IAC-20-A6.4.5

Evaluating the Short and Medium Term Impact of Space Activities in Low Earth Orbit

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Abstract

The evolution of cataloged orbital debris in low Earth orbit (LEO) over the last quarter of century was analyzed in detail, to gather insights on the development of space activities, on the effectiveness of the debris mitigation measures recommended in the meantime, and on the environmental impact of fragmentations, in particular collisions, both intentional and accidental. The main conclusion was that the observed evolution matched on the whole the predictions of the unmitigated business-as-usual scenarios simulated twenty years ago, and that the benefits caused by the progressive worldwide adoption of mitigation measures were unfortunately offset by a couple of catastrophic collisions and prolonged weak solar activity. Nevertheless, and despite the dramatic increase of launched satellites since the mid-2010s, nowhere have the signs of more than linear increases been revealed so far, aside from a few sizable, but circumscribed, fragmentation events. Even though above 700 km the debris population may be intrinsically unstable in the long run, the situation can still be managed and controlled. Therefore, even though the overall picture has worsened during the last 25 years, nothing of irremediable has been done so far. This does not mean that extreme care is not required in planning and conducting new space activities from now on, especially in a phase of increased and ever more rapid exploitation of space, to ensure its long-term sustainability and full utilization. In order to assess the sustainability of space activities, especially in the short and medium term, that is over the next 10-30 years, several environmental criticality indexes have been introduced and discussed, estimating their current values in LEO, as well as their upper limits – sometimes considered tolerable, others not – associated with specific scenarios of debris growth. They could provide simple tools for evaluating the relative and absolute impact on the debris environment, either in LEO as a whole or in specific altitude shells, of new spacecraft deployments and operations, as in the case of mega-constellations of satellites.

Keywords: space debris, low Earth orbit, cataloged objects evolution, environmental criticality indexes, sustainability of orbital activities.

1. Introduction

Space activities in low Earth orbit (LEO) are undergoing an authentic revolution, quietly heralded, around the middle of the last decade, by the sudden and rapid increase in the launch rate of small satellites, and currently made evident and brought to the fore by the deployment of the first large constellations of satellites. Between the beginning of 2014 and the beginning of 2020, i.e. in just six years, the total mass of the artificial objects in orbit around the Earth has grown by approximately 22% [1], but the number of operational spacecraft has more than doubled [2,3], reaching a value close to 2900 in mid-2020 and still rapidly increasing. Moreover, taking into account all the applications filed by satellite operators to the relevant licensing authorities, more than 100,000 new spacecraft might be launched in orbit by 2030 [4-6]. And even if only 10% of these plans were realized, taking into account financial and market constraints, another 10,000 operational satellites could still be added to those currently in service, multiplying by at least a factor of ten the number of functioning spacecraft present at the beginning of 2014.

Since the mitigation measures currently applied worldwide were conceived when space activity was very different from the current one, and the changes underway are very rapid and not well suited to the time needed to reach thoughtful, balanced and effective agreements, with a broad consensus base, in the appropriate international fora, the need to have fast and easy to use methods providing realistic assessments of traffic and Earth orbit usage scenarios, in constant change, is of utmost practical importance. For these reasons, we have been involved in the development of new approaches and procedures for evaluating the operational and environmental impact of massive satellite deployments in LEO, and for providing preliminary quantitative assessments with no need of complex models and computations. Specific indexes were introduced for gauging the environment criticality [7-12], and some of the approaches were applied to several scenarios involving the launch of many small satellites and several large constellations, focusing the attention on the consequences of their level of compliance with appropriate end-of-life disposal, including spacecraft failures [13-15].

After a detailed analysis of how the environment has changed in the last quarter of a century, this paper further develops the above mentioned line of research, proposing several indicators to assess the sustainability of space activities, especially in the short and medium term, that is over the next 10-30 years.

2. Cataloged objects in orbit around the Earth

The catalog maintained by the US Space Surveillance Network (SSN) was for several decades, and still is, the most complete record of artificial objects in circumterrestrial orbit, with sizes around 10 cm or larger. At the beginning of 2020, there were approximately 23,000 objects routinely tracked by the SSN sensors, about 20,000 of which officially cataloged. The objects left out of the catalog had not yet been identified and/or their trajectory had not still reached a sufficiently accurate modeling.

During the years, the performances of the SSN ground based radars and optical sensors gradually improved, making them able to detect and track smaller orbital debris, but since more than one sensor must be capable to track an object before it can be cataloged, the sensitivity of some individual radars is greater than that of the overall network [16]. Moreover, the sensitivity of the network is highly dependent on the altitude of the object [16,17], with the limiting detection size going from ~5 cm around 400 km, for radars, to ~20 cm in geosynchronous orbit (GEO), for optical sensors [17,18]. The catalog is therefore affected by a certain gradient of inhomogeneity as a function of height, due to the selection effect of the varying SSN sensitivity, but in LEO, i.e. below 2000 km, ~10 cm may represent a quite accurate overall sensitivity threshold.

In addition, as well as a consequence, to being inhomogeneous, the catalog is also incomplete, that is a fraction of the objects larger than a given diameter is missing. Apart from specific calibration campaigns of observations with dedicated high sensitivity sensors, totally beyond the reach of the authors, another way, even though purely theoretical, for estimating the completeness of the catalog can be the comparison of the latter with the predictions of some reliable orbital debris environment model, like the various versions of the ESA's Meteoroid and Space Debris Terrestrial Environment (MASTER) model.

For orbital debris ≥ 10 cm and assuming the MASTER models as reference, we obtained a catalog "theoretical" completeness of 75% for 1999, of 65% for 2001, of 67% for 2009, of 63% for 2017, and of 59% for 2020, with a mean value of 66%, using the data found in [1,19-24]. Considering also the objects routinely tracked, but still not included in the official catalog, the missing orbital debris ≥ 10 cm decrease to about 20-30%. Focusing the attention in LEO, i.e. below 2000 km, the completeness of the catalog improves to > 80% for debris ≥ 10 cm, again inferred from the information found in [1,19-24], while for objects ≥ 20 cm the completeness was estimated to be 90% to 99% [25].

Another incompleteness issue derives from the fact that the unclassified catalog available to civilian non-US users, like us, does not include classified objects, i.e. those belonging to the US or allied countries and linked to sensitive intelligence, military or security space missions. However, the fraction of classified objects in the catalog, around 4%, is small compared with the overall incompleteness, and it was found by us quite stable during the last couple of decades (4.0% in 2003, 3.5% in 2017, 4.5% in 2020) [18,19].

In conclusion, the catalog maintained by the US SSN is affected by some limitations, as observational selection effects and incompleteness, varying over the years and with altitude. However, as shown in the previous discussion, such limitations can be evaluated and managed. Moreover, the overall evolution of the catalog was relatively smooth, in terms of sensitivity, over the last quarter of century, and the amount of incompleteness has not dramatically changed during the same period. In addition, there is no alternative as precise and accurate. For this reasons, we used the unclassified catalogs to investigate in detail the evolution of the LEO debris environment from 1994 to 2020.

2.1 Catalogs available for this study

In our laboratory, we had available 14 unclassified orbital debris catalogs for the following years: 1994 (January 1), 1997 (January 1), 1999 (January 1), 2008 (June 10), 2009 (April 1), 2010 (April 20), 2011 (May 1), 2012 (July 18), 2013 (July 8), 2015 (January 7), 2016 (February 17), 2017 (May 3), 2019 (June 26), and 2020 (June 4). From 2008 to 2020 (included), independent catalogs for spacecraft, rocket bodies, intact objects (spacecraft + rocket bodies) and debris (fragmentation pieces + mission related objects) were available as well, together with the CelesTrak catalog of active satellites, but only for 2020.

3. Past evolution of cataloged objects in LEO

During the 60 years from 1960 to 2020, the overall growth of cataloged objects orbiting the Earth can be roughly approximated by a linear increase of nearly 333 objects per year [1], of which 249 objects per year in LEO [20]. In medium Earth orbit (MEO), in GEO and above GEO, linear growths with nearly constant angular coefficients offer quite accurate representations of the observed evolution, even over shorter time spans, while in LEO the details are more complex, leading to several recognizable phases and significant variations, the latter due to sizable fragmentation events [20].

During the first phase in LEO, from 1960 to 1990, the number of cataloged objects increased, on average, by 240 per year. From 1990 to 1996, the mean rate of increase shrank to about 167 objects per year, then dropping practically to zero for a decade, from 1997 to 2007 [20]. This phase of zero growth followed a sizable fragmentation event in 1996 (the third one recorded so far in terms of cataloged debris generated), i.e. the explosion of the Pegasus upper stage used to launch the STEP-2 satellite, which had produced more than 750 cataloged fragments [26,27], causing a sudden jump in the number of cataloged objects [20].

The years 2007-2009 were characterized as well by three significant fragmentation events [26,27]: the destruction of the Fengyun 1C satellite with an impactor fired from the ground, in 2007, which generated more than 3400 cataloged fragments (making of it the worst breakup recorded so far); the explosion of the Cosmos 2421 satellite, in 2008, which generated more than 500 cataloged fragments (fourth breakup in terms of cataloged debris); and the accidental collision between the Iridium 33 and Cosmos 2251 satellites, in 2009, which generated around 2300 cataloged fragments (resulting in the second worst breakup ever occurred). These three events in rapid succession, in particular the first and the last one, caused steep jumps in the number of cataloged objects in LEO, increasing the population by more than 70% [20].

From 2009 to 2015, the LEO population of cataloged objects experienced the longest phase of decline recorded since the beginning of the space age, with an average decrease of nearly 170 objects per year [20]. However, this trend was unfortunately reversed by the battery explosion occurred, at the end of 2015, on the NOAA 16 satellite, which generated more than 450 cataloged fragments (eighth worst breakup ever) [26,27]. Thereafter, between the end of 2015 and the beginning of 2020, a significant change in the launch pattern involving the deployment of several tens of mini or micro-satellites at a time (started in 2014, but accelerating after 2016) [28], coupled with a declining solar activity cycle and, consequently, to less effective atmospheric drag in low LEO, triggered a new growth phase for the LEO catalog, with a mean net increase of 265 objects per year [20].

This new launch trend is destined to continue. During the 2010s, the yearly average growth rate of small satellites was 29%, 2019 had the highest number of small satellites launched to date, i.e. 385, accounting for 10% of the total satellite mass put into orbit, slightly more than 90% of which in LEO, and during the 2020s an average of 1000 small satellites will be launched each year [29].

3.1 Evolution as a function of height (1994-2020)

From 1994 to 2020, the evolution of the density of cataloged objects in LEO as a function of height is shown in Fig. 1. The overall growth was far from uniform, as also highlighted in Fig. 2. Most of the increase actually occurred between 300 and 1000 km, with an enhancement factor significantly higher than 2 in much of the interval and reaching a peak of more than 10 between 450 and 500 km. Below 300 km the number of cataloged objects instead decreased (enhancement factor < 1), while above 1000 km it slightly increased, with an enhancement factor just above 1, except for the range of heights from 1100 to 1300 km, where it was anyway around 2 (Fig. 2).

Concerning the growth of cataloged objects in the quarter of century 1994-2020, the LEO region can therefore be split into three sub-regions: the high LEO, between 1000 and 2000 km; the low LEO, between 300 and 1000 km; and the orbital decay region, below 300 km. Most of the growth observed occurred in low LEO, while in high LEO it was relatively uniform and restrained. In the orbital decay region, finally, there was a decrease of average resident objects in 2020 compared with 1994, but the picture there is quite sensitive to solar activity, space operations and small fluctuations in the number of objects, due to the sizable atmospheric drag, short orbital lifetimes and average low object density.

Analyzing in greater detail what happened in each single 50 km height bin, from 1997 to 2020 the cataloged object density remained practically stable between 200 and 250 km. No systematic growth was also observed, from 1994 to 2020, between 250 and 350 km, but large fluctuations with amplitudes up to ~100% of the average values occurred. From 1994 to 2019, the same was also true between 350 and 400 km, but from 2019 to 2020 the object density increased by 129%, due to a sudden surge in the launch rate of small satellites. This sudden surge was also evident at 400-450 km (+188%, since 2017), at 450-500 km (+368%, since 2016), at 500-550 km (+140%, since 2016), and at 550-600 km (+102%, since 2016), while before 2016-2017 each of these height ranges had been characterized by a practically constant (400-500 km) or slightly increasing (500-600 km) density of cataloged objects for 20 years.

The 50 km altitude bins from 600 to 950 km were characterized by approximately linear increases of the object density during the overall time span considered. The average growth rates were different from bin to bin: as reflected in Fig. 2, some "bumps" due to the large fragmentation events occurred in this altitude range [26,27] were clearly evident in the data, but in general the increasing trend was essentially linear.

