THE LONG-TERM EVOLUTION OF THE SPACE DEBRIS ENVIRONMENT

Luciano Anselmo

Istituto CNUCE, Consiglio Nazionale delle Ricerche, Via Alfieri 1, 56010 Ghezzano – Pisa, Italy
Email: Luciano.Anselmo@cnuce.cnr.it

ABSTRACT

A review of the problem of the long-term uncontrolled growth of man-made objects in earth orbit is presented. After a discussion of the main underlying concepts, the relative effectiveness of the adoption of some mitigation measures over 100 – 200 years is analysed, including the minimisation of mission related objects release, the on-orbit explosion avoidance and the de-orbiting of spacecraft and upper stages in low earth orbit.

It is shown that only the implementation of the full set of mitigation measures discussed would be able to guarantee the long-term approximate stabilisation of the population of large objects, maintaining at acceptable levels the growth of millimetre and centimetre sized debris.

1. INTRODUCTION

Let consider an ensemble of orbiting objects whose evolution is dominated by mutual collisions. It is well known that the mass distribution, after an appropriately long time interval, will relax to a quasi-equilibrium state, represented by a power law of the form

$$dN(M) \propto M^{-q} dM \qquad (1)$$

where N is the number of objects with mass M, or larger. For natural bodies, the equilibrium value of the exponent q seems to be very stable under a wide range of assumptions, being included in the range

$$5/3 \le q \le 2 \qquad (2)$$

where $q = 2$ and $q = 5/3$ correspond, respectively, to an equal mass and area distribution per logarithmic interval. A value of $q > 2$ would imply that most of the mass is concentrated in the smallest particles, while in practice the largest mass fraction is found in the biggest objects ($q < 2$). For the main belt asteroids of our solar system, whose evolution was dominated by mutual collisions over billions of years, $q = 11/6$.

The artificial objects accumulated around the earth during more than forty years of space activity presents many qualitative analogies with natural systems like the asteroid main belt or the rings of the giant planets [1]. However, the population of earth orbiting objects is still not in collisional equilibrium, even though, by continuing to accumulate objects at the present rate and/or waiting for an appropriately long period of time, such a destiny will be mathematically inevitable, at least above a certain altitude [2][3][4].

In the past many studies investigated the possibility of an exponential growth of the artificial space objects population due to runaway collisions [2] [3] [4] [5] [6] [7] [8]. On the other hand, the chain reaction effect was built in the mathematics of the problem, under a very wide range of initial conditions and model assumptions, so the real unknown was not “if”, but “when” the exponential growth was supposed to start.

The answer to this question is not just of purely academic interest, because the effectiveness of the space debris mitigation measures considered at present, as either interim or definitive solutions, depends, critically, on the actual time scale of the runaway collisional growth. The evaluation of such a time scale is not an easy task, depending on source and sink mechanisms, which change the number and mass distribution of orbital objects, and on the vulnerability of spacecraft and upper stages to catastrophic collisional breakups.

2. SOURCES AND SINKS

There are only a few sources of orbiting objects able to catastrophically fragment by impact spacecraft and rocket bodies: launches, on-orbit explosions and, of course, collisions. Because at present the collision probability is still very low, new launches – involving satellites, upper stages and mission related objects – and explosions are the leading sources and this explains why a large international effort was put in place in order to passivate spent rocket stages and remove spacecraft at the end-of-life from critically important regions of space (e.g. the geostationary ring).

As far as the sinks are concerned, aside from high eccentricity orbits, for which the luni-solar perturbations may produce an effective reduction of the orbital lifetime, the only mechanism able to remove sizeable objects from space is the air drag. Nevertheless, its effectiveness is proportional to the local atmospheric

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density and area-to-mass ratio of space objects, so it is not very efficient in removing large orbital debris above 650 – 700 km. This means that even maintaining the relatively modest level of space activity carried out at present, the number of abandoned satellites, spent upper stages and large debris is destined to grow, at altitudes greater than 650 km, providing one of the ingredients needed to trigger a collisional chain reaction.

