EFFECTS OF THE MITIGATION MEASURES DISCUSSED AT INTERNATIONAL LEVEL ON THE SPACE DEBRIS LONG-TERM EVOLUTION IN LOW EARTH ORBIT

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ABSTRACT

The effects, on the low earth orbit environment, of different mitigation measures discussed at international level are illustrated with simulations spanning more than 200 years in the future. The analysis took into account a detailed traffic model, explosions, collisions and the effects of air drag.

The simulations carried out confirm the importance of spacecraft and rocket bodies passivation to avoid in-orbit explosions, but the de-orbiting of upper stages is needed as well to curb the debris and collision rate increase and to avert the onset of an exponential growth of artificial objects in the near earth space. The additional removal of end-of-life spacecraft does not improve the outcome dramatically, but seems to be the only additional measure able to reduce the collision rates in low earth orbit, reversing the historical trend of the last four decades.

INTRODUCTION

Today earth mission planning and operations must deal with a problem mostly ignored just twenty years ago: non-catalogued space debris. Beside 8000-9000 objects larger than 10-20 cm tracked by the US Space Command sensors, the circumterrestrial space is populated by a very large number of artificial debris, down to sub-millimeter particles, produced over the years and continually replenished by international space activities.

Particles in the millimeter and centimeter size range are particularly interesting because they can severely damage critical spacecraft sub-systems. Cost effective shielding against millimeter sized debris is sometime feasible, but the penetration of particles close to one centimeter is much more expensive and difficult to avoid, as shown by the International Space Station design.

Therefore, the artificial orbital debris generated by more than 40 years of space activities are, by now, a common concern for officials and engineers involved in mission design, planning and operations. If left unchecked, they could imperil, in a not too far future, the exploitation of the near earth space. For this reason, there is an interest to simulate in a realistic way the long-term evolution of space debris, in order to assess the relative merits and drawbacks of the mitigation measures proposed and discussed at international level.

During the nineties, a dedicated effort was carried out in Pisa to develop computer codes specifically tailored for the detailed analysis of the long-term evolution of orbital debris (Anselmo *et al.*, 1996; Rossi *et al.*, 1998). One of them, the Space Debris Model for long-term analysis (SDM-98), has been designed to follow, as much as possible, the actual orbital evolution of individual space objects. Developed under ESA contract and upgraded with ASI funding, SDM uses a very fast semi-analytical propagator to compute the orbital evolution of a huge set of objects for very long time spans, under the influence of the atmospheric drag perturbation.

Typically, all the largest space objects (corresponding, approximately, to the size class of the catalogued population) and a big sample of the smallest debris (down to 1 mm) may be propagated for one century or more. The sampling factors and the time span allowed depend on the performances of the specific computer used to run the Monte Carlo simulations, and may be selected by the user. Complex traffic projections and mitigation scenarios can be modeled in detail, including the possibility of simulating the phased deployment and maintenance of satellite constellations and space stations.

ORBITAL DEBRIS ENVIRONMENT

Any realistic space debris study must be based on a good environmental model. For such a reason, a massive effort was carried out to estimate the contribution of the historical orbital events able to produce a large number of particles in the 0.1-10 cm size range. The sources considered as of 1 January 1997 - reference epoch of the model - were 140 spacecraft and upper stage breakups and 16 sodium-potassium liquid metal leaks from the last Soviet radar ocean reconnaissance satellites (RORSAT).

Using a dedicated software system developed to simulate the generation and orbital propagation of debris clouds produced by explosions, collisions and RORSAT-like coolant leakage events, each debris source was simulated independently with the most appropriate models and parameters, and the resulting debris clouds were propagated - including all the relevant perturbations - to the chosen reference epoch. At this point, the particles obtained were merged with the US Space Command catalogued objects, propagated to the same epoch. The resulting model, the 1997.0 CNUCE Orbital Debris Reference Model (CODRM-97), included all the simulated particles heavier than 1 mg (or larger than 0.9 mm) still in earth orbit (Pardini *et al*., 1998).