The growth of cataloged object was even better fitted by linear trends in the altitude bins from 950 to 1150 km, and from 1350 to 1550 km. Between 1150 and 1250 km, a linear increase well represented the situation until 2019, when the rise took on a significantly steeper slope due to the launch of new satellites. Between 1250 and 1350 km, on the other hand, a quite regular linear growth, displayed before 2011 and after 2013, was perturbed by the cataloging, mostly between 2011 and 2012, of additional debris shed in space by the SNAP-10A satellite, launched in 1965 with a nuclear power plant on board. This caused the rise of the cataloged debris density by more than 60% at 1250-1300 km.

Between 1550 and 1600 km, the density of cataloged objects was stable from 1994 to 2008, then increased linearly by more than 15% from 2008 to 2020, mainly due to an almost doubling of the (abandoned) spacecraft. From 1600 to 1750 km, a quite regular and moderate linear increase was again recorded over the time span considered. Globally, the same basically applied also from 1750 to 2000 km, even though a nearly stable phase of object density characterized the period from 1997-1999 to 2016. Before and after this stable phase, the increase was linear and mainly due, since 2016, to the raising number of disposed spacecraft.

3.2 Evolution of types of objects (2008-2020)

Focusing the attention on the period 2008-2020, with the data available we were able to analyze the evolution of the catalog in LEO also for specific classes of objects, that is intact objects, i.e. spacecraft + rocket bodies (Figs. 3 and 4), spacecraft (Figs. 5 and 6), rocket bodies (Figs. 7 and 8), and debris, i.e. breakup fragments + mission related objects (Figs. 9 and 10). The situation in LEO in June 2020 is summarized in Fig. 11, in which also the distribution of active satellites, courtesy of the CelesTrak website maintained by T.S. Kelso, is presented.

For the purposes of this paper, the time span considered offered as well various advantages: it was sufficiently long, i.e. 12 years; it included in the first half the old traffic and mission pattern, while in the second half the transition to the emerging trends of the so called new space economy, i.e. small satellites, multiple launches and mega-constellations, was well represented; and, finally, no significant intentional breakup with lasting consequences occurred since 2008, so the evolution observed was entirely ascribable to new launches, normal space operations, disposal practices, natural orbit perturbations and accidental breakups, the latter consistent with the inventory of satellite and rocket stages in LEO (old and new designs), with the passivation measures applied, and with the probability of unintentional collision among cataloged objects.

Therefore, the period 2008-2020 was believed very useful to characterize the effects of relatively recent and current space activities carried out in accordance with the goals and capabilities of the public and private players involved, while avoiding, at the same time, particularly deplorable behaviors, such as the deliberate production or release of debris with significant orbital lifetime.

3.2.1 Intact objects: spacecraft and rocket bodies

Figs. 3 and 4, and Figs. 12-16, present the combined density evolution of intact objects, with the density evolution of spacecraft shown in Figs. 5 and 6, and Figs. 17-21, and that of rocket stages shown in Figs. 7 and 8, and Figs. 22-26.

From 2008 to 2020, most of the growth of intact objects, by a factor higher than 3, occurred between 350 and 600 km (Fig. 4), mainly due to spacecraft (Fig. 6). The new spacecraft launched in this period also dominated the smaller growth observed elsewhere (Figs. 4 and 6), i.e. below 350 km and between 600 and 2000 km, while the increase of upper stages was always less than a factor of 2, from 200 to 750 km and from 1050 to 1350 km, and basically nil from 750 to 1050 km and from 1350 and 2000 km (Fig. 8).

Between 200 and 250 km the density of intact objects remained practically stable, and slightly increased between 250 and 300 km (Fig. 12), mostly reflecting the trends observed for spacecraft (Fig. 17), while the density of rocket bodies fluctuated around a stable value (Fig. 22). Between 300 and 700 km, however, there was a significant increase in the growth rate of intact objects during the second half of the period (Figs. 12 and 13), driven uniquely by spacecraft (Figs. 17 and 18), being the density of rocket bodies essentially stable (Figs. 22 and 23).

Above 700 km (Figs. 14-16) the evolutionary trends were much more steady and regular, and the growths, in the altitude bins in which they occurred, were moderate, still mostly in line with old-fashioned space activities, even though the signature of the new space economy launch patterns can be glimpsed in the last years of the period considered, in particular between 700 and 1000 km (Fig. 14). Again the spacecraft (Figs. 19-21) were the driving players, both as new deployments (Fig. 19) and end-of-life disposals (Fig. 21), while the density of rocket bodies remained almost steady even between 700 and 2000 km (Figs. 24-26).

3.2.2 Debris: breakup pieces and mission related objects

Figs. 9 and 10, and Figs. 27-34, present the density evolution of cataloged debris, comprising the fragments of on-orbit breakups and the mission related objects. For the purposes of this paper, this component of the catalog is very important, because it represents the collateral effect of space activity, often unwanted and unexpected, as in the case of accidental fragmentations. At least in principle, with an appropriate design, spacecraft and upper stages might be controlled, managed and properly disposed directly, while debris can only be controlled indirectly, by implementing mitigation measures, which may however be insufficient or fail. Therefore, the analysis of the debris evolution over time offers a simple, but effective, metric for assessing the intrinsic global ability of our space policy, technology, operational practices and mitigation measures in addressing the long-term sustainability of the circumterrestrial environment. And as shown in previous studies [30-38], it is precisely the exponential growth of collisional debris that can trigger a chain reaction capable of rendering certain regions of space around the Earth unusable, the so-called Kessler Syndrome.

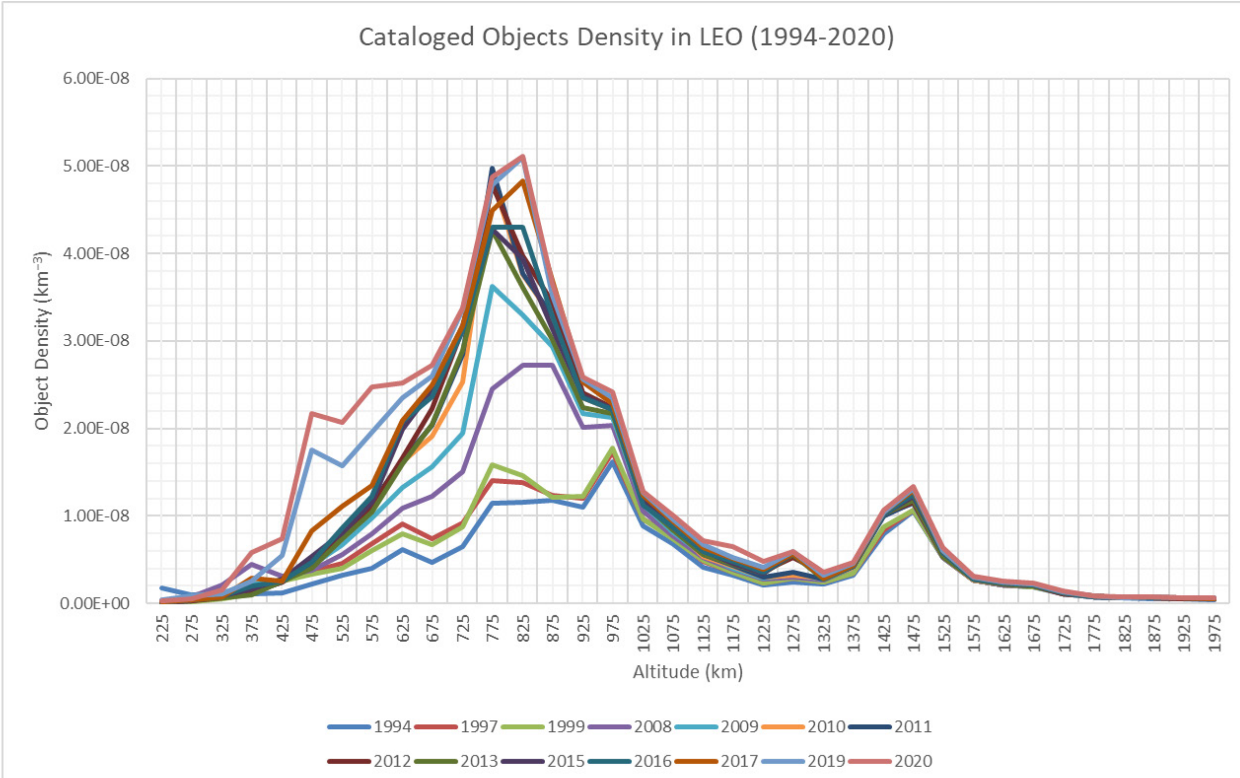

Fig. 1. Evolution of the density of cataloged objects in LEO, averaged over 50 km altitude bins, from 1994 to 2020 (the altitude is counted from the mean equatorial Earth's radius)

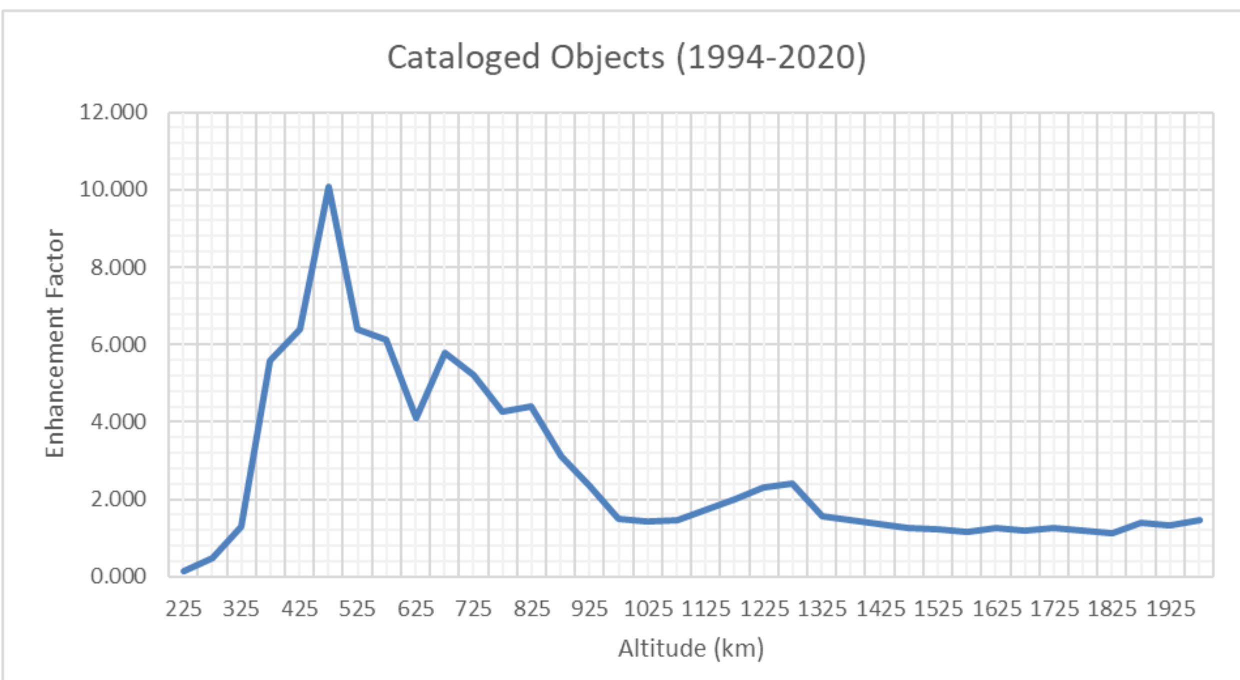

Fig. 2. The enhancement factor, plotted as a function of the altitude with respect to the mean equatorial Earth's radius, shows how many times the cataloged objects in LEO multiplied from 1994 to 2020

