophic collision as a function of altitude in LEO [12]

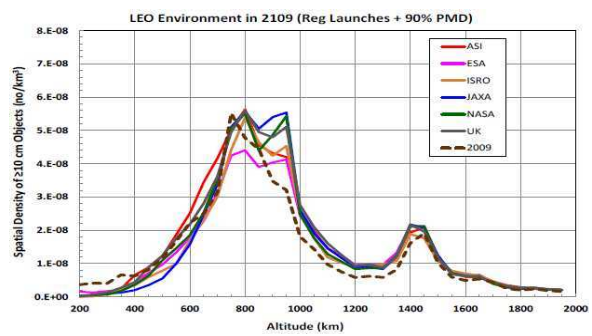

Figure 12 – Spatial density as a function of altitude, for different simulation dates [12].

From Figs. 10 and 11 we observe that while predictions in Ref. [12] highlights two well defined regions in altitude, around 800 and 950 km, where most of the catastrophic collisions occurs, MEDEE predicts a wider region covering both zones. This bigger dispersion on the zone where collisions are taking place, could come from the fact that if our semi-major axis decreasing rate is higher than the one for the other models, we could have a higher circulation of objects going from upper to lower altitudes. This will lower the concentration of objects in 800 to 1000 altitude regimes, in comparison with other models, and will generate a dispersion on the altitude regimes where the collisions will take place.

9.5 Future LEO Environment

Another interesting point about MEDEE is its ability to forecast the evolution of the spatial density of the space debris population as a function of time and of the orbital regime (e.g. Altitude or inclination).

Fig. 12 presents the spatial density, number of objects by unit of volume, as a function of altitude for the initial population (i.e. 2009), the population in 2109 and the one in 2200.

By comparing the spatial density evolution predicted by MEDEE, with the spatial densities of reference evolutionary models for year 2109, we observe that MEDEE reproduces quite well the evolution of the initial spatial density with time, as a function of the altitude. We can notice slightly lower values for MEDEE, which is quite in line with the differences already stated in the previous paragraphs.

10 CONCLUSION AND PERSPECTIVES

On this paper we have given an overview of the new space debris evolutionary model in development at CNES (MEDEE – Modelling the Evolution of Debris in the Earth's Environment) after one year of development. In addition to this first presentation, preliminary results have been compared withother reference evolutionary models.MEDEE has been developed using a module based architecture. This architecture offers MEDDE a high degree of flexibility and the ability of being able to modify the computation hypothesis or even the algorithms defined in one of these modules, independently of the rest of the functions. Evolutionary model like MEDEE have an extremely large number of degrees of freedom, and a module base architecture allows to carry out easily sensitivity analysis of the space debris evolution results with respect to those degrees of freedom.

The preliminary results of this paper have been established from the reference scenario presented in Ref. [12]. Indeed, Ref. [12] constraints the many degrees of freedom of an evolutionary model by the clear statement of the computation hypothesis. Additionally, Ref. [12] is an excellent reference to perform a first validation of MEDEE, as results of six reference evolutionary models are presented.

Those comparisons revealed differences.

These differences need to be deeply analysed and understood, in order to successfully complete the validation of our model

During 2013, the development of MEDEE is going to continue in order to upgrade the traffic model, by integrating additional and more realistic PMD scenarios (e.g. use of de-orbiting kits, modelling the de/re orbiting orbit, …) and launch traffic scenarios (e.g. time varying launch traffic scenarios). The development of the post-processing tool will be completed, in order to offer to the user all the information needed to the proper analysis and understanding of the space debris evolution results, under the user's defined computation hypothesis. Extensive sensitivity analyses of the model to the computation hypothesis are also planned during 2013.

11 ACKNOWLEDGEMENTS

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