ORBITAL DEBRIS IN LOW EARTH ORBIT: HOW THE SITUATION HAS CHANGED SINCE THE ADVENT OF MEGA-CONSTELLATIONS

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ABSTRACT

Despite the crude impression from looking superficially only at the total numbers, the situation in low Earth orbit has not deteriorated appreciably from late 2009 to early 2025, as far as orbital debris proper is concerned, even though satellite mega-constellations have appeared in the meantime, and the number of active spacecraft has increased tenfold. This is because mega-constellations have so far been handled appropriately, putting effective debris prevention and mitigation measures in place.

But luck also played its part, as no serious accidents occurred, nor any catastrophic accidental collisions, which would have had more than a 50% chance of happening. The sensitivity of the low Earth orbit environment to sporadic single catastrophic events, as collisions involving abandoned spacecraft and upper stages, especially above 650 km, remains a pending threat that cannot be ignored.

Therefore, a combination of adequate mitigation and remediation measures is needed to ensure smooth short-term operations in low Earth orbit and the long-term sustainability of space activities.

1 INTRODUCTION

In the late 1970s and early 1980s, the problem of orbital debris was raised, studied, and addressed when the number of operational spacecraft represented only a modest fraction of all objects, typically larger than 10 cm, cataloged by surveillance systems [1,2]. This situation continued over the next four decades until around 2020, when recommendations, guidelines, standards, and laws for space debris mitigation were developed and gradually implemented nationally and internationally [3–9].

Although implemented incompletely and unevenly, the mitigation measures achieved a fair degree of success, taking into account the type of space activities then prevalent, significantly reducing the growth rate of objects in low Earth orbit (LEO) until 2007 [10,11]. But then, in just two years, the intentional destruction of the Fengyun 1C satellite (2007) and the accidental collision between the operational Iridium 33 and the defunct Cosmos 2251 (2009) suddenly thwarted decades of effort, undoing all the progress achieved [12,13]. However, after these two particularly catastrophic events, both avoidable, at least in principle, the cataloged objects in LEO practically stabilized for a decade until about 2020 [10,11], when their total number was about what one would have expected to find by extrapolating the space activity recorded from 1960 to 1980 without debris mitigation.

The first 40 years of debris mitigation have shown that the recommended measures, especially if applied systematically, can reduce or cancel cataloged object growth for extended periods. However, the environment remains highly unstable and vulnerable to single catastrophic events triggered by intact defunct objects at sufficiently high altitudes, legacies of past space activities.

This paper focuses on how this classic situation has changed with the advent of mega-constellations in LEO. The main differences to take into account compared with the first 60 years of the space age are the following:

1. The large number of operational spacecraft involved, mostly maneuverable;
2. The significant fraction of operational spacecraft compared with the cataloged objects and the actual debris;
3. The very low Earth orbits used by most of these mega-constellation spacecraft.

Considering the numbers and distribution of these new satellite systems, the debris environment in low Earth orbit has been analyzed to understand if and how the deployment of so many active satellites has changed the classical perception of the orbital debris problem.

2 ORBITAL DEBRIS CATALOG DATA

Tab. 1 lists the epochs of the orbital debris catalogs from 1994 to 2024 available for the study. They include functional satellites and debris, the latter defined in this paper as «all non-functional, human-made objects, including fragments and elements thereof, in orbit or reentering into Earth's atmosphere» [14]. These catalogs, containing the objects tracked by the U.S.

Proc. 9th European Conference on Space Debris, Bonn, Germany, 1–4 April 2025, published by the ESA Space Debris Office
Editors: S. Lemmens, T. Flohrer & F. Schmitz, (http://conference.sdo.esoc.esa.int, April 2025)

Space Surveillance Network, were obtained from the Space Track Organization (www.space-track.org). From 2020 to 2024, separate catalogs of the functional satellites were available as well, courtesy of the Union of Concerned Scientists (UCS) Satellite Database (www.ucsusa.org/resources/satellite-database) and the CelesTrak website (celestrak.org), created and managed by Dr. T.S. Kelso.