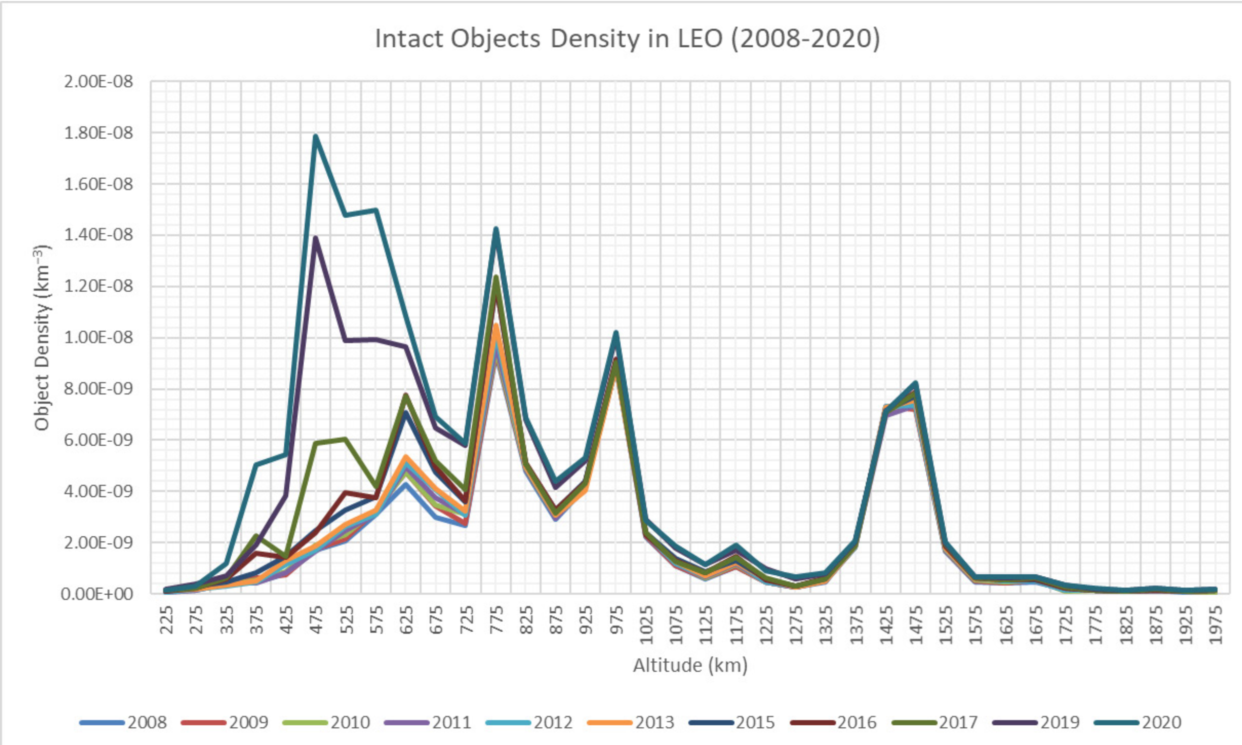

Fig. 3. Evolution of the density of cataloged intact objects in LEO, averaged over 50 km altitude bins, from 2008 to 2020 (the altitude is counted from the mean equatorial Earth's radius)

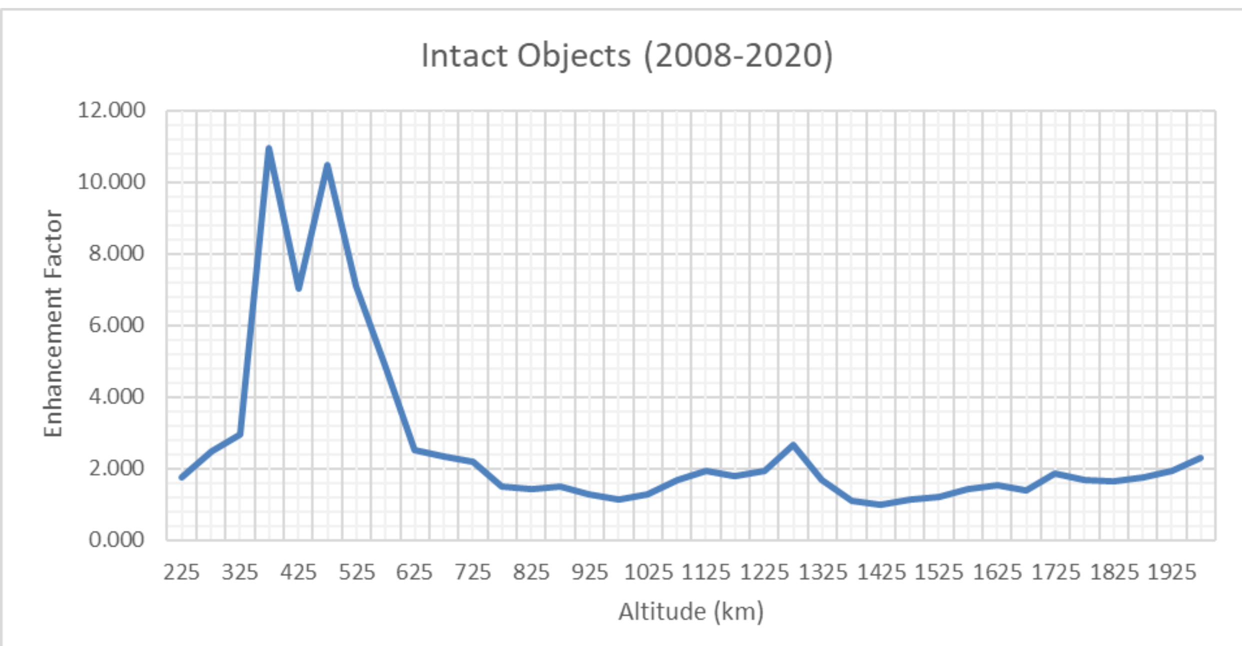

Fig. 4. The enhancement factor, plotted as a function of the altitude with respect to the mean equatorial Earth's radius, shows how many times the cataloged intact objects in LEO multiplied from 2008 to 2020

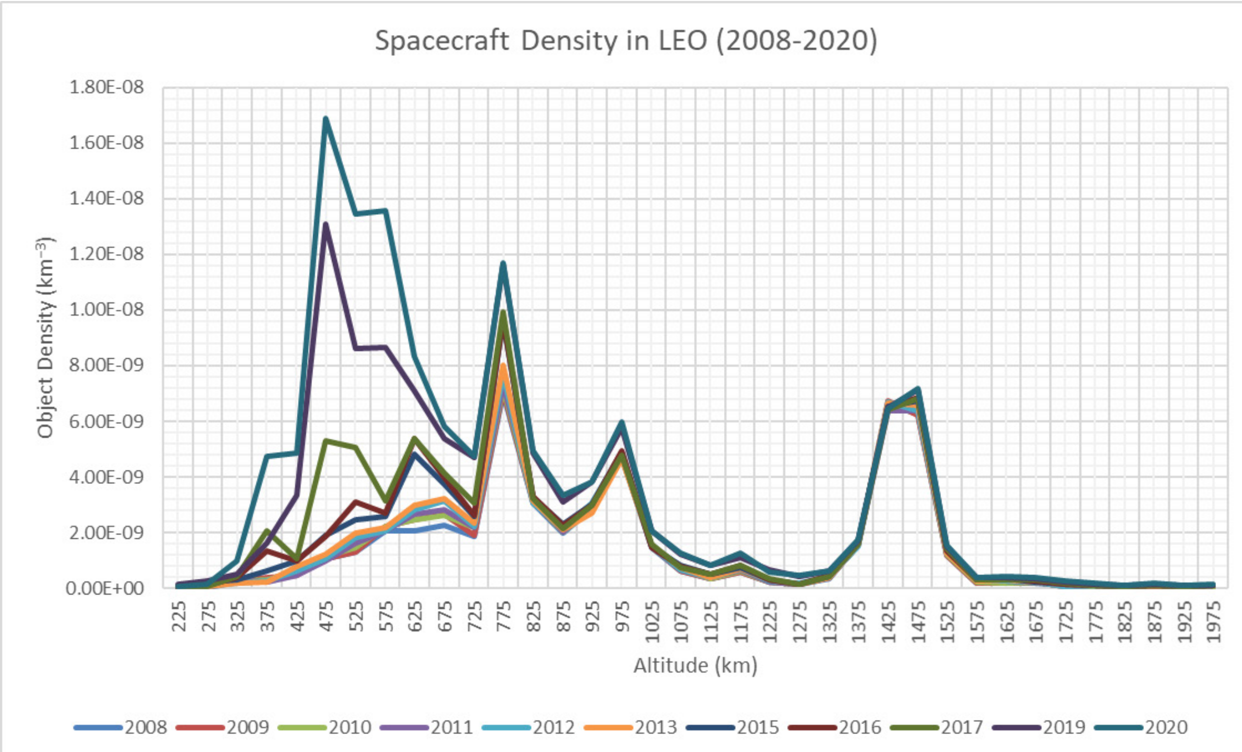

Fig. 5. Evolution of the density of cataloged spacecraft in LEO, averaged over 50 km altitude bins, from 2008 to 2020 (the altitude is counted from the mean equatorial Earth's radius)

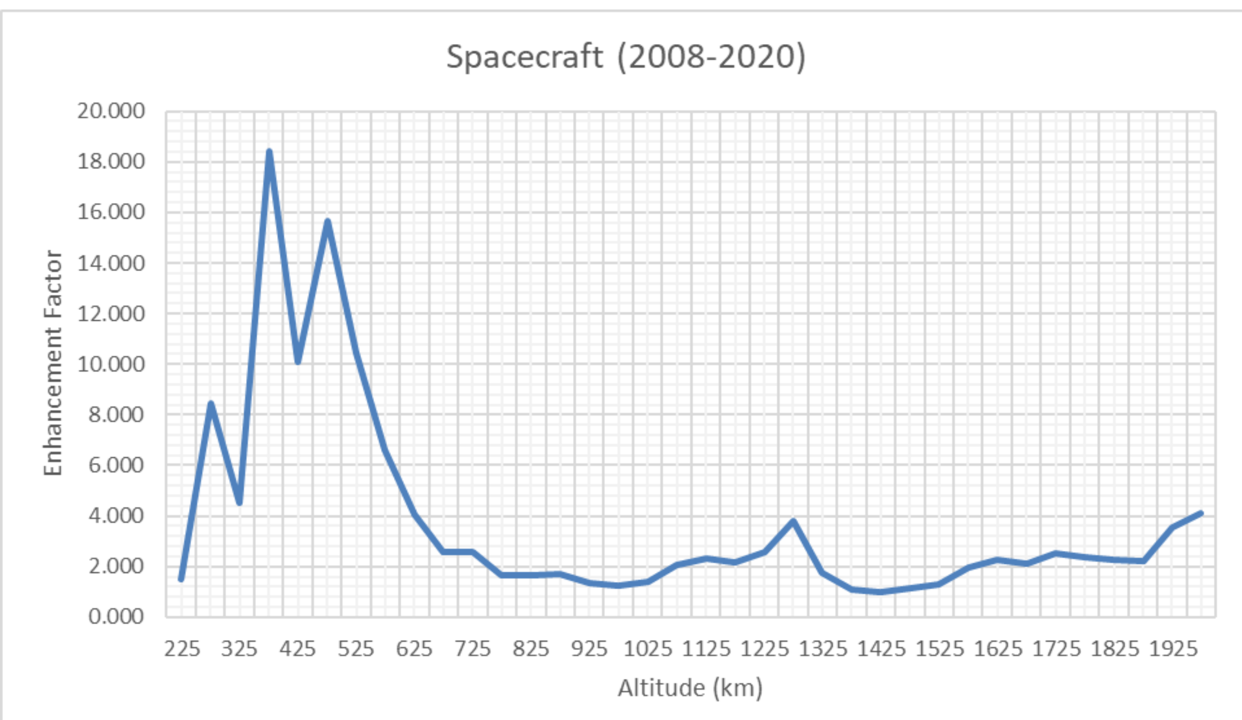

Fig. 6. The enhancement factor, plotted as a function of the altitude with respect to the mean equatorial Earth's radius, shows how many times the cataloged spacecraft in LEO multiplied from 2008 to 2020

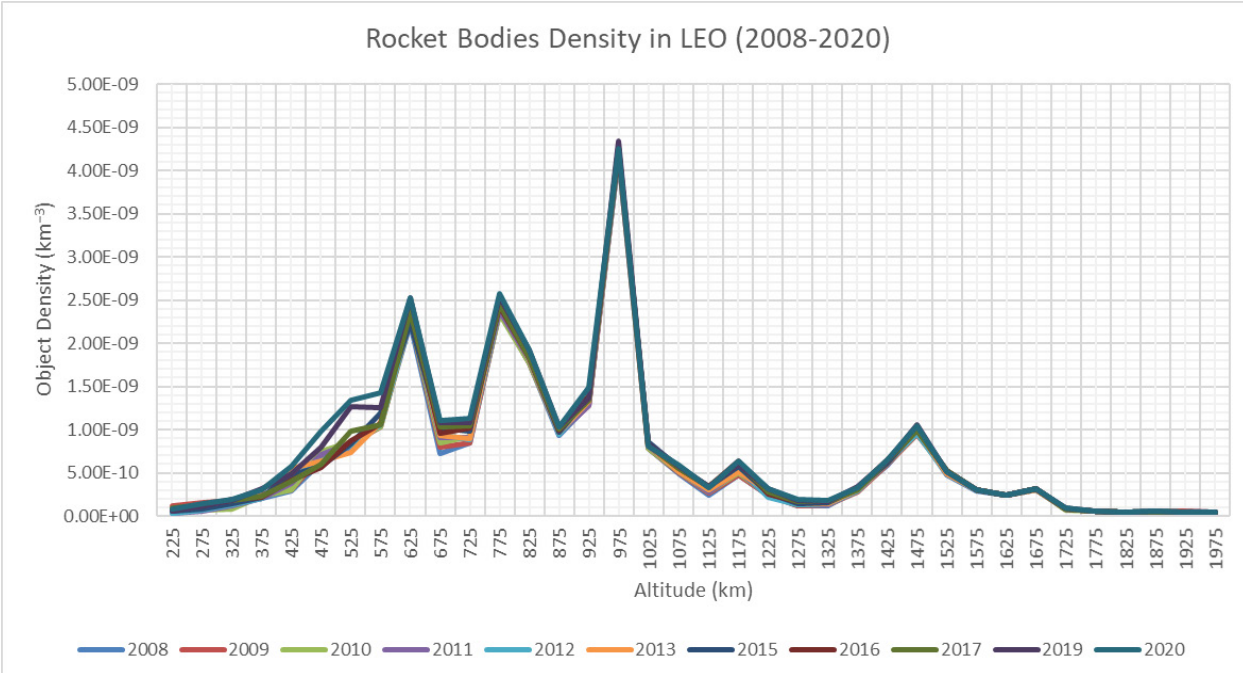

Fig. 7. Evolution of the density of cataloged rocket bodies in LEO, averaged over 50 km altitude bins, from 2008 to 2020 (the altitude is counted from the mean equatorial Earth's radius)