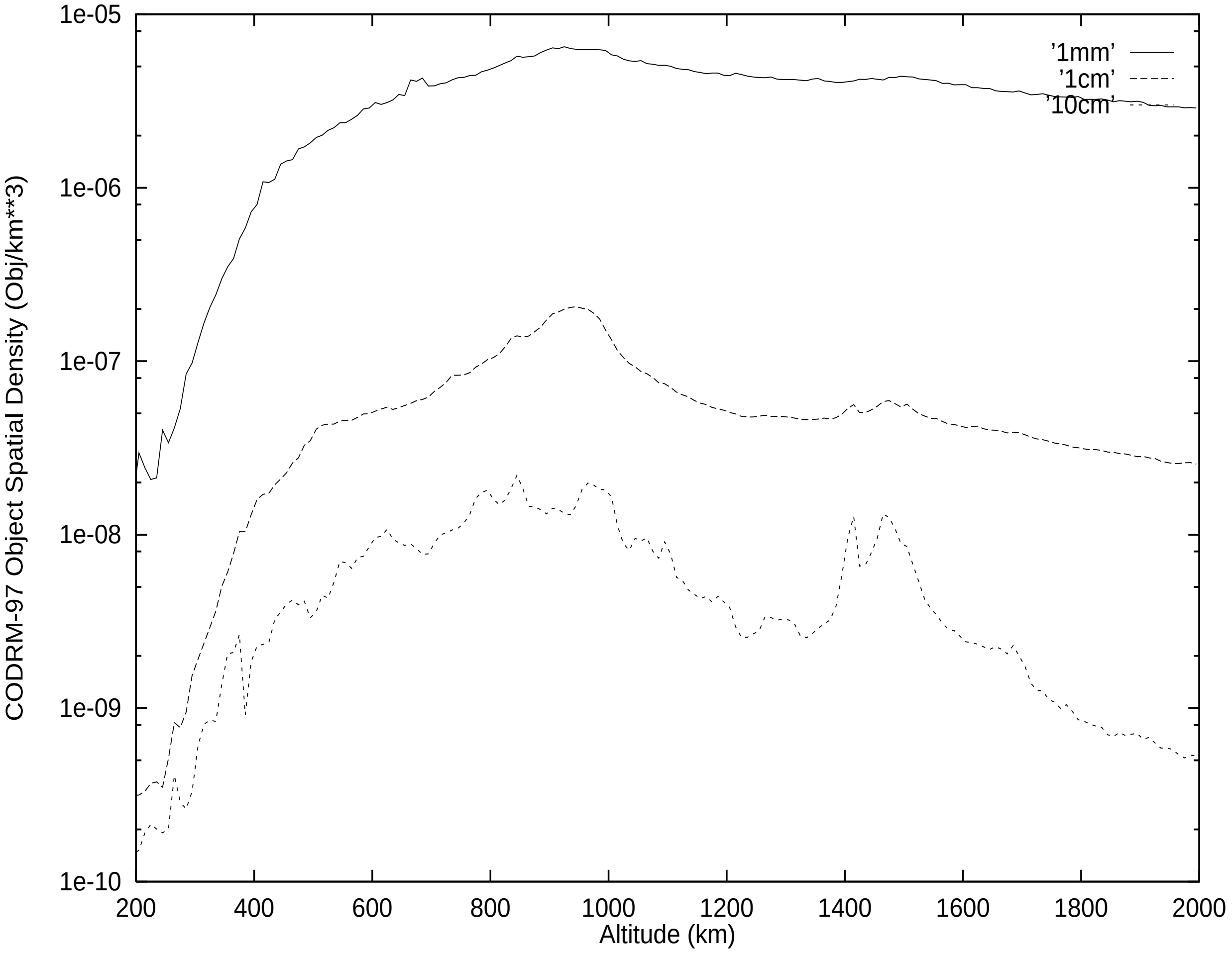

Figure 1. CODRM-97 spatial density below 2000 km for objects with diameter ≥ 1 mm, 1 cm and 10 cm.

In total, including the RORSAT droplets down to 1 mg, more than 55 million particles resulted still in orbit at the reference epoch. The total mass was close to 3500 metric tons, while the overall cross-sectional area was about 40,000 m^2. However, 99.94% of the mass and 99.79% of the cross-sectional area resulted concentrated in the catalogued population. The CODRM-97 object density distribution below 2000 km is shown in Figure 1.

TRAFFIC MODEL

In order to follow the evolution of the debris population over several decades, it is necessary to define an appropriate traffic model. The baseline traffic prediction adopted was quite conservative for the *routine space activity*, for which a constant launch rate of 79 per year was assumed. The orbital distribution and the physical characteristics of payloads and upper stages were assumed in agreement with the record of the 1993-1997 five years interval.