Table 1. Available catalogs of artificial objects (functional satellites + debris) in orbit around the Earth. From 2020 to 2024, separate catalogs of active satellites (*) were available as well

Year	Date
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
2020*	June 4
2021*	June 28
2022*	June 20
2023*	October 18
2024*	November 5

3 EVOLUTION OF THE CATALOGED OBJECTS

Fig. 1 shows how the spatial density of cataloged objects in LEO evolved over 30 years, from 1994 to 2024. Until 2019, when the first OneWeb and Starlink constellation satellites were deployed, respectively, at about 1200 and 550 km, the growth of cataloged objects, mainly fragmentation debris and dead payloads, was concentrated between 600 and 1000 km. Since then, this pattern in LEO has changed radically, clearly dominated by the dramatic increase of active constellation spacecraft around 1200 km and, above all, below 600 km.

Broadening the perspective to the entire space age and the whole circumterrestrial space, the number of spacecraft in orbit, both functional or dead, has increased by an average of about 50 per year from 1960 to 1980 (20 years) and by about 71 per year from 1980 to 2013 (33 years). Since 2013, growth has been more than linear, first because of the CubeSat boom and then because of the advent of mega-constellations [11]. As of 15 November 2024, there were 3148 dead satellites in orbit, 1690 active spacecraft without propulsion systems, and 8869 active spacecraft with propulsion systems, of which 6566 Starlinks [15]. Among the working spacecraft, only 16% were not maneuverable, nearly doubled in number by dead satellites.

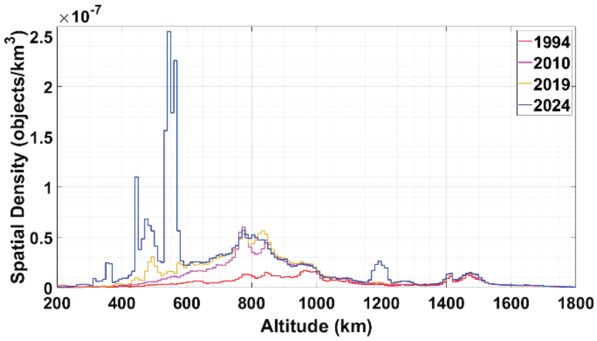

Figure 1. Evolution of the spatial density of cataloged objects, below 1800 km, from 1994 to 2024

The growth of the number of orbital rocket stages has instead always remained approximately linear [11], increasing by an average of about 39 per year from 1960 to 1998 (38 years) and by about 23 per year from 1998 to 2024 (26 years). At the end of 2024, approximately 2000 rocket stages were in orbit.

The same applied to the so-called mission-related objects [14]. Their growth has also remained substantially linear [11], increasing by an average of about 46 per year from 1960 to 1998 (38 years) and by about 10 per year from 1998 to 2024 (26 years). At the end of 2024, approximately 2000 mission-related objects were also in orbit.

However, the most significant indicator of the state of the environment is represented by fragmentation debris, that is, the object pieces resulting from surface degradation, low-energy fragmentations, energetic explosions, and collisions with meteoroids or other artificial objects. The most damaging events for the environment, that is, energetic explosions and collisions among artificial objects, are mostly unwanted and accidental, but in some cases were and are intentionally caused to destroy classified spacecraft, for structural trials, or to test anti-satellite weapons.

From 1961 to 1987 (26 years), the number of cataloged fragments increased, on average, by 192 pieces per year [11]. From 1987 to 2007 (20 years), the growing and widespread implementation of debris mitigation measures, such as the end-of-life passivation of spacecraft and orbital rocket stages to prevent accidental explosions, strongly reduced the average increase of fragments to 25 per year [11].

However, in just 3 years, from 2007 to 2010, two major breakup events in LEO [12,13], namely the intentional destruction of the Chinese Fengyun 1C satellite with a hypervelocity collision during an anti-satellite weapon test in 2007 and the accidental (and potentially avoidable) collision, in 2009, among a functional and maneuverable American satellite (Iridium 33) and a dead and abandoned Russian satellite (Cosmos 2251), increased the cataloged fragmentation debris by about 6000 pieces, more than doubling their number in orbit [11].