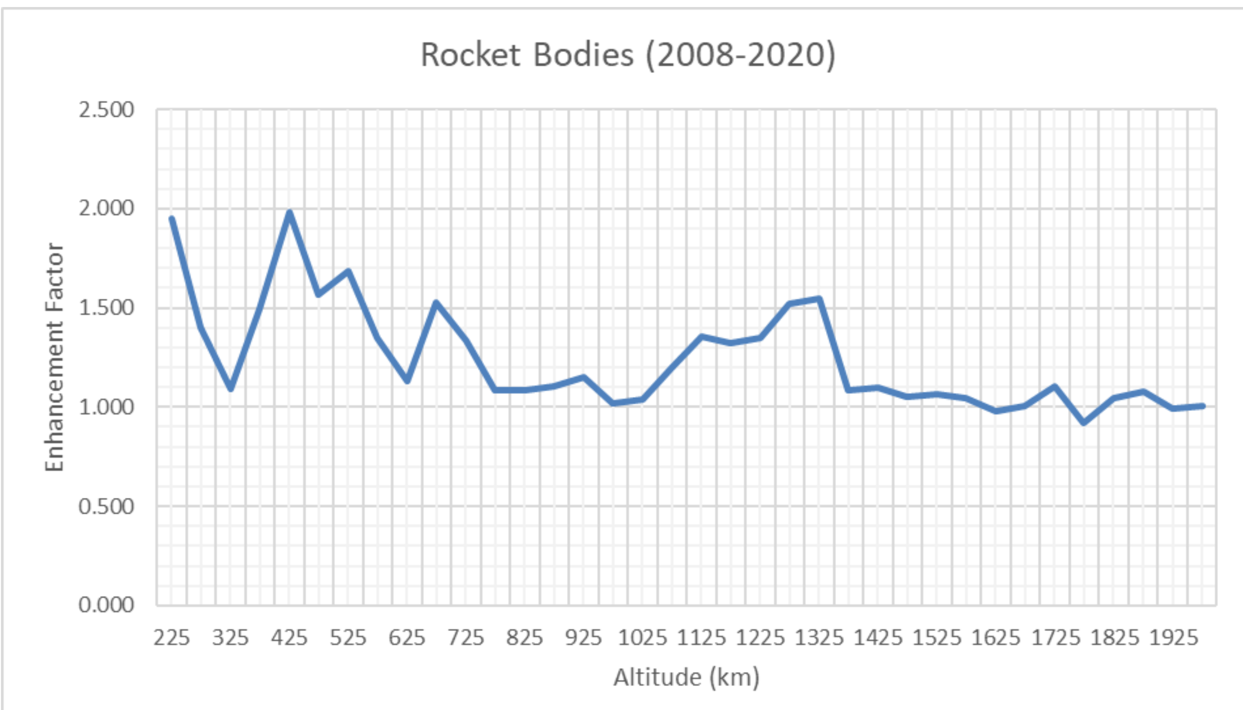

Fig. 8. The enhancement factor, plotted as a function of the altitude with respect to the mean equatorial Earth's radius, shows how many times the cataloged rocket bodies in LEO multiplied from 2008 to 2020

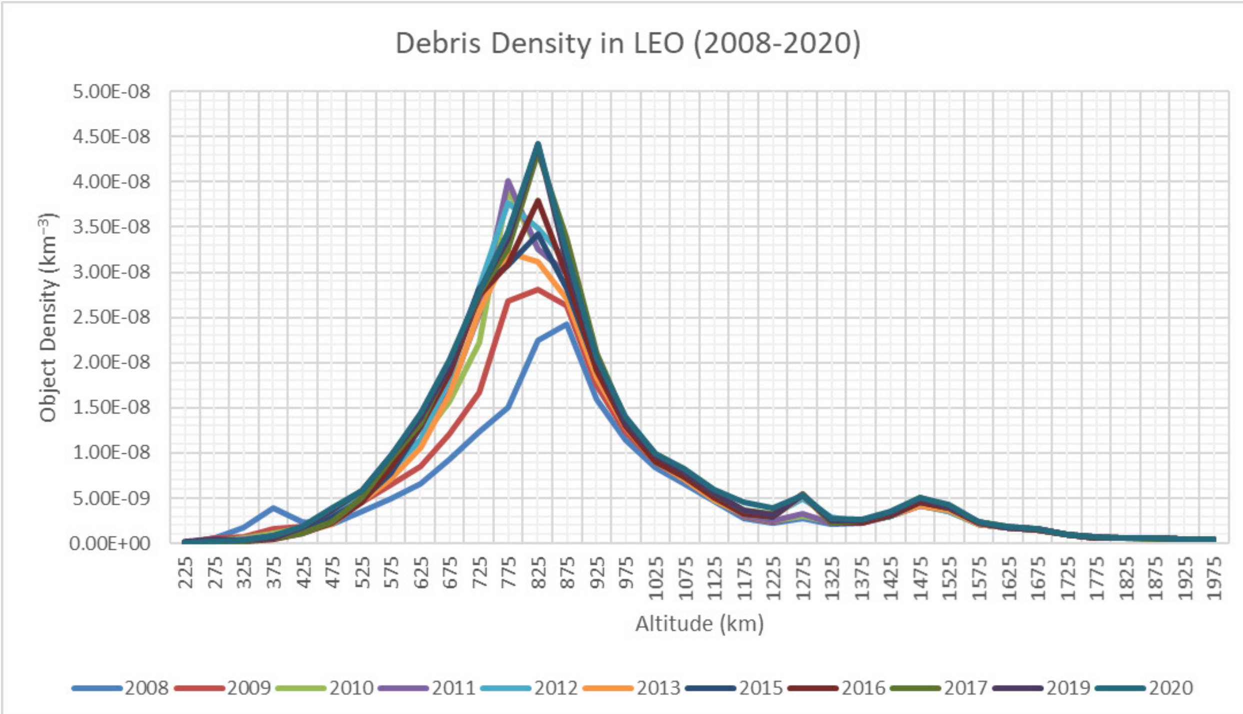

Fig. 9. Evolution of the density of cataloged debris in LEO, averaged over 50 km altitude bins, from 2008 to 2020 (the altitude is counted from the mean equatorial Earth's radius)

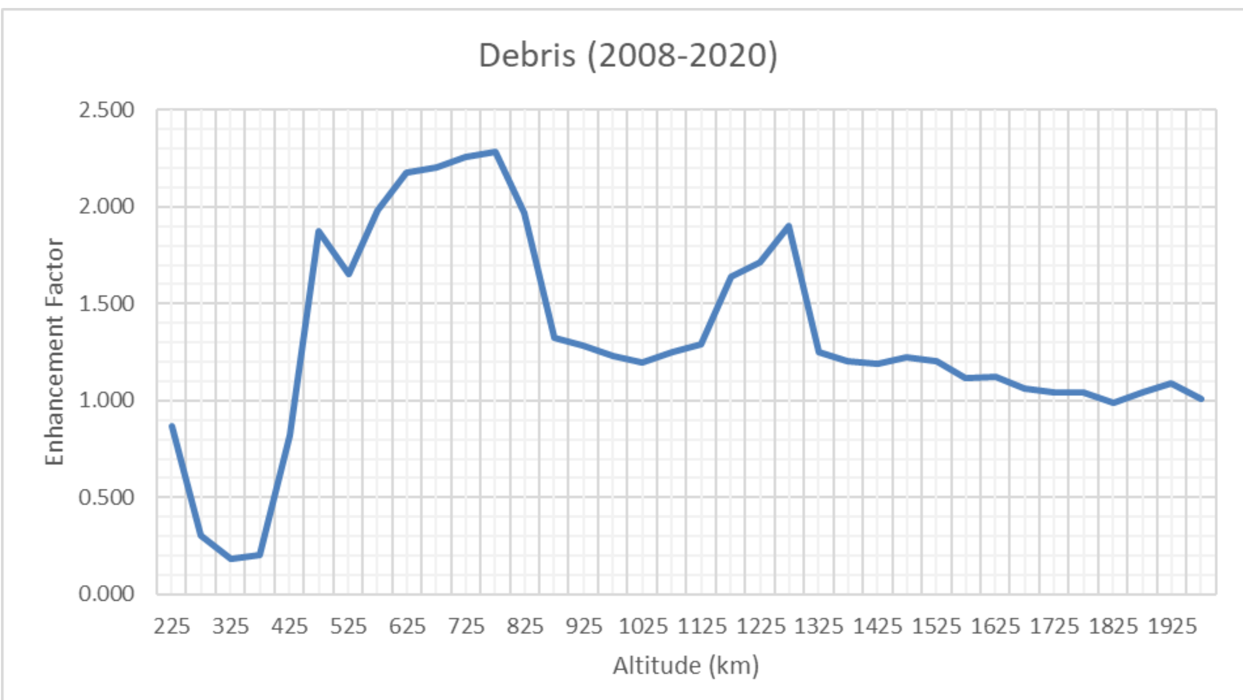

Fig. 10. The enhancement factor, plotted as a function of the altitude with respect to the mean equatorial Earth's radius, shows how many times the cataloged debris in LEO multiplied from 2008 to 2020

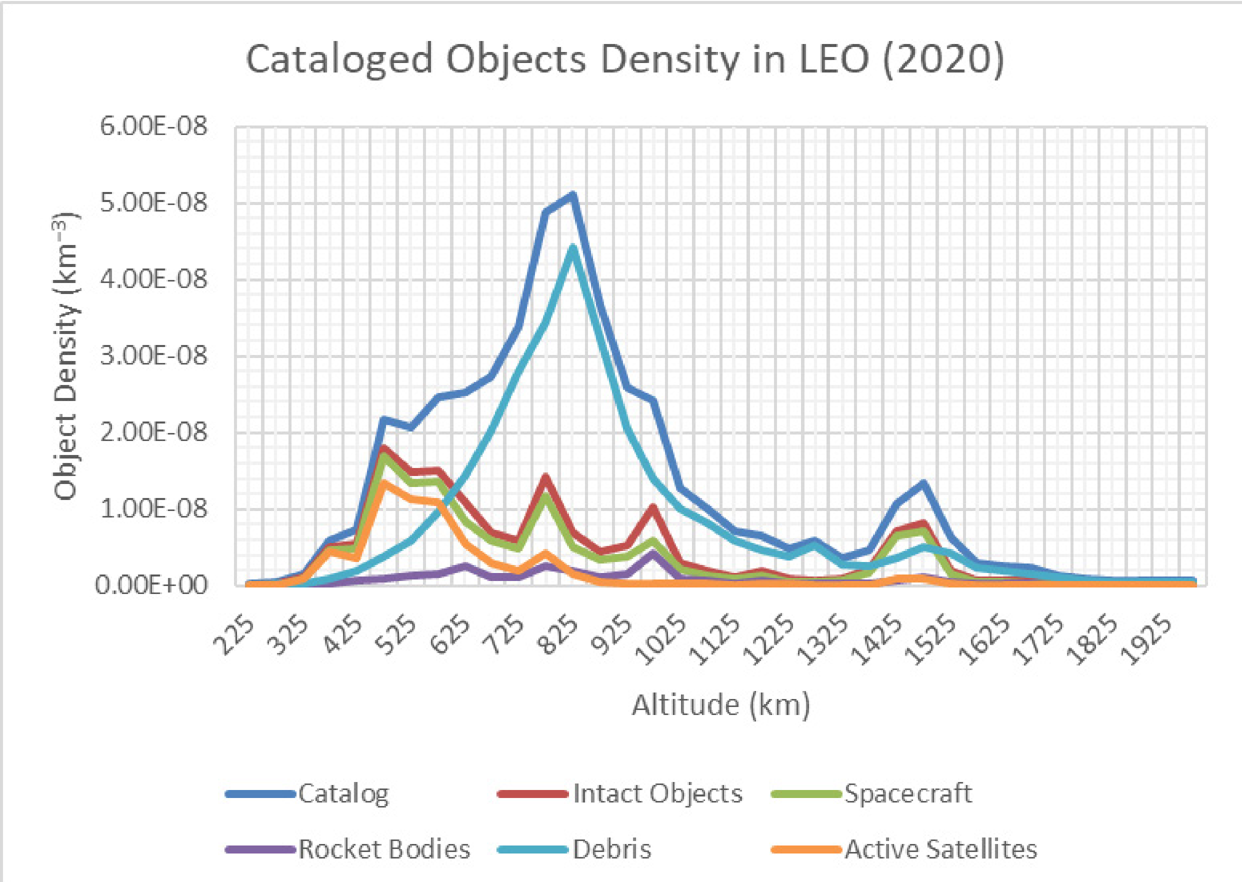

Fig. 11. Distribution in LEO, in June 2020, of cataloged objects, spacecraft, rocket bodies, intact objects (spacecraft + rocket bodies), debris (breakup fragments + mission related objects) and active satellites