3. CRITICAL DENSITY

In order to evaluate if a given population of orbital debris, for instance in a certain altitude shell, could be dominated by a collisional evolution, the concept of critical density was introduced [2][7][8][9][10]. The number density of intact objects and large debris is above the critical density if fragments able to produce a catastrophic breakup are created, by mutual random collisions, faster than they are removed by air drag. In other words, if the object density is higher than the critical one, the number of orbital debris will increase, even if new space launches and on-orbit explosions were avoided. After an appropriate time interval, that may be quite long, the system will reach a collisional equilibrium state.

In orbit around the earth, at altitudes where the atmospheric drag is not very effective in removing the large space objects, the critical density barrier has already been exceeded. However, from a practical point of view, this information alone is not very useful, because the expected increase in the number of debris might be very slow, with associated collisional equilibrium time scales of hundreds or thousands of years. Therefore, a realistic estimation of the debris growth rate is needed, together with a guess of the time scale linked to the transition from approximately linear to exponential growth. This information is fundamental to evaluate the timing and effectiveness of any mitigation measure to be adopted.

4. COLLISIONAL BREAKUPS

The vulnerability of intact space objects (i.e. spacecraft and upper stages) to catastrophic breakups and the mass distribution of the fragments are essential in determining the critical density level and the eventual debris growth rate.

For the mass distribution, a few relationships have been proposed [9][11][12] and compared in their effects on the long-term evolution of the debris population [9][13]. The propensity of an object to a catastrophic disruption is a function of the target impact strength or fragmentation threshold, which for spacecraft is about 40,000 J/kg, but may be significantly higher (60,000 J/kg) for spent and passivated rocket bodies.

However, in order to have a catastrophic fragmentation, the collision must occur close enough to the centre of mass of the interacting objects, to obtain an appropriate transfer of the impact energy to the structure of the bodies. If this is not the case, a CERISE-like event will result, with the creation of a limited number of new debris. Because many satellites presents very large structures (solar panels, radiators, booms) loosely connected to the main spacecraft bus, where most of the mass is concentrated, in dealing with collisions it is very important to define an effective collisional breakup cross-section, which in numerous occasions may be much smaller than the average cross-sectional area of a spacecraft. This not negligible difference makes many satellites much more resistant to random collisions with respect to the simple estimations based on the average cross-section. Satellite constellations, for instance, may be not so vulnerable to collisional breakups as deduced by too simplified analyses.

5. LONG-TERM SIMULATIONS

One possible approach to investigate the evolution of orbital debris and the practical effectiveness of mitigation measures was to develop models and software codes able to realistically describe the relevant physical processes (orbital dynamics, air drag, on-orbit explosions, collisions, etc…) and the operational practices (launches, mission related objects, disposal options) connected to the space activities in orbit around the earth. However, this can be made quite easily for short periods of time, but becomes a very demanding task if the goal is to model the orbital debris evolution over one century or more.

In spite of the inherent difficulties and limitations involved, a few groups developed a quite complex set of computer codes to simulate in detail the long-term evolution of the debris population in earth orbit [9][11][14][15][16]. One of the groups active in the field was based in Pisa, and during the 1990's developed, under European and Italian Space Agency contracts, a couple of independent software tools. One of them, the Semi-Deterministic Model for Space Debris Mitigation analysis (SDM) was continuously upgraded to include more and more sophisticated traffic and mitigation options [9][17].