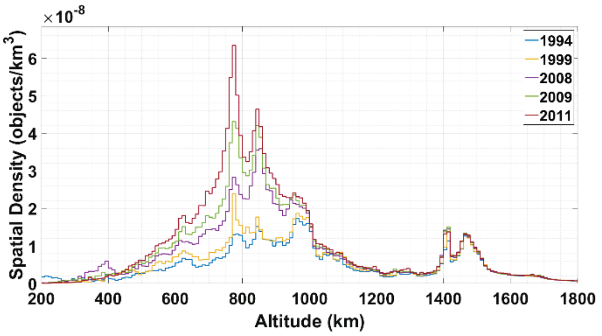

Figure 2. Evolution of the spatial density of cataloged objects below 1800 km from 1994 to 2011; the small transient peak of objects, around 400 km and below, recorded during 2008, was produced by three fragmentations, for unknown causes, of the Russian reconnaissance satellite Cosmos 2421 [16]

These huge debris-generating events, which occurred at around 800 km altitude, had a profound and lasting impact on the debris population in LEO, as shown in Fig. 2, where the spatial density increase of cataloged objects between 600 and 1000 km since 2008 is quite evident. They demonstrate that, in the current situation, the environment can be radically modified by sporadic single events of low but non-negligible probability. In other words, just preventing the production of new fragmentation debris from material degradation, explosions, and intentional collisions, in addition to collision avoidance of maneuverable spacecraft, could secure us, if we are lucky, a few decades of stable or slightly decreasing fragmentation debris environment in LEO. But the heavy legacy of thousands of dead or non-maneuverable satellites and rocket stages still in orbit is there to remind us that a catastrophic collision involving them could happen at any moment, dramatically changing the population of fragmentation debris again, as already seen between 2007 and 2010.

This is confirmed by what has occurred since 2010. Although there have been some noteworthy breakup events in LEO, as the Russian anti-satellite weapon test carried out at the end of 2021 against Cosmos 1408 [17], and a couple of major explosions, in 2022 and 2024, involving Long March 6A upper stages [18], their effects were short-lived or compensated by other debris decays. Then, at the end of 2024, the overall number of cataloged fragmentation debris, about 12,000, was pretty much the same as 15 years earlier, in the second half of 2009, despite the enormous growth of spacecraft registered in the meantime [11,15].

This can also be seen indirectly in Fig. 3, where, between 2012 and 2019, the distribution of cataloged objects remained substantially unchanged above 700 km, dominated by fragmentation debris and abandoned objects, while in 2019 the contribution in low LEO of the numerous CubeSats and the first satellites of the large constellations became evident.

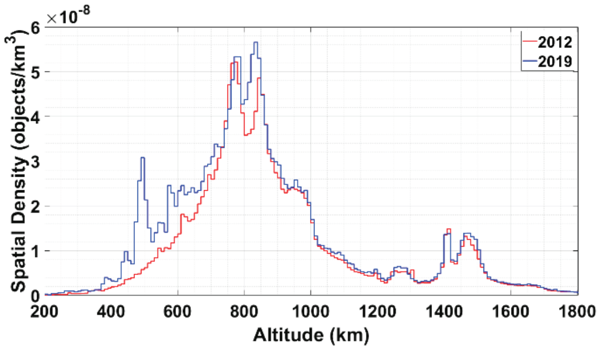

Figure 3. Evolution of the spatial density of cataloged objects below 1800 km from 2012 to 2019

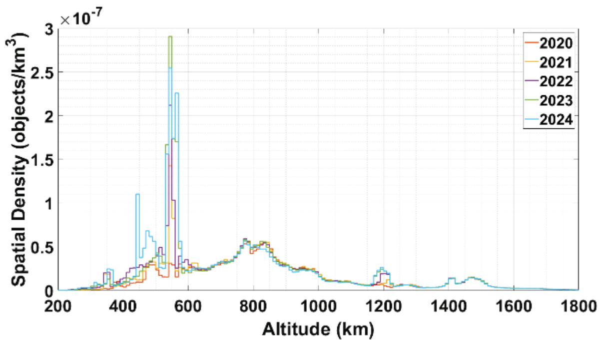

Figure 4. Evolution of the spatial density of cataloged objects below 1800 km from 2020 to 2024

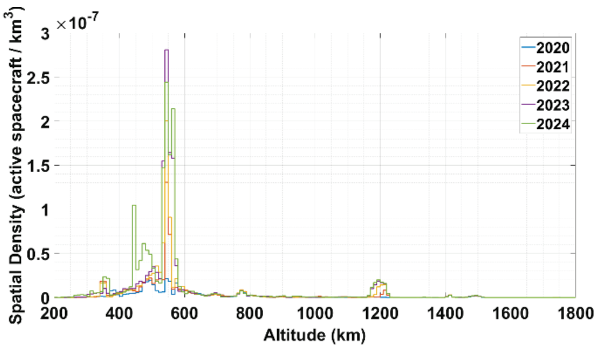

Figure 5. Evolution of the spatial density of active spacecraft below 1800 km from 2020 to 2024