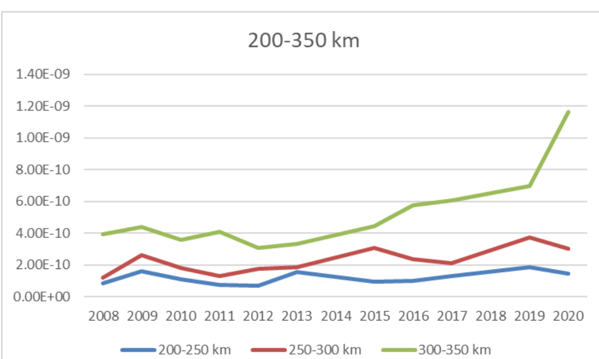

Fig. 12. Intact objects: spatial density (km^{-3}, in the ordinate) as a function of the year (in the abscissa), from 200 to 350 km

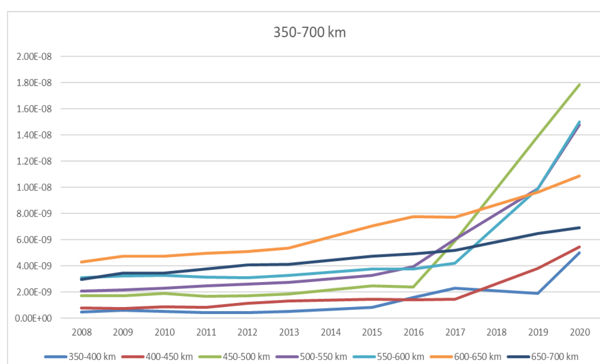

Fig. 13. Intact objects: spatial density (km^{-3}, in the ordinate) as a function of the year (in the abscissa), from 350 to 700 km

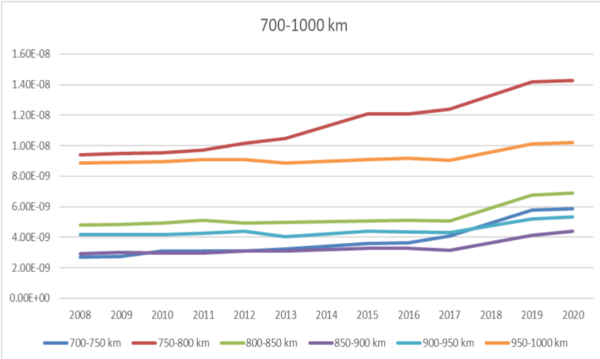

Fig. 14. Intact objects: spatial density (km^{-3}, in the ordinate) as a function of the year (in the abscissa), from 700 to 1000 km

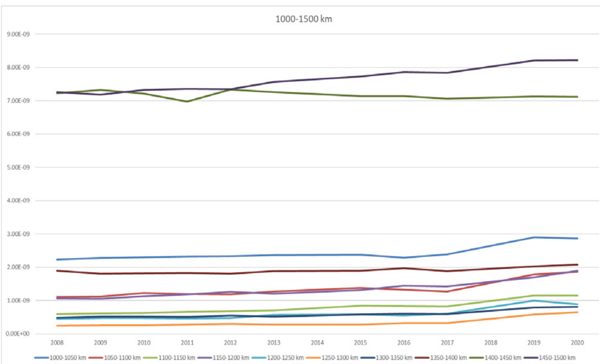

Fig. 15. Intact objects: spatial density (km^{-3}, in the ordinate) as a function of the year (in the abscissa), from 1000 to 1500 km

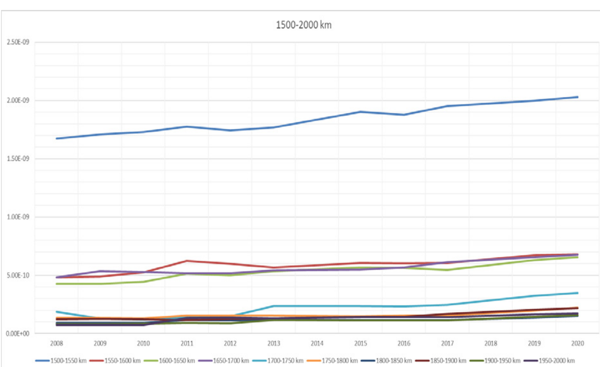

Fig. 16. Intact objects: spatial density (km^{-3}, in the ordinate) as a function of the year (in the abscissa), from 1500 to 2000 km

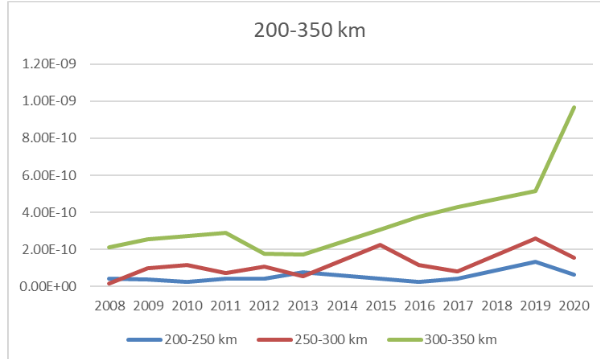

Fig. 17. Spacecraft: spatial density (km^{-3}, in the ordinate) as a function of the year (in the abscissa), from 200 to 350 km

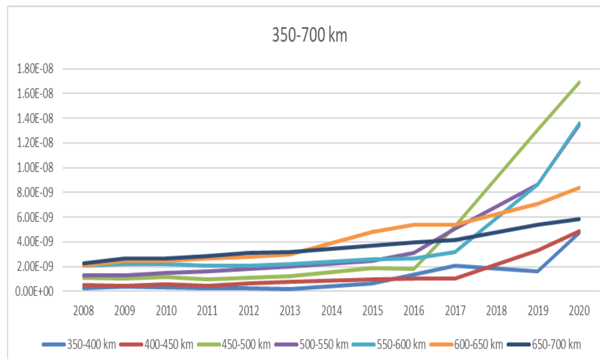

Fig. 18. Spacecraft: spatial density (km^{-3}, in the ordinate) as a function of the year (in the abscissa), from 350 to 700 km

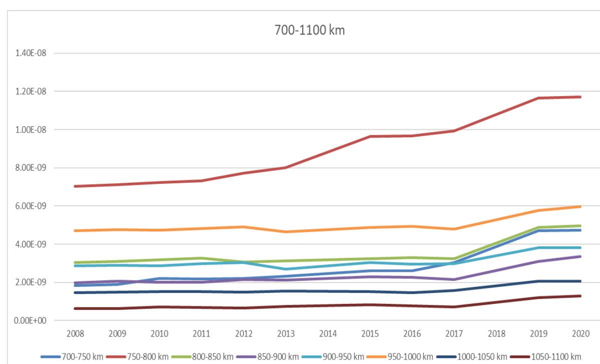

Fig. 19. Spacecraft: spatial density (km^{-3}, in the ordinate) as a function of the year (in the abscissa), from 700 to 1100 km

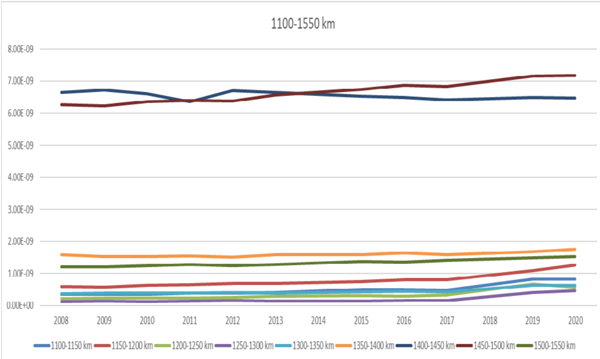

Fig. 20. Spacecraft: spatial density (km^{-3}, in the ordinate) as a function of the year (in the abscissa), from 1100 to 1550 km

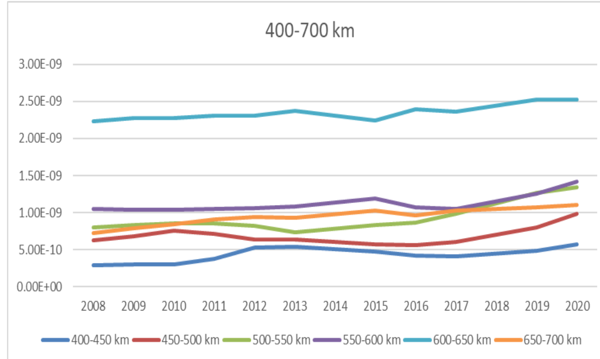

Fig. 23. Rocket bodies: spatial density (km^{-3}, in the ordinate) as a function of the year (in the abscissa), from 400 to 700 km

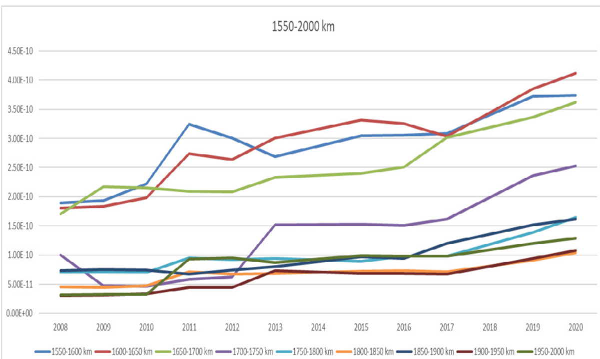

Fig. 21. Spacecraft: spatial density (km^{-3}, in the ordinate) as a function of the year (in the abscissa), from 1550 to 2000 km

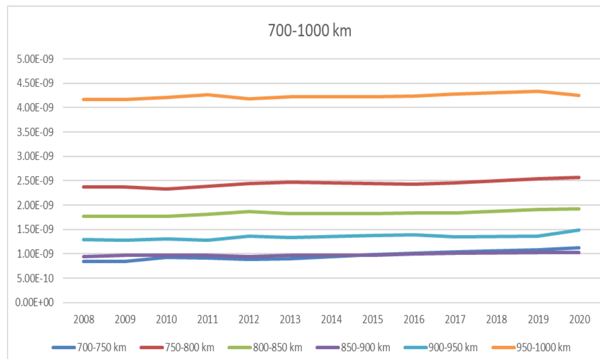

Fig. 24. Rocket bodies: spatial density (km^{-3}, in the ordinate) as a function of the year (in the abscissa), from 700 to 1000 km

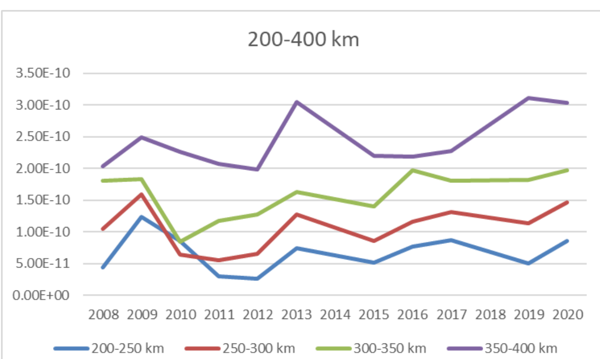

Fig. 22. Rocket bodies: spatial density (km^{-3}, in the ordinate) as a function of the year (in the abscissa), from 200 to 400 km

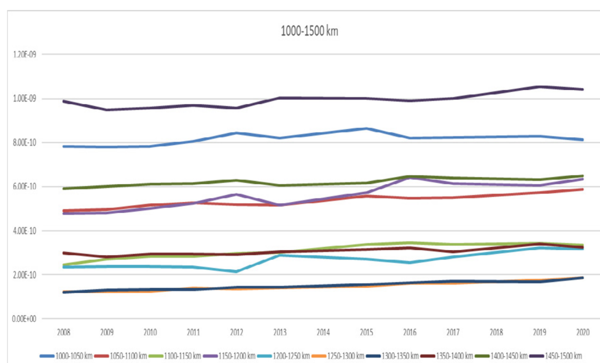

Fig. 25. Rocket bodies: spatial density (km^{-3}, in the ordinate) as a function of the year (in the abscissa), from 1000 to 1500 km