The most relevant results obtained for the low earth orbit regime, with simulations spanning up to 200 years, were presented elsewhere [13][18] and will be only briefly recalled here:

1. Assuming a business-as-usual launch activity, only the adoption of a full mitigation strategy, including on-orbit explosion avoidance and immediate or delayed de-orbiting for new satellites and upper stages, is able to roughly stabilise the number of objects larger than 10 cm, or at least to guarantee a very slow linear growth during the next two centuries.
2. The amount of delay (0, 25 or 50 years) in the satellite end-of-life de-orbiting slightly affects – by less than 10% – the quasi-equilibrium number of objects larger than 10 cm, a longer delay corresponding to a larger number of objects in orbit. However, as soon as the dynamical equilibrium between launches and de-orbiting is reached, the small growth rates observed are similar in the three cases.
3. For millimetre and centimetre sized particles, no combination of the mitigation measures analysed (on-orbit explosion avoidance, suppression of mission related objects, immediate or delayed de-orbiting) is able to stop the debris growth. However, only the combined adoption of all the mitigation measures considered may guarantee a linear growth during the next two centuries, even though the de-orbiting strategy adopted (with residual lifetime of 0, 25 or 50 years) has no clear influence on the final numbers. On the other hand, explosion and mission related objects suppression alone cannot avoid the onset of the exponential growth in a few decades.
4. The suppression of mission related objects generated at the present rate has negligible long-term effects.
5. For the collision rates, the same conclusions presented above apply. In particular, the end-of-life de-orbiting is needed to stabilise the collision probability, apart from a modulation due to the air density variations linked to the solar cycle. The amount of the residual lifetime of the disposal orbits only affects the quasi-equilibrium value. For objects larger than 10 cm, the adoption of a full mitigation strategy entails a collision rate, after one century, of 0.20 – 0.25 per year, against 1.5 – 1.6 per year if no mitigation measure is applied.
6. If a full mitigation strategy is adopted, the expected cumulative number of collisions between objects larger than 10 cm is reduced by 2/3 – 3/4 after one century and by more than 90% after 200 years. The same reduction factors apply, approximately, to collisions between debris larger than 1 cm.
7. As said before, in a few decades the onset of the exponential growth is observed for millimetre and centimetre sized particles, unless a full mitigation strategy is adopted. On the other hand, the growth of the objects larger than 10 cm remains approximately linear in the first century, even in the business-as-usual and explosion suppression cases, beginning to show a clear exponential increase only during the second century spanned by the simulations.

Of course, many of the basic assumptions adopted today in such simulations might (and will) fail in a so long time interval, spanning one or two centuries, but only by looking at the results of very long model runs it is possible to evaluate the measures to be taken in the next few decades, tearing away the confounding message of a few stochastic events superimposed to smaller, but steady, long-term trends. In other words, to clearly understand which mitigation measures should be adopted today or in the near future, the effects of any action proposed must be propagated for one century or more. Therefore, a long time span must be used not to provide accurate, and meaningless, debris predictions after one or two centuries, but to put in a clearer perspective the long-term effectiveness of the mitigation measures under investigation.

The results obtained confirm the importance of spacecraft and rocket bodies end-of-life passivation to avoid on-orbit explosions, but the de-orbiting of new satellites and upper stages at the end of their mission is needed as well to maintain under control the debris and collision rate increase and to avert the onset of an exponential growth for at least a couple of centuries. The strategy adopted for the de-orbiting, immediate or delayed, did not significantly affect the output of the simulations, provided that the maximum residual lifetime in disposal orbit were maintained below 50 years and the measure were implemented quite soon. However, a longer residual lifetime in disposal orbit (e.g. 75 or 100 years) may be too risky, because too close to the time scale associated to the onset of the exponential growth. Moreover, the reasonable perspective of a moderate future increase in the launch rate would imply the adoption of a smaller residual lifetime (i.e. 25 – 30 years), in order to compensate for the greater number of objects put in orbit.

Of course, the results just discussed offer a picture limited by the specific assumptions made, the model uncertainties and the time span considered. However, the results of a sensitivity analysis carried out by considering different collisional fragmentation models and thresholds show that the conclusions presented are qualitatively and quantitatively both consistent and reliable, at least for the first century [13].