4 THE IMPACT IN LEO OF MEGA-CONSTELLATIONS

Since 2019, the impact of the deployment in LEO of mega-constellations has been massive in numbers (and spatial density), as shown in Figs. 4 and 5. Comparing the two figures, it is quite obvious that almost all of the increase found, apart from a few transient events of relatively short duration, such as the intentional destruction of the Russian satellite Cosmos 1408 in 2021, is attributable to the launch of new satellites, mostly belonging to large constellations, around 1200 km and, especially, below 600 km.

Of the approximately 30,000 cataloged objects in orbit at the end of 2024 [11], nearly 36% were active satellites, and over 30% (that is about 84 out of 100 satellites) were also maneuverable [15]. Historically, these are record numbers that have never been achieved before. In the decade 2008-2018, leading up to large constellations, the percentage of active satellites varied between 6% and 9%, and still in mid-2019 active satellites accounted for just over 11% of cataloged objects.• Among these working spacecraft, about half were maneuverable in more recent years, relatively less at earlier times.

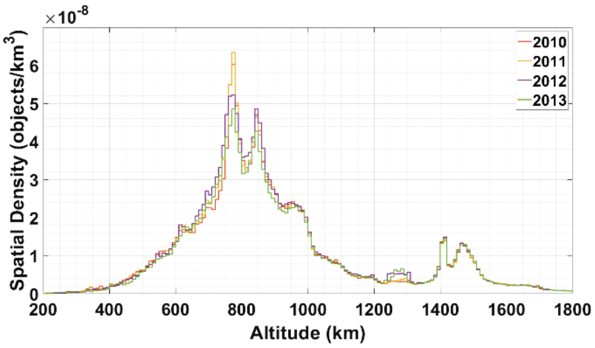

Figure 6. Evolution of the spatial density of cataloged objects below 1800 km from 2010 to 2013; active spacecraft, about 7% or less, are included

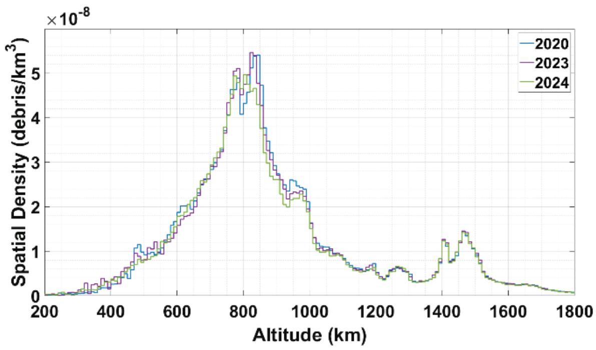

Figure 7. Evolution of the spatial density of cataloged debris [14] below 1800 km from 2020 to 2024; active spacecraft are excluded

•According to the Union of Concerned Scientists (UCS) Satellite Database (www.ucsusa.org/resources/satellite-database).

Recently, popular and specialist information sources have greatly emphasized the growth in the number of objects in orbit, placing it directly in relation to a significant worsening of the space debris problem. However, if we focus our attention on the debris proper [14], the situation has not changed significantly in the 15 years between the end of 2009 and the end of 2024, as partly anticipated in the previous section and shown in Figs. 6 and 7. Fig. 6 highlights that, after the catastrophic fragmentations occurred between 2007 and 2010, the population of cataloged objects in LEO, including a small fraction – about 7% or less – of active spacecraft, remained substantially stable in numbers and distribution from 2010 to 2013. Fig. 7, on the other hand, displays the evolution in LEO of the debris proper, excluding active spacecraft, during the large constellation deployment phase from 2020 to 2024. And, again, the population of cataloged debris remained remarkably stable in numbers and distribution.