Mission related objects of 5 kg, i.e. in the class of the catalogued population, were included as well, reproducing, as far as possible, the observational record. The value adopted (1 per average launch) takes into account the 0.6-0.7 operational debris per launch observed in the last few years plus an additional fraction (0.3-0.4) due to the fact that 1.3-1.4 upper stages are typically left in orbit after each mission. When more than one upper stage is left in space, the greatest in a long lifetime orbit is taken into account. Space Shuttle and deep space missions are included in the launch statistics, but do not contribute to the terrestrial debris environment, due to the nature of their space flights.

In addition to the routine space activity, the injection and maintenance, in low earth orbit, of several commercial satellite constellations was considered too. Between 1997 and 2062, the deployment of 20 commercial constellations was simulated. Fifteen were similar to projects currently envisaged or under development; five more, modeled on the now defunct M-Star, were wide-band telecommunications systems, introduced to cover the far future with a consolidated configuration. Satellite in-orbit spares were included and the operational life of the constellations took into account the deployment of new generations of spacecraft in the same satellite system. One upper stage and two mission related objects were associated to every constellation deployment or maintenance launch.

FRAGMENTATION MODELING

In addition to launches, the debris population is increased by orbital breakups due to explosions and collisions. The full details of the simulation models adopted, both for explosions and collisions, are discussed in Rossi *et al.*, 1998.

Explosions are responsible for a large fraction of the current orbiting debris population. Usually they can be classified in two different classes: low and high intensity. In this study, a nominal explosion pattern (exploding objects, occurrence rates, exploding mass fraction, breakup orbits) based on the record of the 1993-1997 time span was assumed. The resulting average explosion rate was 5.2 per year: 2 high intensity explosions, with an effective exploding mass of 120 kg, and 3.2 low intensity events, with an effective exploding mass of 2821 kg.

For collision events, the fragment mass distribution was based on the assumption that, depending on whether the ratio between the projectile kinetic energy and the target mass is lower or higher than a critical threshold value, either a *cratering regime* (localized damage on part of the target) or a *catastrophic disruption regime* (complete fragmentation of the target) drives the target breakup process. Reasonable values of the impact strength parameter for artificial orbiting objects lie in the 30,000-60,000 J/kg range (McKnight *et al.*, 1992). In this study, two different catastrophic disruption thresholds were adopted: 40,000 J/kg for spacecraft and 60,000 J/kg for rocket bodies.

MITIGATION SCENARIOS EFFECTIVENESS

In order to evaluate the long-term effectiveness of some debris mitigation measures, several scenarios were simulated with SDM-98 for a 200-year time span. For each of them the results were obtained by averaging

10 different Monte Carlo runs, in order to smooth out the stochastic effects and exhibit the main trends of the evolution. The scenarios considered are the following:

1. Business as usual (BAU). It includes a constant routine launch rate plus the commercial satellite constellations. No orbital debris mitigation measure is adopted.
2. No explosion (NOEX): as BAU, but with both spacecraft and rocket bodies effectively passivated at the end of their life, in order to completely prevent in-orbit explosions after 2010.
3. De-orbiting of upper stages (DEOUP): as NOEX, but with the de-orbiting of the new rocket bodies, with perigee altitude below 2000 km, launched after 2010. Constellation upper stages are de-orbited as well, below 2000 km, according to their deployment and maintenance launch schedule.
4. De-orbiting of constellation spacecraft (DEORCO): in addition to DEOUP, all constellation satellites below 2000 km are de-orbited at the end of the operational life.
5. De-orbiting of all spacecraft (DEOALL): in addition to DEORCO, all spacecraft (not belonging to commercial constellations) in high eccentricity orbits, with perigee altitude below 2000 km, or in near circular orbits, in between 600 and 2000 km, are de-orbited at the end of the operational life, after 2030.

The results obtained, below 2000 km, are summarized in Figures 2-5 in terms of debris number and collision rate. The elimination of in-orbit explosions seems to be the single most effective measure to limit the growth of decimeter sized debris, which are the projectiles able to breakup a satellite. However, the collision rate in that size class is only slightly reduced with respect to the business as usual scenario, due to the increasing number of spacecraft and upper stages, that account for most of the collisional cross-section. A significant improvement is obtained only through the de-orbiting of the new rocket bodies launched in space, while the further removal of spacecraft at the end of life is useful (the number of objects and the collision rate decrease), but the proportional gain is smaller.