In conclusion, the orbital debris environment is already collisionally unstable in some orbital region [8], but the intrinsic growth rate is still very low. The mitigation measures analysed will be insufficient to reverse this situation, ensuring a very long-term debris stability or reduction, but they will be able, if applied soon and consistently, to gain precious time, giving the possibility to manage and control the debris growth, delay the onset of the exponential increase and develop new revolutionary technologies for the access to space.

6. THE GEOSTATIONARY ORBIT

Since the beginning of the space age, the geostationary ring has been regarded as a fundamental resource of humankind. At present, a large fraction of space launches (30-40%) and satellites put in orbit are reserved for missions in geostationary orbit. As of 31 December 2000, 878 objects were known to be present in the geosynchronous region, though the number of operational spacecraft was just 305 [19]. Moreover, preliminary observations with the European Space Agency Zeiss telescope in Tenerife have revealed a significant population of debris in the 0.1 – 1 m range, indicative of the presence of about 1600 uncatalogued objects, probably produced by the explosion of abandoned spacecraft and rocket bodies [20].

Due to the extremely rapid increase in the number of spacecraft and apogee kick motors at the geosynchronous altitude, a growing concern developed in the 1980s regarding the possible overcrowding of this important region of space, also because no effective natural mechanism was in place to remove the abandoned objects. For this reason, the Inter-Agency Space Debris Coordination Committee (IADC) proposed and endorsed a re-orbiting strategy for end-of-life geostationary satellites [20]. Following this recommendation, any spacecraft should be disposed, at the end-of-life, in a region above the geostationary ring and passivated, in order to reduce the risk of inadvertent explosions. The perigee of the disposal orbit was stipulated to be higher than the geostationary altitude by an amount ΔH (km) given by

$$\Delta H = 235 + C_r \times 1000 \times A / M \qquad (3)$$

where A is the satellite cross-sectional area (m^2), M is the satellite mass (kg) and C_r is a radiation pressure corrective coefficient, typically between 1 and 2, which specifies the amount of solar radiation transmitted, absorbed and reflected by the spacecraft [20].

From a purely mathematical point of view, the population of objects in the geostationary region is collisionally unstable in the very long-term, because no effective sink, like air drag, is present to remove the new fragments eventually created by catastrophic impacts. However, from a practical point of view, the present debris population can still be considered reasonably stable, as far as only the collisions are concerned, at least for a couple of centuries. In fact, the volume of space in which the motions occur is larger by a factor 5 – 6 with respect to the low earth orbit region and the average spatial density of spacecraft, rocket stages and large fragments is only 1/30, even including the recent optical observations. Moreover, although the spatial density close to the geosynchronous altitude may be an order of magnitude higher, including about 300 operational spacecraft, the typical collision velocities are slower then in low earth orbit by the same factor [21].

The relatively slow collision velocities at the geostationary altitude have the important consequence that a much heavier projectile is needed to catastrophically break up a given target. For instance, assuming a fragmentation threshold of 40,000 J/kg, at 10 km/sec – a typical collision velocity in low earth orbit – a satellite may be completely shattered by an impactor having just 1/1250 of its mass. But with an impact velocity of 1 km/sec or less, as in the geostationary orbit, only projectiles at least 100 times so massive can produce the same result. Therefore, for a catastrophic fragmentation to occur, the impactor mass should be at least 1/10 of that of the target.

For all these reasons, the geosynchronous environment is less exposed than the near earth region to the long-term risk of a significant collisional debris growth. However, if left unchecked, the overcrowding of the geostationary ring will create substantial operational problems well in advance of any major collision rate increase. On the other hand, the implementation of the Inter-Agency Space Debris Coordination Committee recommendation will be able to stabilise the debris population for at least a few centuries and, if needed, progressively higher (and/or slightly elliptic) graveyard orbits might be adopted [22].