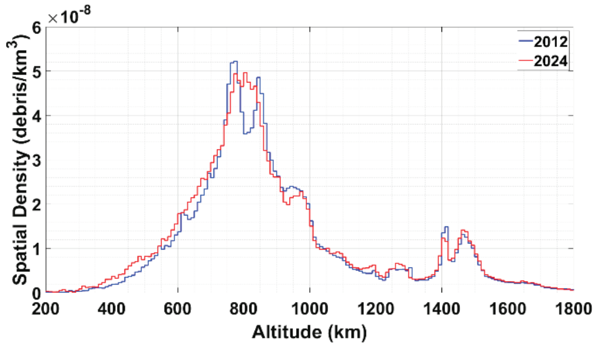

Figure 8. Comparison, below 1800 km, of the distribution of cataloged objects in 2012, including less than 7% of active spacecraft, with the cataloged debris [14] in 2024, obtained by excluding active spacecraft

Nevertheless, as shown in Fig. 8, the even more notable fact is that the curves in Fig. 7 overlap well with those in Fig. 6, although not entirely homogeneous, the latter including a small percentage of active satellites. This implies that although the number of active satellites in 2024 was one order of magnitude higher than in 2010, the orbital debris proper in LEO was neither better nor worse than 15 years earlier.

This indicates that large constellations and other recent satellite systems, on the whole, have so far been planned and operated quite responsibly and effectively from the debris mitigation point of view, apart from a few cases, such as the two major breakups of Long March 6A upper stages and the anti-satellite test involving the Russian Cosmos 1408 satellite, which had transient environmental consequences or were compensated by other debris decays. However, it should be pointed out that we have also been somewhat lucky, as there have been no further unintentional catastrophic collisions between old and new non-maneuverable intact objects or serious accidents involving new space missions. In particular, considering only unintentional catastrophic collisions between intact objects, the probability of none of these events occurring in the 15 years between the end of 2009 and the end of 2024 was no more than about 45%, but probably less [19].

5 DISCUSSION AND CONCLUSIONS

Since it was first highlighted in 1978 [1], and in the 40 years since, the debris problem has been addressed with the goal of preserving the long-term use of circumterrestrial space by preventing such a large increase in objects that could make most sufficiently long orbital missions impractical or unsafe in some regions of space, with the available technology and operational capabilities. Thus, the emphasis was on taking action as soon as possible to limit the release of mission-related objects and to prevent the production of fragmentation debris, that is of potential collisional "bullets," in addition to reducing mass accumulation in orbit, that is, the source of potential fragments from accidental explosions and collisions, in the form of abandoned spacecraft and orbital stages.

These goals were pursued with mitigation measures, such as reducing operational debris released by each mission, preventing explosions with specific technical solutions, collision avoidance for maneuverable satellites, and end-of-life removal from the most congested regions of spacecraft and orbital stages, limiting their residual lifetime in LEO. Over the years, the incremental implementation of these measures has been incomplete, uneven, and not always successful. Positive environmental results have nonetheless been observed, as outlined in Sections 3 and 4, such as from 1987 to 2007 and from 2010 to 2024.

However, it then became clear that mitigation measures alone would not be sufficient to ensure the stability of the debris environment in the long term by avoiding catastrophic collisions [20], in particular at altitudes where air drag is ineffective in removing the fragments fast enough. Indeed, due to the numerous spacecraft and orbital stages abandoned over time above 650 km and their large mass, a couple of thousand metric tons in LEO alone [21], to statistically reverse the long-term trend would also have required some form of remediation, such as active recovery and removal of old massive objects [21,22].

Since the advent of mega-constellations in the late 2010s, characterized by huge numbers of spacecraft especially deployed and operated (so far) at relatively low altitudes, that is, below 600 km, the focus has understandably shifted to short-term space traffic management issues and related debris mitigation measures, as:

1. Managing the operations of so many objects;
2. Avoid collisions between constellation satellites and with all other cataloged objects in the background, whether functional or not, planning and coordinating a tremendous number of collision avoidance maneuvers (at the rate of more than 100,000 per year, for Starlink, at the end of 2024) [23];
3. Testing spacecraft in very low orbit before their final deployment at the operational altitude;
4. Properly disposing of upper stages and satellites at the end of their operational life;
5. Ensure that failed satellites are quickly removed from orbit by natural perturbations, namely air drag.

As of mid-March 2025, such measures, systematically and successfully implemented for Starlink, have proven to be highly effective in avoiding in LEO a noticeable proliferation of abandoned satellites and orbital stages, mission-related objects, and fragmentation debris in the face of an increase in the number of operational satellites by a factor of five since 2019. This means that the alarmist picture presented for the evolution of the situation in orbit in recent years by various articles that have appeared in the popular media, and also by some papers and reports in the technical literature, is not justified by the facts, the debris environment proper having remained practically the same as it was 15 years ago.