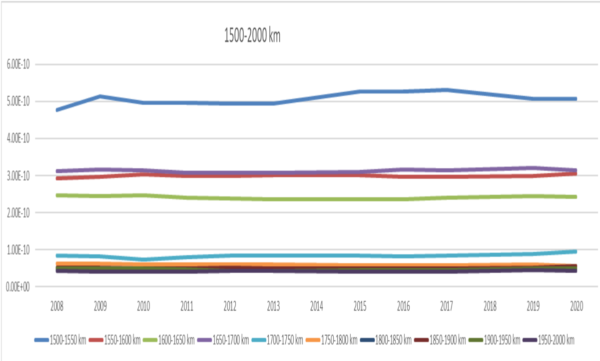

Fig. 26. Rocket bodies: spatial density (km^{-3}, in the ordinate) as a function of the year (in the abscissa), from 1500 to 2000 km

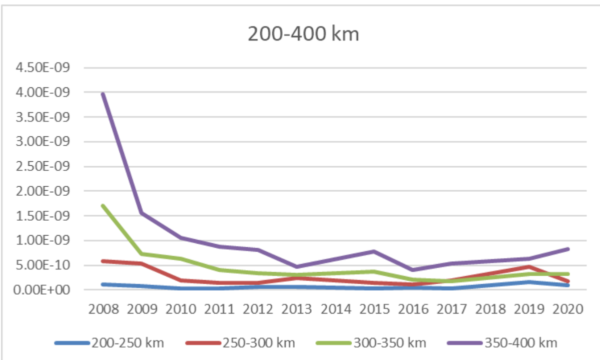

Fig. 27. Debris: spatial density (km^{-3}, in the ordinate) as a function of the year (in the abscissa), from 200 to 400 km

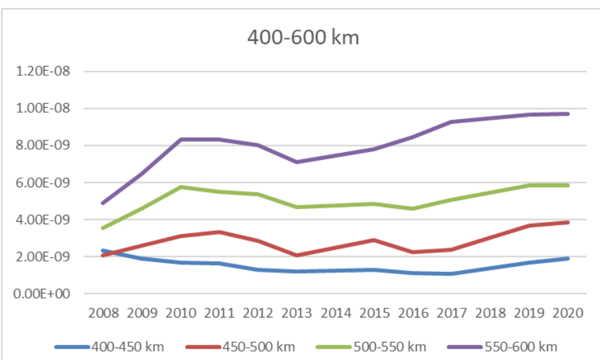

Fig. 28. Debris: spatial density (km^{-3}, in the ordinate) as a function of the year (in the abscissa), from 400 to 600 km

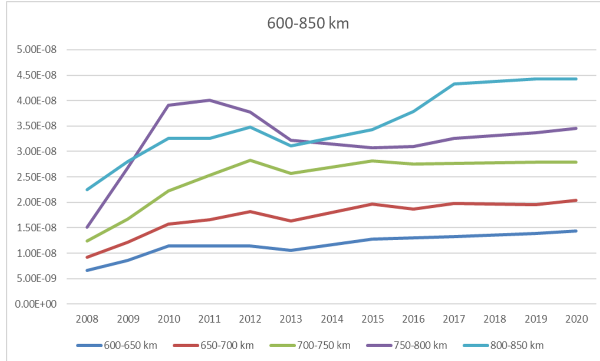

Fig. 29. Debris: spatial density (km^{-3}, in the ordinate) as a function of the year (in the abscissa), from 600 to 850 km

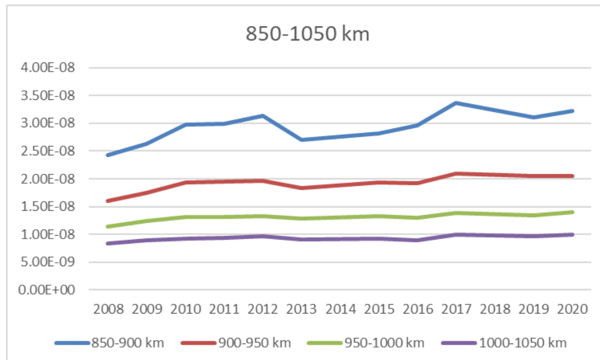

Fig. 30. Debris: spatial density (km^{-3}, in the ordinate) as a function of the year (in the abscissa), from 850 to 1050 km

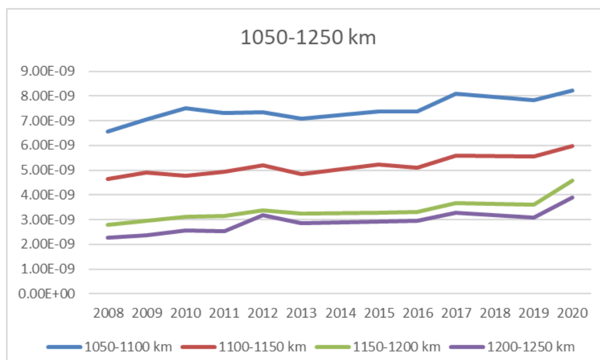

Fig. 31. Debris: spatial density (km^{-3}, in the ordinate) as a function of the year (in the abscissa), from 1050 to 1250 km

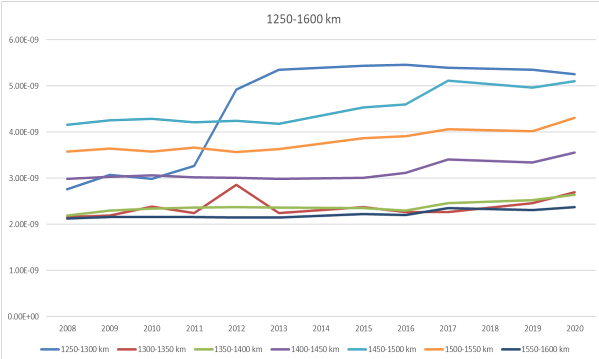

Fig. 32. Debris: spatial density (km^{-3}, in the ordinate) as a function of the year (in the abscissa), from 1250 to 1600 km

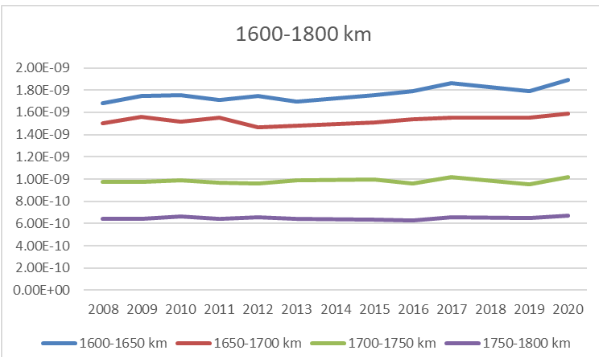

Fig. 33. Debris: spatial density (km^{-3}, in the ordinate) as a function of the year (in the abscissa), from 1600 to 1800 km

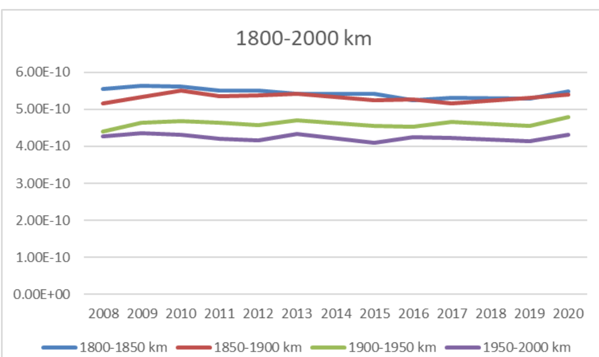

Fig. 34. Debris: spatial density (km^{-3}, in the ordinate) as a function of the year (in the abscissa), from 1800 to 2000 km

From 2008 to 2020, the cataloged debris actually decreased below 450 km (Figs. 9 and 10). Between 450 and 850 km they grew by factors between 1.6 and 2.3, between 850 and 1150 km by 20-30%, between 1150 and 1300 km by 60-90%, and from zero to no more than 25% between 1300 and 2000 km (Fig. 10). During the period considered, the relative increase of intact objects was therefore significantly higher than that of cataloged debris, in particular below 700 km.

Looking in more detail at the growth patterns of debris depending on the height, below 450 km (Figs. 27 and 28) their density remained practically steady during most of the time span considered. The sharp decline recorded from 2008 to 2010, evident between 250 and 450 km, and chiefly between 300 and 400 km, was due to the rapid decay of a large fraction of the fragments generated by the breakup of the Cosmos 2421 satellite, occurred in March 2008 at an altitude of about 410 km.

Between 450 and 900 km (Figs. 28-30), the first part of the period was marked by the great catastrophic breakup occurred in February 2009 at 790 km, when two intact satellites, the abandoned Cosmos 2251 and the functional Iridium 33, accidentally collided. The density bulges created by the new fragments, as they were cataloged and gradually decayed, are quite evident in the density plots, but afterwards, in the second part of the period, a more regular behavior was recorded, characterized in certain height bins by a nearly steady debris density, and in others by a moderate, and almost linear, growth.

An approximately stable density over the entire period also characterized the altitudes between 900 and 1050 km (Fig. 30), as well as those between 1650 and 2000 km (Figs. 33 and 34). A modest linear increase was instead displayed between 1050 and 1250 km (Fig. 31), and between 1350 and 1650 km (Figs. 32 and 33). The altitude interval from 1250 to 1350 km (Fig. 32), on the other hand, was marked, as previously discussed, by the cataloging, mostly between 2011 and 2012, of many debris lost by the SNAP-10A satellite. However, before and after such low energy fragmentation event, even in this region the debris density trend was basically stable, or slightly growing.

4. Considerations on past object evolution in LEO

How has the evolution of cataloged objects in LEO, during the last quarter of a century, compared to expectations? Based on detailed long-term simulations carried out in 1999 [39,40] and in the second half of the 2000s [41,42], the recorded evolution matched the predictions of the business-as-usual scenarios, i.e. those assuming a continuation of space activities (e.g. launch rates, payload and mission related object deployments per launch, etc.) according to the patterns prevailing at that time, and the adoption of no remediation (e.g. active debris removal) or mitigation measures (i.e. explosion and collision prevention, end-of-life orbital lifetime reduction, de-orbiting or re-orbiting).

On the other hand, the period considered was also characterized by the progressive recommendation and adoption of debris mitigation measures, first championed by NASA and later on supported by all the major space agencies in the world, in the framework of the Inter-Agency Space Debris Coordination Committee (IADC)

[43]. From 1990 to 2006, the growing implementation of mitigation measures, in particular the end-of-life passivation of upper stages and spacecraft for explosion prevention, had a clear beneficial impact in LEO, nearly stabilizing the number of debris, both from breakups and mission related. In addition, the maximum of solar cycle 23, from 1999 to 2003, and the declining launch rate (Fig. 35), following the dissolution of the Soviet Union, played a not negligible role.

However, these conditions abruptly changed, because in 2006 the launch rate started to increase again (Fig. 35) and in January 2007 the intentional destruction, during an anti-satellite weapon test, of the Fengyun 1C spacecraft suddenly caused a jump in the number of cataloged objects in LEO equivalent to that accumulated over the preceding 30 years. Moreover, the solar activity experienced one of the deepest lows since recordings are available, followed by one of the weakest cycles ever, the 24th. To make matters worse, the accidental but preventable collision between Cosmos 2251 and Iridium 33, in February 2009, caused another sudden jump in the number of cataloged objects which, combined with the Fengyun 1C event, was equivalent to the objects accumulated in LEO from 1970 to 2007.

Despite this, from the second quarter of 2009 to the third quarter of 2015 – a period coinciding, from 2011 onwards, with the (low) maximum of the solar activity cycle 24 – the number of cataloged objects in LEO experienced the longest declining phase ever recorded, due to a significant decrease, by about 12%, of fragmentation debris. Nevertheless, from 2016 to mid-2020, even though the number of fragmentation debris and mission related objects remained almost steady, the increase of the launches associated with the new space economy, characterized by multiple deployments of dozens of small satellites, coupled with a declining solar activity cycle, again marked a turnaround, with a growth trend of cataloged objects in LEO equivalent to that observed during the first space age, from 1960 to 1990, i.e. before the widespread adoption of mitigation measures.

Concerning the intrinsic physical nature of the growth of cataloged objects, nowhere have the signs of more than linear increases been revealed so far, in LEO as a whole and in each single altitude bin as well, aside from a few sizable, but circumscribed, fragmentation events. Even though above 700 km the population may be intrinsically unstable in the long run, i.e. it may continue to grow even by suspending all new launches, due to the sporadic breakups of old spacecraft and rocket bodies and to the mutual collisions among cataloged objects not counterbalanced by the cleaning effects of natural orbit perturbations [41,42,44], the situation can still be managed and controlled.

This moderate optimism finds its justification in the fact that from 2008 to mid-2020 the increase in LEO of spacecraft alone represented approximately 70% of that of cataloged debris, even including the collision between Cosmos 2251 and Iridium 33, i.e. the second worst breakup ever. And spacecraft might and should be designed to be fully compliant with debris mitigation guidelines. In addition, as shown in Figs. 5 and 6, most of the new spacecraft were launched below 650 km, where the natural lifetime is anyway less than 35 years (Fig. 36), thereby preventing their long-term accumulation in space.