The long-term simulations carried out with SDM confirm this picture [17][18]. Between 35,700 and 35,900 km of altitude, a steady increment of satellites and apogee kick motors was observed, in the business-as-usual case, over one century. On the other hand, the systematic adoption of satellite end-of-life re-orbiting, as recommended by the Inter-Agency Space Debris Coordination Committee, resulted quite effective in stabilising the number of both satellites and debris. In any case, no collision occurred in the simulation period.

7. SATELLITE CONSTELLATIONS

The long-term simulations performed have shown that satellite constellations with a moderate number of spacecraft (< 100) are not able to disrupt the debris environment if the full set of mitigation measures proposed for non-constellation satellites – including end-of-life de-orbiting – is strictly implemented [13][17][18]. In this case, several constellations can be operated at the same time, ensuring a stable large debris environment and a linear growth of centimetre and millimetre sized particles over at least two centuries.

However, a constellation with hundreds of satellites, placed in an altitude shell with already a high object density, may adversely interact with the background, creating a local debris population instability, able to significantly increase the risk of damaging collisions. The augmented collision risk will not be limited to the constellation spacecraft, but will extend several tens of kilometres, both below and above the constellation altitude.

8. SMALL SATELLITES

Current technology developments and cost saving considerations may promote in the future the growing use of mini and micro-satellites. How this traffic model change might affect the long-term evolution of the debris environment?

First of all, the generalised utilisation of mini and micro-satellites will make more difficult the broad adoption of an active de-orbiting option, because many of them will not carry on-board a suitable propulsion sub-system. In the long-term, this would produce an additional accumulation of abandoned satellites in orbital regimes scarcely affected by the atmospheric drag, with a consequent degradation of the debris environment. Moreover, by assuming that the classical relationship between satellite cross-section A (m^2) and mass M (kg) [11]

$$M = 62.013\, A^{1.13} \quad (4)$$

were approximately valid also for mini and micro-satellites, to a certain total mass of small spacecraft put in space would correspond a total collisional cross-section larger than that exhibited by big objects with the same launch weight (Table 1). For instance, if a given mass of big satellites were replaced by the same mass of micro-spacecraft, each weighting just 1/100 of the original average satellite, the total cross-sectional area would increase by 70%, even though the cross-section of a single satellite would be reduced by a factor 60 (Table 1).

However, the area-to-mass ratio of small satellites is generally higher, reducing proportionally their lifetime where the air drag is not negligible (Table 2). In addition, the purpose of many small satellites is mainly to obtain the same for less, thus resulting in an overall reduction of the mass and area put in space. At the limit, if each big satellite were substituted by a smaller one, the total cross-sectional area in orbit would be reduced considerably (Table 1).

Table 1. Small vs. Typical Satellites Cross-Section

Small Satellite Mass as a Fraction of a Typical Satellite	Cross-Section Reduction Factor for a Single Satellite	Cross-Section Enhancement Factor for an Equivalent Mass
1/10	1/8	1.3
1/100	1/60	1.7
1/1000	1/450	2.2

Table 2. Small to Typical Satellite Lifetime Ratio

Small Satellite Mass as a Fraction of a Typical Satellite	Area-to-Mass Ratio Increase Factor	Lifetime Ratio (Ignoring Solar Cycle and Luni-Solar Attraction)
1/10	1.3	0.77
1/100	1.7	0.58
1/1000	2.2	0.45

In conclusion, if in addition to the business-as-usual launch activity a significant number – a few dozens per year – of mini and micro-satellites will be launched, the stabilisation of the debris population in low earth orbit will be jeopardised, unless practical means to de-orbit also very small satellites are found. On the other hand, if used in alternative to standard large spacecraft, mini and micro-satellites may give a contribution to the debris environment mitigation. The final outcome will depend on the details of the actual launch traffic and orbital distribution.