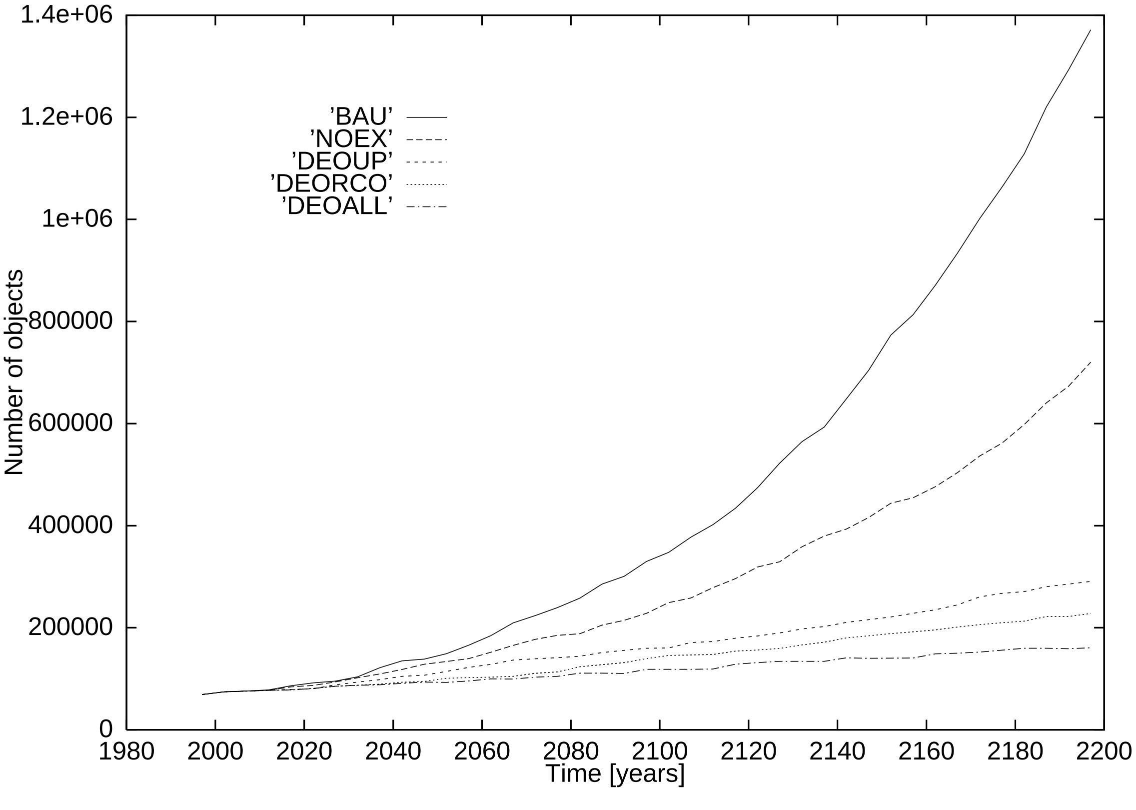

Figure 2. Number of orbital debris larger than 1 cm for the five simulated scenarios.