Therefore, even though the situation has worsened overall in the last quarter of a century, despite the adoption of various mitigation measures, nothing of irremediable has been done so far. However, extreme attention will be necessary in planning and conducting new activities from now on, especially in a phase of increased and ever more rapid exploitation of space, to ensure the long-term sustainability of its full and effective utilization.

5. How to define an acceptable debris environment

Limiting the generation of debris in the environment during space operations makes obviously sense, but it is just a qualitative principle. Guidelines and standards often provide specific instructions and quantitative targets applicable to each new space mission, but nowhere is there explicitly stated what is the global goal to be achieved, or rather what are the thresholds not to be exceeded, in quantitative terms, to avoid the transition to an unacceptable situation.

As shown in the previous section, the evolution in LEO recorded during the last twenty years matched the predictions of the business-as-usual scenarios devised at the end of the 1990s, as if there had been no mitigation in the meantime, but space operations are still being carried out successfully, and on an unprecedented scale. So what is the limit that cannot be exceeded and that mitigation (and, perhaps, remediation) measures should allow us not to cross?

Unfortunately, it is not easy to answer this question in quantitative terms and there is no widespread consensus. Aside from complex international and national law issues, which are however outside the scope of this article, even from a purely technical point of view it is not easy to arrive at convincing answers, because technologies evolve very quickly and situations that twenty years ago might have seemed unmanageable can now be addressed without excessive difficulty.

5.1 Preventing a runaway debris growth

A first obvious target goal might be avoiding an uncontrolled runaway growth of debris in specific LEO altitude shells, triggered by collisional fragments impacting and destroying intact objects, then producing new fragments able to breakup other intact objects, and so on. But even if, above 700 km, a runaway growth might be possible, the scale times we are talking about are probably of the order of one century, by extrapolating current space activities.

So far, at least among cataloged objects, no collision feedback between collisional fragments and intact objects has been observed and the population growth was driven by new launches (payloads + upper stages + mission related objects), low energy fragmentations of intact objects due to design faults or aging, explosions (some of them possibly triggered by the impact of small uncataloged objects), intentional collisions and a few sporadic accidental collisions involving cataloged objects of non-collisional origin. And if an exponential debris growth should occur, it would probably already be too late to intervene and remedy.

5.2 Limiting total mass and cross-sectional area

Other target goals might be to set upper limits to the total mass and/or to the total cross-section of the objects left in orbit above a certain altitude, for example 700 km, where the environment is already intrinsically unstable [41,42,44] and the orbital lifetimes of intact objects are generally greater than 60 years (Fig. 36).

The total mass, about 3230 metric tons in LEO, including the International Space Station (ISS), in mid-2020 [45], represents the potential source of debris from collisional breakups. Just to give a rough idea, in terms of orders of magnitude, as of June 4, 2020, there were 5105 intact objects in LEO plus the ISS, with an average mass of about 550 kg (excluding the ISS). According to the NASA breakup model [46,47], the collisional destruction of a "mean" intact object would lead to the generation of ~590 fragments ≥ 10 cm, so the number of potential collisional fragments contained in the total mass resident in LEO is of the order of 3×10^6 objects ≥ 10 cm.

The total cross-sectional area, on the other hand, is approximately proportional (if the "typical projectile" size is significantly smaller than the "typical target" size) to the mean frequency of catastrophic collisions. As of mid-2020, we estimated a total cross-section of cataloged objects in LEO of ~35,000 m^2, and a corresponding collisional cross-section of ~70,000 m^2, taking into account the significant probability of collision between intact objects of comparable size.

5.3 Constraining the "collisional mass flux"

A simple measure of an acceptable or limiting "collisional mass flux" (CMF) might be built, for each altitude range Δh_i, through a combination of the total object mass $M(\Delta h_i)$, of the total collisional cross-section $A(\Delta h_i)$, of the density of objects $\rho(\Delta h_i)$ above a certain size threshold, e.g. 10 cm, and of the average relative velocity $V_R(\Delta h_i)$ among the objects, as in the following relationship:

$$CMF(\Delta h_i) = \rho(\Delta h_i) \cdot A(\Delta h_i) \cdot V_R(\Delta h_i) \cdot M(\Delta h_i), \qquad (1)$$

where the product between density, collisional cross-section and average relative velocity represents the average frequency of collisions among the objects larger than the threshold considered, while the collisional fragments that might be generated are a function of the mass.

As an example, applying Eq. (1) to LEO as a whole, we obtained a total $CMF \sim 3 \times 10^{-2}$ kg/s for mid-2020, always excluding the ISS, and a reasonable (and manageable) upper limit should probably not exceed the present value by more than a factor of 2 or 3, if the results of past long-term debris simulations are taken into account [39,40]. But, of course, a more detailed analysis, carried out above 650-700 km and focused on each designated altitude shell Δh_i, should be performed for estimating the "space filling" constraints as a function of the altitude. Taking, for instance, the LEO region between 700 and 2000 km, where the density of objects is probably already exceeding the critical threshold for long-term growth even if all new launches were immediately suspended [33,41,42], we obtained a total $CMF \sim 8 \times 10^{-3}$ kg/s for mid-2020. Again, based on past long-term simulations [39,40], a further increase by a factor of 2 or 3 might be the maximum acceptable in order to maintain manageable space operations.

5.4 Constraining the "impact debris expectancy"

Another useful gauge for evaluating the "capacity" of space might be the "impact debris expectancy" (IDE), that is the average number of fragments above an assigned size threshold expected each year as a result of accidental collisions [11,48]. For any applicable target, it can be calculated by multiplying the expected annual rate of catastrophic collisions with the number of fragments beyond the threshold that would be produced. The results obtained for all possible targets within a given altitude shell Δh_i can then be summed to obtain the total impact debris expectancy as a function of height.

From 1999 to 2020, only two accidental collisions among cataloged objects has been confirmed, so far, in LEO, one of which involving two intact objects, Cosmos 2251 and Iridium 33, in 2009 [49]. In total, 2301 cataloged fragments were generated [26,49], corresponding to an average of nearly 110 collisional debris per year during the time interval considered. This value represents 34% of the average yearly increase of cataloged objects recorded in the same period, i.e. 323 objects per year [20].

For 2020, using the approach and the results presented in [49], the updated average mass of intact objects in LEO found in Subsection 5.2, i.e. 550 kg, and the assumption that 50% of the operational spacecraft below 2000 km execute collision avoidance maneuvers, we obtained IDE(LEO) ≈ 165 collisional fragments ≥ 10 cm per year. A value like this could still be manageable for over one century [41,42], but again a further increase by a factor of 2 or 3 would probably be too high, according to the results of past long-term debris simulations.

5.5 Limiting the debris number or density

In mid-2020, there were nearly 15,000 cataloged objects in LEO. This number matched well the Semi-Deterministic Model (SDM 2.0) unmitigated predictions of 1999 (about 15,000 objects ≥ 10 cm) [39,40] and the scenario simulated in 2008 with SDM 4.0 assuming the compliance with the main IADC recommendations, i.e. on-orbit explosion prevention and spacecraft residual lifetime limited to 25 years after mission completion (approximately 17,000 objects ≥ 10 cm) [41,42]. Around 2100, both simulation rounds predicted a number of LEO objects ≥ 10 cm between 27,000 (SDM 4.0, mitigated) [40,41] and 36,000 (SDM 2.0, unmitigated) [39,40]. At the time the simulations were carried out, the latter result was considered unacceptable, while the former one might still be considered barely tolerable. Therefore, just in terms of number of objects, an admissible ceiling might be placed around 30,000 objects ≥ 10 cm in LEO, that is at twice the current value. However, this limiting number would be strongly affected by the actual object distribution; in other words, many more objects could be allowed, from an exclusively debris mitigation point of view, if mostly packed below 600 km.

The concept of "critical density" was proposed by Donald J. Kessler [33]. As previously pointed out, above 700 km we are already in a situation in which, even if all new launches were suspended, the number of debris would continue to grow, being the orbital decay induced by the more and more tenuous atmosphere overwhelmed by the production of new fragments through mutual collision among the objects already present there [41,42]. The critical density has therefore already been exceeded, at least above 700 km, and cannot be used anymore as a limiting threshold. Alternatively, density values corresponding to specific short-term environmental consequences could be used. In the latter case, again on the basis of the long-term assessments carried out in the past, a tolerable upper limit might be represented by an overall doubling of the average debris density above 700 km, even though the details can differ strongly as a function of the height.

5.6 Constraining the collision rate

Another indicator of environmental criticality in LEO might be the average rate of accidental collisions among cataloged objects or debris ≥ 10 cm ($CR_{\rm LEO}$). For this purpose, we had previously defined the "collision rate increase" (CRI), in which the additional average collision rate due to new objects, among themselves ($CR_{\rm NN}$) and with the pre-existing background of objects already in orbit ($CR_{\rm N0}$), is compared with the current overall collision rate in LEO among the background objects (CR_{00}) [10,14,15]:

$$CRI \equiv (CR_{\rm NN} + CR_{\rm N0})/CR_{00}\ . \qquad (2)$$

The current overall collision rate in LEO among objects ≥ 10 cm was estimated to be the following, depending on whether maneuverable spacecraft do or not collision avoidance [39,40,49]:

$$CR_{00} \approx 0.2\ a^{-1} \text{ (with collision avoidance);} \qquad (3)$$

$$CR_{00} \approx 0.3\ a^{-1} \text{ (without collision avoidance).} \qquad (4)$$

Regarding what can be considered a bearable upper limit of CRI, it should be emphasized that all the mitigation measures devised and recommended over the last 20 years had as their main goal the long-term stabilization of the debris environment in LEO. Just recalling the SDM long-term simulations mentioned in Subsection 5.5, the most mitigated scenarios aimed at an asymptotic collision rate in between 0.22 and 0.24 per year around 2100, with a cumulative number of collisions, always among objects ≥ 10 cm, less than 25. A doubling of the current collision rate by 2050 would have led, instead, to more than 50 collisions by 2100, with an asymptotic collision rate of 1 per year. An increase by a factor of three by 2050, finally, would have resulted in 70 collisions by 2100, with an asymptotic collision rate of 1.6 per year [39,40]. However, the latter outcome, based on an unmitigated business-as-usual scenario, was considered unacceptable at that time, and also the intermediate result, consequence of a partially mitigated scenario (i.e. on-orbit explosion prevention), was regarded as unsatisfactory.

It will never be reiterated enough that if such an effort was made to achieve a broad international consensus on the adoption of certain mitigation measures, it has been precisely to prevent scenarios like these from happening. Therefore, during the next 30 years, the collision rate increase (CRI) in LEO among objects ≥ 10 cm should be constrained to less than 100%, that is to an overall value $CR_{\rm LEO} < 0.4\ a^{-1}$, corresponding to less than one collision every 2.5 years. This goal, the less the better, could be achieved either by minimizing the number of new objects in orbit and possibly retrieving some of those already in space, or by a massive recourse to collision avoidance and end-of-life de-orbiting, in particular regarding the mega-constellations of satellites. It should, however, be emphasized the extremely high reliability required for mega-constellation spacecraft (~99%), in order to prevent, in particular above 700 km, a too rapid and significant increase of the collision rate due to satellites lost and abandoned [10,14,15].