9. THE IMPLICATIONS OF DE-ORBITING

As said before, spacecraft and upper stages end-of-life de-orbiting, immediate or delayed for a few decades, is absolutely needed to roughly stabilise the number of large space objects and to maintain under control the growth of centimetre and millimetre sized debris. Unfortunately, the impact of such a mitigation measure is quite significant in terms of mass and cost, as shown in Fig. 1 for standard mono and bi-propellant chemical propulsion systems.

The injection into a disposal orbit with a residual lifetime of 25 – 30 years implies a propellant saving of the order of a few percent of the total satellite launch weight, but the mass penalty remains considerable, even ignoring the propulsion sub-system. Low-thrust, high specific impulse motors (e.g. ion thrusters) need only a few percent (< 2 – 3%, depending on the initial altitude) of the satellite mass in propellant to obtain the same results, but they must be operated for very long times, also in atmospheric regions rich in atomic oxygen, and require a significant amount of electrical power. For these reasons, other solutions, like drag augmentation devices and electro-dynamic tethers, are sought.

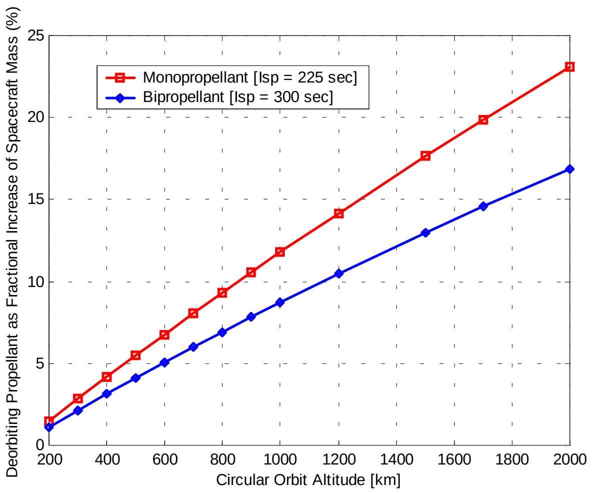

Fig. 1. Chemical Propellant Requirement for Satellite De-orbiting from Near Earth Circular Orbits

The most convenient way to implement a de-orbiting strategy with the existing chemical motors would be to lower the perigee altitude in order to attain the desired residual lifetime (elliptical disposal orbit). Obtaining a circular disposal orbit with the same residual lifetime would be, in fact, significantly more expensive in terms of the total velocity variation required (as a matter of fact, for circular orbits above 1200 km, the direct reentry would be less expensive). However, the generalised use of elliptical disposal orbits, with perigees close or below the altitude of the International Space Station and other important space assets, may involve, in the long-term, operational and political problems.

Assuming end-of-life disposal orbits with 25 years of residual lifetime, no significant debris environment difference was observed, in one century, between the elliptical and circular disposal options, and the number of collisions predicted in low earth orbit was practically the same. Therefore, the widespread adoption of elliptical disposal orbits, more convenient from the energetic standpoint, would not involve a global increase of the collision probability with respect to circular disposal orbits with the same residual lifetime [18]. But when the steady state between launches and re-entries is finally reached, perhaps a thousand of satellites might be in elliptical disposal orbits at any given time, approaching (or crossing) about 15,000 (30,000) times per day the altitude of the International Space Station and many other critical platforms. If the reentry were delayed by 50 years, the steady state number of satellites in disposal orbits would be even larger, with consequences easy to imagine.

Even though, at any given moment, the number of potentially risky objects might be significantly reduced, due to simple geometrical and dynamical arguments, it is not clear, at present, if such a situation could be acceptable from an operational (frequency of the avoidance manoeuvres disrupting critical spacecraft missions) and political (too many debris crossing the altitude of high priority space platforms) point of view. If this were not the case, the only options left would be the immediate end-of-life reentry or the increased orbital decay in circular orbit, by using electric thrusters, drag augmentation devices, or electro-dynamic tethers.