However, although the management of the massive new launch traffic that materialized in the late 2010s was, in general, quite responsible and effective, except for non-maneuverable satellites, especially CubeSats, launched above 450 km, nothing was done about the debris proper already in orbit as the result of previous space activities, except to try to avoid it, when necessary and possible, with the new maneuverable spacecraft placed in space recently. Moreover, no significant accident or failure involved the newly launched systems with more than transitory consequences, the Indian [24] and Russian [17] anti-satellite weapon tests of 2019 and 2021, respectively, had short-term effects, and all the unintentional breakups recorded in LEO, including the collision between the Chinese spacecraft Yunhai 1-02 and a small mission-related object associated with the Zenit launch vehicle used to place in orbit the Russian Cosmos 2333 satellite in 1996 [25], were compensated by the natural orbital decay of fragmentation debris occurred in the meantime [11]. Therefore, even if the debris environment has not discernibly deteriorated between 2010 and 2025, a considerable degree of luck has also been a factor, and there is no assurance that this favorable trend will persist.

As shown in the past [11], the LEO debris environment above 650 km is very sensitive to sporadic single catastrophic collisions, currently predicted to occur, on average, every 13-20 years, depending on the degree of collision avoidance carried out by active spacecraft, from zero (~13 years) to 100% (~20 years) [19]. Even if highly improved and more effective tracking, surveillance, collision avoidance, mitigation, and protection will be achievable with a combination of new sensors, innovative technologies and artificial intelligence, making it possible to operate missions even in regions of space that until a few years ago would have been considered too congested with debris, a further significant increase in LEO debris proper would complicate life and increase costs for all operators, even those active at very low altitudes, as well as worsening the medium- and long-term prospects for the environment above 650 km.

From now on, it will therefore be wise to combine short-term operational requirements with long-term environmental goals, supplementing enhanced tracking, surveillance, collision avoidance, mitigation, and protection with some form of remediation, such as just-in-time collision avoidance, which involves subtly changing the trajectory of large debris, for example using a ground-based laser, to prevent, when necessary, potential collisions leading to the catastrophic breakup of massive abandoned or non-maneuverable objects, and removal of centimeter-size debris, again with a laser system, to reduce the chance of spacecraft failures due to debris impacts. A detailed NASA study found that these two remediation options might be the most cost-effective, comparing favorably with the best cost-benefit ratios in mitigation, protection, and tracking, namely rapid deorbiting of spacecraft at the end-of-life, shielding satellites to protect them from the impact of debris up to 2-5 mm, and reduction of the orbital uncertainty of cataloged objects by a factor of 10 [26].

In conclusion, although in some respects the problem of space debris proper may not have worsened since the advent of mega-constellations, the vulnerability and sensitivity of the LEO environment to sporadic single catastrophic collisions remains a pending threat that cannot be ignored. Therefore, a combination of effective mitigation and remediation measures is highly endorsed to ensure the smooth short- and medium-term fruitful use of LEO orbits, as well as the sustainability of space operations in the long term. In this regard, the *Zero Debris Charter*, promoted by the European Space Agency, outlines a set of valuable guiding principles [14].

However, always keeping in mind the sensitivity of the current debris environment to sporadic single catastrophic events, one should never forget the paradoxical nature of practicable mitigation and remediation measures, the benefits of which can, on average, be appreciated in a statistical sense only over the medium and long term. In the short term, on the other hand, a single random catastrophic event could cause a significant deterioration of the environment despite the systematic application of all appropriate measures to deal with the debris problem. But, in any case, this should not call into question the original protection and sustainability objectives.

6 ACKNOWLEDGMENTS

The activity presented in this paper was carried out in the framework of the ASI-INAF agreement No. 2023-50-HH.0 on “Space Debris and Sustainability of Long-Term Space Activities”, and of the research project “Safety and Sustainability of Space Operations (SAFE-SPACE)”, funded by CNR-ISTI (No. DIT.AD012.225).

The authors would also like to thank the U.S. Space Track Organization for the catalog of objects tracked by the U.S. Space Surveillance Network. Concerning the operational status of the satellites, special thanks go to the Union of Concerned Scientists (UCS) Satellite Database and to the CelesTrak website, created and managed by Dr. T.S. Kelso.

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