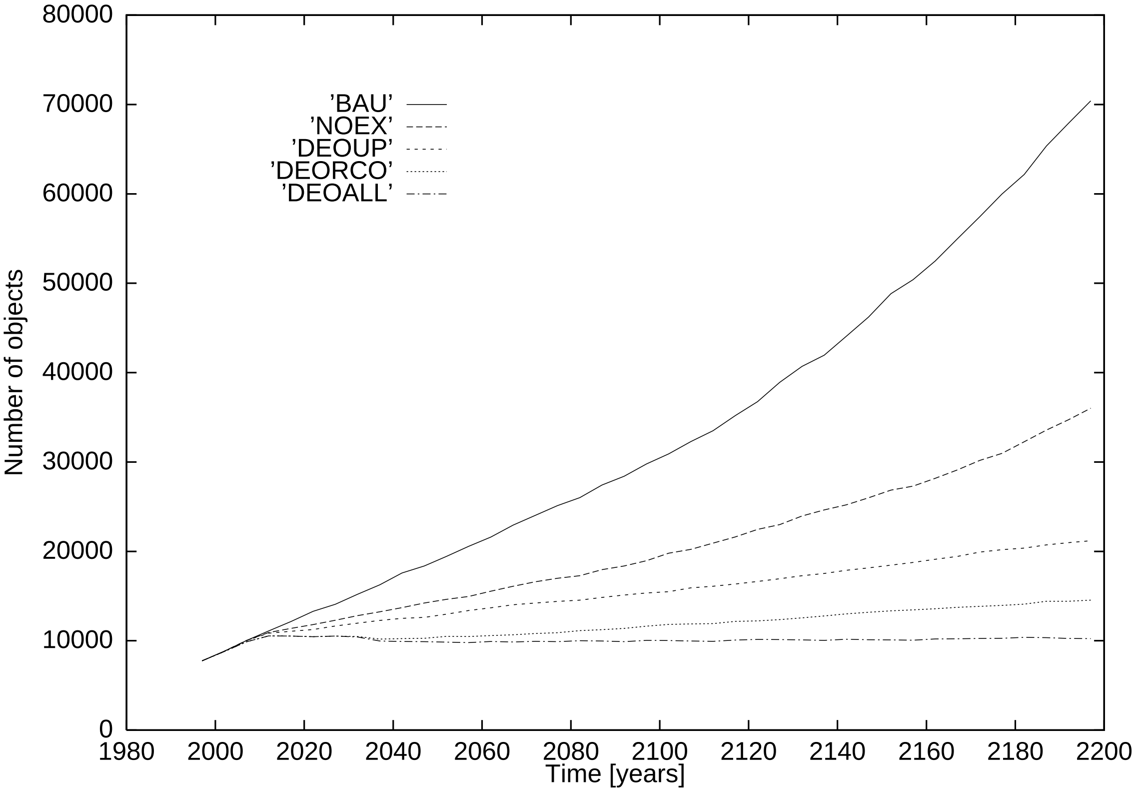

Figure 3. Number of orbital debris larger than 10 cm for the five simulated scenarios.

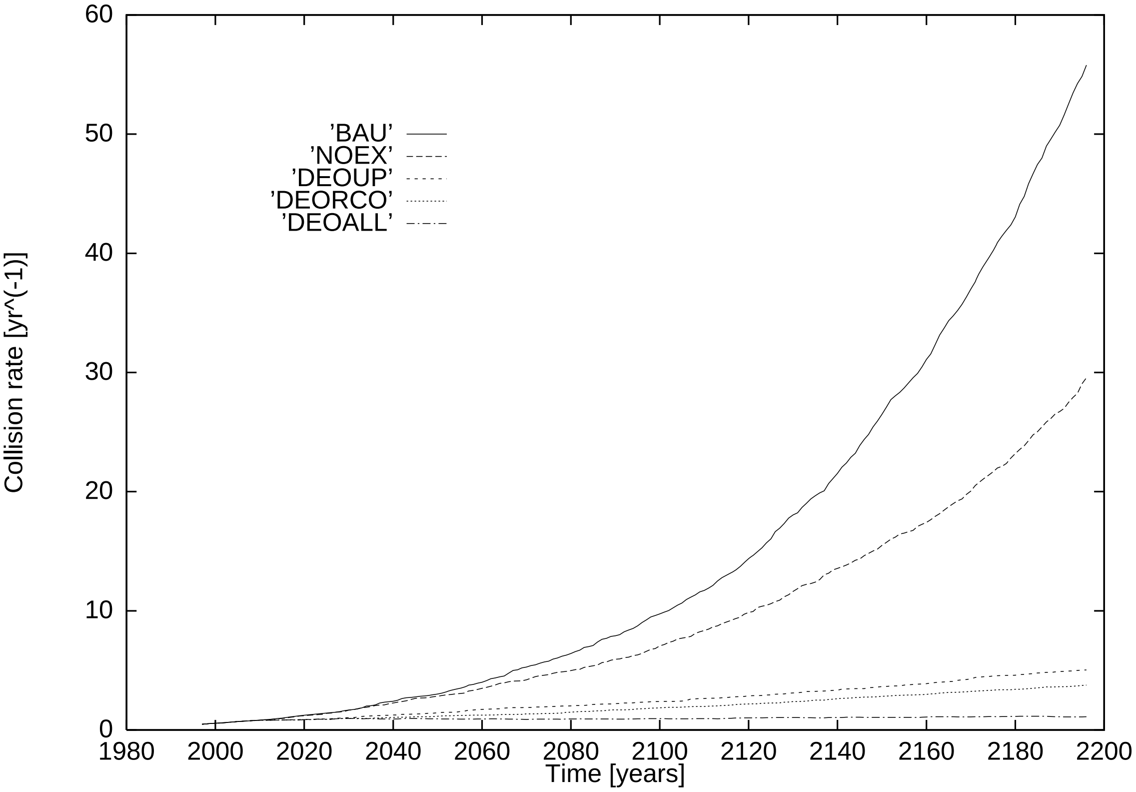

Figure 4. Collision rate for orbital debris larger than 1 cm for the five simulated scenarios.