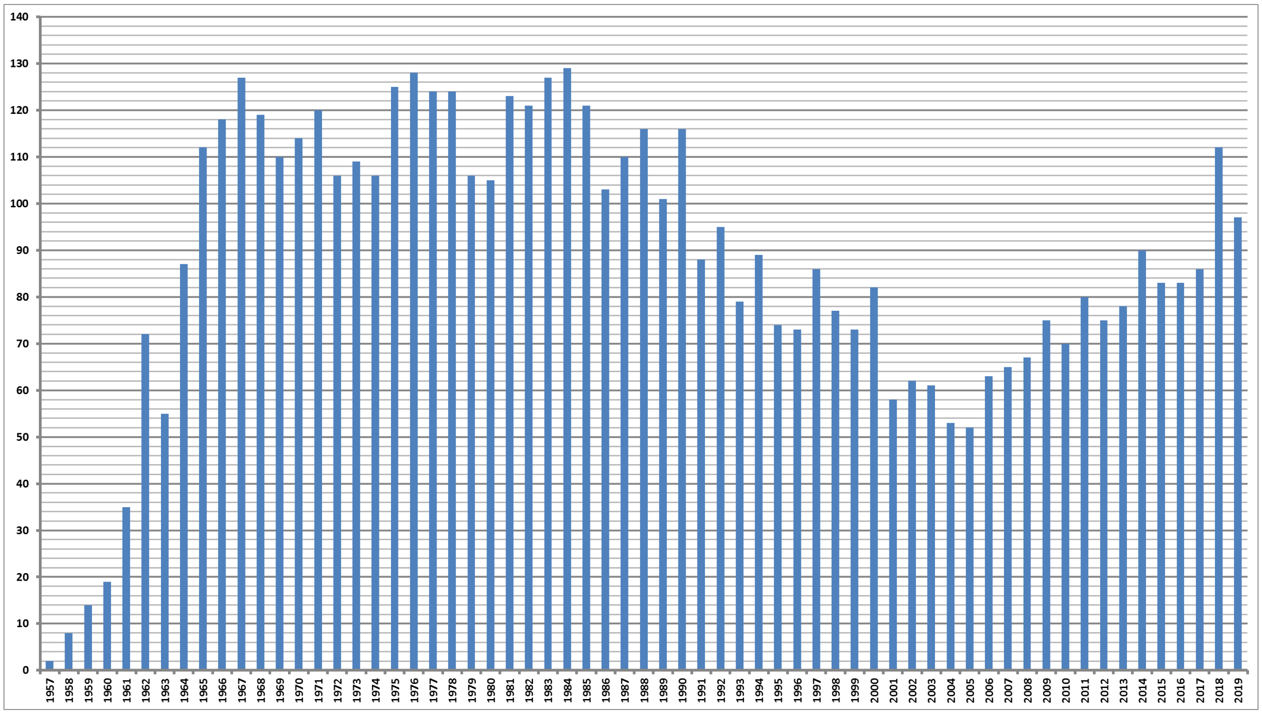

Fig. 35. Number of launches carried out each year, since the beginning of the space age, resulting in at least one cataloged object (1957-2019)

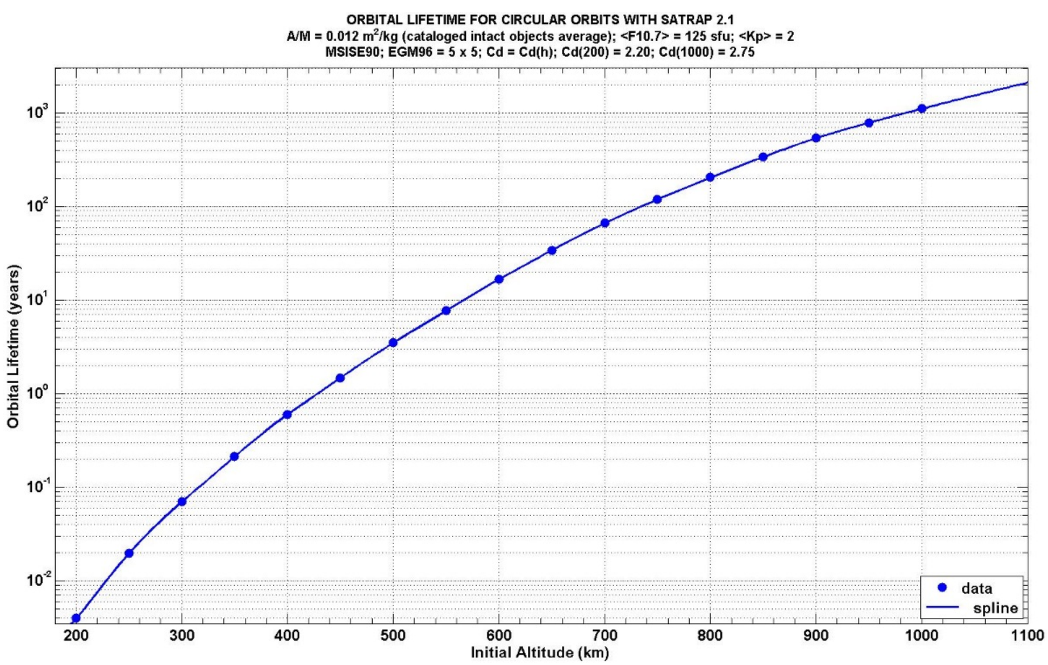

Fig. 36. Mean orbital lifetime in LEO for the average intact object

5.7 Limiting the "collision rate exponential index"

The average rate of accidental collisions in LEO among cataloged objects ≥ 10 cm can be expressed in the following way, using the notation introduced is Sub-section 5.6:

$$CR_{\text{LEO}}(t) = CR_{00}(t) + CR_{\text{NN}}(t) + CR_{\text{N0}}(t), \quad (5)$$

where CR_{00} represents the average collision rate among the resident objects at the initial epoch ($t = 0$), CR_{NN} the collision rate among the new objects launched and produced in orbit after the initial epoch, and CR_{N0} the collision rate among the new and the background objects still in space at time t. Assuming CR_{00} = constant, a good approximation for a few decades above 700 km, and an exponential behavior for $CR_{\text{LEO}}(t)$, characteristic of an evolution in which accidental collisions begin to assume a significant role, Eq. (5) can be rewritten as follows:

$$CR_{\text{LEO}}(t) \approx CR_{00}\, e^{Kt}, \quad (6)$$

where

$$e^{Kt} - 1 \approx \frac{(CR_{\text{NN}} + CR_{\text{N0}})}{CR_{00}} \equiv CRI \quad (7)$$

and the "collision rate exponential index" K is given by:

$$K \approx \ln(CRI + 1)/t. \quad (8)$$

Adopting for the current value of CR_{00} the figure given in Eq. (3), Table 1 shows the values of K leading to assigned increases of the overall collision rate in LEO by 2050. In order to limit the growth of the average collision rate in LEO to no more than 100% by 2050, the exponential index K should be < 0.0231 a^{-1}, meaning an increase < 26% by 2030 and < 59% by 2040. A more tolerable ceiling of 50% by 2050 would correspond to K < 0.0135 a^{-1}, meaning an increase < 14% by 2030 and <31% by 2040. Unfortunately, as already shown elsewhere [10,14,15], a few large constellations of satellites above 700 km with spacecraft reliabilities comparable with those recorded so far would be enough to exceed the 50% ceiling, and maybe also the 100% one, in the coming 30 years.

6. Conclusions

A detailed analysis of the cataloged objects in LEO over the last 25 years has led to the following conclusions:

1. Overall, the evolution observed was consistent with the forecasts of unmitigated business-as-usual scenarios, i.e. those assuming a continuation of space activities according to the patterns prevailing 20 years ago, without mitigation and remediation;
2. Actually, the mitigation measures gradually recommended and adopted over the last thirty years have shown evident positive effects over some periods of time, but unfortunately their benefits were nullified by some major fragmentation events, in particular a couple of catastrophic collisions, by prolonged periods of extremely low solar activity, characterized by low maxima, deep minima and very cold thermosphere, and by a strong increase of the launch rate of satellites since the mid-2010s;
3. Concerning the recorded growth of cataloged objects, nowhere have the signs of more than linear increases been revealed so far, aside from a few sizable, but circumscribed, fragmentation events;
4. In other words, even though above 700 km the debris population may be intrinsically unstable in the long run, that is it may continue to grow even by suspending all new launches, due to the sporadic breakups of old spacecraft and rocket bodies and to the mutual collisions among cataloged objects not counter-balanced by the cleaning effects of natural orbit perturbations, the signature of a collisional chain reaction was not yet detected and the situation can still be managed and controlled;
5. Consequently, even though the overall picture has worsened during the last quarter of a century, despite the adoption of various mitigation measures, nothing of irremediable has been done so far;
6. Nevertheless, great attention must be paid to the way of designing, planning, launching and operating new systems and missions from now on, especially in a phase of rapidly increasing satellite launches, to ensure the long-term sustainability of space activities around the Earth.

Table 1. Values of the collision rate exponential index K leading to assigned increases of the overall collision rate in LEO by 2050 ($CR_{00} = 0.2\ a^{-1}$)

K (a^{-1})	CRI (%)	CR_{LEO} (a^{-1})
0.053648	400	1.000
0.050136	350	0.900
0.046210	300	0.800
0.041759	250	0.700
0.036620	200	0.600
0.030543	150	0.500
0.023105	100	0.400
0.013516	50	0.300
0.011216	40	0.280
0.008745	30	0.260
0.006077	20	0.240
0.003177	10	0.220

To aim for the goal of long-term sustainability of space activities, however, it is necessary to define an acceptable orbital debris environment. The latter, of course, is not immutable, but depends on the technical solutions available at a certain time, and on how and for what the circumterrestrial space is used. Extrapolating too much into the future can therefore be risky, and for this reason the attention here was focused on the next thirty years.

During the last quarter of century, many scenarios were simulated around the world concerning the long-term growth of orbital debris, according to a wide range of launch traffic, mitigation and remediation measures, solar activity conditions, and so on. Moreover, the main satellite applications are now well established and due to the relatively long planning and procurement times associated with space systems, and to the large investments of money required, no radical changes are expected in the coming three decades. The main change will be represented by a growing and increasingly irreversible use of mini, micro and nanosatellites, as well as by large constellations made up of hundreds or thousands of maneuverable spacecraft.

The evolution scenarios investigated in the last two or three decades have already implicitly defined, both qualitatively and quantitatively, the desirable, tolerable or unacceptable orbital debris environments, for instance in terms of the number of objects above a certain threshold, of the accidental collision rate, or of the number of catastrophic collisions expected in a certain time interval. The aim of this paper was to present, and sometimes to introduce, a set of environmental criticality indexes that could be used as the measurement devices of a control panel to check in a simple and direct way if and how much certain environmental conditions are close or not to thresholds considered critical for the sustainability of space activities.

The criticality indicators discussed were the following:

1. The total mass (possible source of collisional debris) and the total collisional cross-section (related to the collision rate), either in LEO or in a given altitude shell;
2. The "collisional mass flux", resulting from the product of the total mass with the total collisional cross-section, with the density of objects above a certain size and with the average relative velocity among the objects considered, again either in LEO or in a given altitude shell;
3. The "impact debris expectancy", i.e. the average number of fragments above a given size threshold expected each year as a result of accidental collisions;
4. The debris number or density, either in LEO or in specified altitude shells;
5. The amount of "collision rate increase", with respect to the current situation, caused by new space systems and their operations;
6. The "collision rate exponential index", in which the collision rate increase is represented by an exponential function.

A more in-depth and detailed application of these indexes will be the subject of future studies: consequently, only values applicable to LEO as a whole, or to large fractions of it, and, in certain cases, only order of magnitude estimates, were obtained for this paper.

Considering the "collisional mass flux", in mid-2020 it was estimated to be ~ 3×10^{-2} kg/s in LEO as a whole and ~ 8×10^{-3} kg/s between 700 and 2000 km. Assuming the results of past long-term simulations, a further increase by a factor of 2 or 3 might be the maximum acceptable in order to maintain manageable space operations with current technologies and procedures, that is without having to resort to collision avoidance driven by artificial intelligence and to extended "maneuvering" capabilities, including "just in time" collision avoidance [50].

Regarding the "impact debris expectancy", for mid-2020 and supposing that 50% of the operational spacecraft below 2000 km execute collision avoidance maneuvers, an estimate of about 165 expected collisional fragments greater than 10 cm per year, on average, was obtained. A value like this could still be manageable for over one century, but again a further increase by a factor of 2 or 3 would probably be too high, according to the results of past long-term debris simulations.

Coming to the debris number, an admissible ceiling in LEO might be placed around 30,000 objects greater than 10 cm, that is at twice the current value. However, this upper limit would be strongly affected by the actual object distribution; in other words, many more objects could be allowed, from a purely debris mitigation point of view, if mostly concentrated below 600 km.

Always taking into account the results of long-term simulations, during the next 30 years the "collision rate increase" in LEO among objects greater than 10 cm should be constrained to less than 100%, that is to an overall value < 0.4 a^{-1}, corresponding to less than one collision every 2.5 years. This goal, the less the better, could be achieved either by minimizing the number of new objects in orbit and possibly retrieving some of those already in space, or by a massive recourse to collision avoidance and end-of-life de-orbiting, in particular regarding the mega-constellations of satellites, whose overall proper end-of-life disposal reliability will have to be pushed close to 99%.

Finally, adopting as criticality gauge the "collision rate exponential index", it should be < 0.0231 a^{-1} in order to limit the growth of the average collision rate in LEO to no more than 100% by 2050. A more tolerable ceiling of 50% would instead correspond to an exponential index < 0.0135 a^{-1}. Unfortunately, as already shown elsewhere [10,14,15], a few large constellations of satellites above 700 km with spacecraft reliabilities comparable with those recorded so far would be enough to exceed the 50% ceiling, and maybe also the 100% one, in the coming 30 years.

Acknowledgements

The authors would like to thank the US Space Track Organization (www.space-track.org) for sharing the catalog of unclassified objects tracked around the Earth by the US Space Surveillance Network.

Concerning the operational status of the satellites, special thanks go to the Union of Concerned Scientists (UCS) Satellite Database (www.ucsusa.org/nuclear-weapons/space-weapons/satellite-database) and to the CelesTrak website, created and managed by Dr. T.S. Kelso (www.celestrak.com/NORAD/elements/).

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