10. DRAG AUGMENTATION DEVICES

A mass and cost effective method to reduce the orbital lifetime of space objects could be the adoption of drag augmentation devices (e.g. balloons, sails), inflated at the end of the mission. However, from a debris mitigation point of view, the common wisdom is that what is gained in terms of lifetime reduction is lost in terms of collisional cross-section, leaving practically unaltered the debris impact probability, at least if the solar activity cycle and the luni-solar perturbations are disregarded.

Nevertheless, a drag augmentation device is, by definition, a very low mass system. This means that its eventual breakup would create exceedingly low mass fragments, characterised by high area-to-mass ratios, short orbital lifetimes, and the inherent inability to cause catastrophic impacts. On the other hand, the area of the spacecraft vulnerable to catastrophic collisions will remain the same, even after the deployment of the device. Therefore, the drag augmentation devices can be considered advantageous as de-orbiting means to mitigate and stabilise the debris environment in low earth orbit, reducing a satellite lifetime without increasing its expected rate of catastrophic collisions.

11. SPACE TETHERS

Another promising method proposed for the end-of-life de-orbiting of spacecraft and upper stages is based on the use of electro-dynamic tethers [23][24], but they are particularly vulnerable to small debris – artificial and natural – impacts, due to the peculiar structure and geometry. In low earth orbit, even a particle smaller than ½ of the tether diameter may cut a single-strand cable, compromising its mission. A tether system is, therefore, much more sensitive to space debris impacts than a typical spacecraft, because it can be severed by a single hit of a very small particle. In addition, a long tether can increase significantly the collision probability with spent upper stages and spacecraft, including operational satellites. The expected average impact rates, per kilometre of tether length, are of the order of $10^{-2} – 10^{-3}$ per year, in the 600 – 1000 km altitude range [25].

Again, the suitability of electro-dynamic tethers for end-of-life de-orbiting and long-term debris mitigation depends on their ability to withstand the small impacts, avoiding at the same time the collision with large and/or sensitive space objects (e.g. the International Space Station). Yet, the results of detailed computations [25] demonstrate that is possible to design and realise tethers for long duration missions, for instance by adopting a redundant wire, multi-strand, or ribbon-like design. However, if the number of long tethers in space at the same time were too large (several tens or a few hundred), the collision probability with spacecraft and upper stages – and between the tethers themselves – could not be neglected anymore. For this reason, the future tether systems in low earth orbit should also be able to control their internal and trajectory dynamics, in order to avoid collisions with operational and abandoned satellites.

12. CONCLUSIONS

From a collisional point of view, the debris environment around the earth is already unstable in several altitude intervals, but because the growth of impact fragments would be very slow, if any space activity were suspended now, the situation is still manageable.

The results of many detailed simulations of the long-term evolution of the debris environment, over one or two centuries, show that the generalised and consistent adoption of a full set of mitigation measures, including explosion suppression and end-of-life de-orbiting of spacecraft and upper stages, would be able to approximately stabilise the population of large objects, maintaining, at the same time, under control the linear increase of millimetre and centimetre sized debris. In certain orbital regimes, as the geosynchronous and semi-synchronous ones, the end-of-life satellite passivation and re-orbiting in higher graveyard orbits will be appropriate and effective as well, for the centuries to come, but this mitigation strategy is not recommended for low earth orbits, because the rapid accumulation of spacecraft and rocket bodies in a narrow altitude shell above 2000 or 2500 km would create in a few decades a new region of space prone to collisional instability.

Therefore, end-of-life de-orbiting in low earth orbit is absolutely necessary to preserve the circum-terrestrial environment in the long-term, but it may be expensive if carried out with the conventional chemical propulsion. However, some alternatives do exist, i.e. electric thrusters, drag augmentation devices and electro-dynamic tethers. Many technical problems must still be solved, including the minimisation of secondary debris production by the latter two, but several solutions have been proposed and are waiting for a practical validation.

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