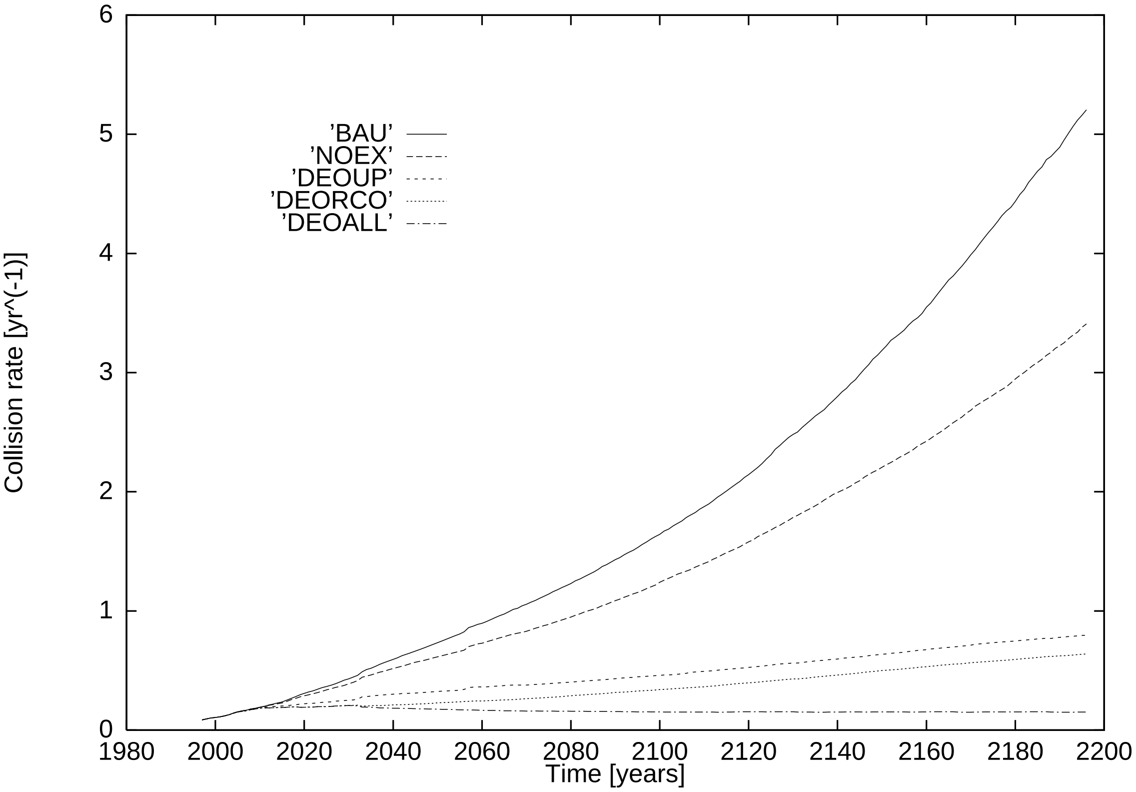

Figure 5. Collision rate for orbital debris larger than 10 cm for the five simulated scenarios.

Most of the same conclusions apply to centimeter sized debris, produced in large numbers both by explosions and collisions (craterizations included). On the other hand, only the adoption of all the mitigation measures analyzed here (DEOALL scenario) can guarantee a global long-term reduction of the collision rates and a very slow growth of the debris population in low earth orbit.

CONCLUSIONS

Very long-term simulations of a realistic orbital debris environment are needed to evaluate the relative effectiveness of different mitigation measures. The results of the simulations carried out at CNUCE/CNR confirm the importance of spacecraft and rocket bodies passivation to avoid in-orbit explosions, but the de-orbiting of upper stages is needed as well to curb the debris and collision rate increase and to avert the onset of an exponential growth for a couple of centuries, or more. The additional removal of end-of-life spacecraft does not improve the outcome dramatically, but may be able to reduce the collision rates in low earth orbit, reversing the historical trend of the last four decades.

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