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Research paper

Environmental sustainability of large satellite constellations in low earth orbit

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ABSTRACT

A specific criticality index, the collision rate percentage increase, was introduced in 2017 to assess the environmental impact of large satellite constellations in low Earth orbit (LEO). That index was estimated in this paper for various constellation arrangements, ranging in altitude from 800 km to 1400 km. The results obtained clearly show that in the regions of space where the current density of cataloged debris is already significant, such as around 800 km, just one hundred more abandoned satellites would increase the current collision rate by ~10%. In less congested LEO regions, as near 1110 km and 1325 km, a comparable increase in the collision rate could be achieved by a number of abandoned satellites between 200 and 500. Taking into account the new planned constellations from 800 km to 1400 km (consisting of approximately 6000 satellites), an increase by nearly 20–30% of the total collision rate among cataloged objects in LEO might be expected, assuming an immediate spacecraft de-orbiting at the end-of-life, with a success probability of 90%. Of course, a greater number of satellites, as well as a reduced probability of successful disposal, would affect the environment even more negatively. Moreover, if the many disposed satellites were not de-orbited immediately, or in a relatively short time, the collision rate in LEO would further increase, at least in the medium term, unless the satellites do not continue to be controlled and maneuverable until they reenter the atmosphere. As an example, if a thousand satellites were disposed on elliptical orbits between 300 km and 1000 km, the collision rate among cataloged objects in LEO might grow by an additional 30% during the few years needed to decay. That said, even assuming a willingness to endure a maximum 50% increase in the collision rate in LEO among objects greater than 10 cm, in the next 25 years, it is clear that an extended and expanded use of large constellations would be consistent with the environment sustainability only if it were possible to increase the post-mission disposal success probability to at least 95%, and hopefully to 99%. At the same time, the de-orbiting phase should be either quite short or fully controlled, in order to avoid the prolonged presence of several hundred or thousands of abandoned satellites in disposal orbits, further increasing the collision rate in low LEO.

1. Introduction

The current plans envisaging the deployment of very large constellations in low Earth orbit (LEO), some consisting of thousands of spacecraft, raised a growing concern regarding the long-term sustainability of the near-Earth space environment with the present-day guidelines recommended around the world [1,2]. Assessing the impact of the proliferation of small satellites and large constellations has therefore been identified as a priority, in order to evaluate if additional, and more stringent, mitigation measures might be needed to preserve the long-term access and utilization of the LEO protected region. However, this task may be quite complex, because traffic models and constellation deployment plans are, of course, subject to sudden changes, driven by economic and technical issues, and are anyway very uncertain beyond twenty years in the future. Detailed mission profiles, satellite failure rates and disposal strategies are affected by significant uncertainties as well. The same applies to technological developments and breakthroughs, which could change completely the nature of space systems, as in part it is already occurring with the very fast increase of mini, micro and nanosatellites.

Therefore, it might be desirable to address the problem avoiding the intricate simulation of complex and highly speculative scenarios, concentrating instead on a simplified and fast analysis, able to provide some preliminary clues and insights, perhaps useful for steering further refinements with more complex and CPU time consuming techniques. With this goal in mind, during the last few years we have developed

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some approaches, based on reasonable simplifying assumptions, for the assessment of the environment criticality of large constellations and huge numbers of small satellites in LEO [3,4]. They can provide preliminary quantitative answers to difficult questions, with no need of complex models and computations, and can be implemented either with analytical expressions or with very fast numerical tools. Moreover, a specific figure of merit was introduced, since 2017, for gauging the environment criticality of new large constellations: the collision rate percentage increase [3,4].

In this paper, such criticality index was estimated, in some representative and relevant orbital regimes, to evaluate the potentially adverse environmental impact of large constellations as a function of spacecraft failures in, or close to, the operational orbits, i.e. before the execution and successful completion of appropriate end-of-life disposal maneuvers. In particular, the increased collision rate with cataloged debris of failed constellation satellites was estimated and compared with the current global collision rate among cataloged objects in LEO, i.e. below the altitude of 2000 km.

2. Large constellations in LEO

Currently, several private companies are planning the deployment in LEO of the so-called large or mega-constellations of satellites, involving hundreds or thousands of spacecraft working in concert to carry out specific functions. Very often the satellites belonging to such constellations (or to separate groups of the same constellation) are placed in circular orbits at nearly the same altitude, trying to obtain an even coverage of the Earth's surface with an appropriate choice of inclination, nodal separation of orbital planes, and spacecraft separation, either along the same plane and between adjacent planes [5–11].

Providing a complete, accurate and up-to-date outline of the large constellations planned in LEO is not easy, because the field is rapidly evolving, the economic profitability and the market potential of the intended activities must still be demonstrated, and, last but not least, the companies and the licensing authorities involved belong to several countries. As of September 2019, only two large constellations have started their deployment in LEO: OneWeb at 1200 km (first launch on February 27, 2019) and Starlink at 550 km (first launch on May 24, 2019).

2.1. Orbits of new constellations in LEO

In September 2019, according to the publicly available information, mainly from the U.S. Federal Communications Commission (FCC), the mean altitudes and inclinations considered for new constellations, or sub-constellations, consisting of more than 80 satellites in nearly circular LEO orbits are listed in Table 1. For the purposes of the present study, these orbit selections can be arranged in two groups: those with a typical natural lifetime of less than 20 years for intact satellites, i.e. with a mean altitude around 600 km or less, and those for which the typical natural lifetime is greater than 100 years, i.e. with a mean altitude greater than 750 km. This means that if a satellite, failing at the operational altitude of its own constellation, belongs to the first group, it will typically reenter the Earth's atmosphere in less than 25 years, then being naturally compliant with the mitigation guidelines of the Inter-Agency Space Debris Coordination Committee (IADC) [1] and of the International Organization for Standardization (ISO) [2]. Instead, if a satellite belongs to the second group, it will remain in orbit for a much longer time, perhaps contributing to the long-term increase of orbital debris.

The launch and operation of large satellite constellations might cause disparate problems in any orbital regime. In low LEO, below 600 km, they were outlined elsewhere [12]. However, since this study is focused on the adverse long-term effects on the debris environment, only altitudes between 800 km and 1400 km were considered. The six combinations of altitude and inclination for which detailed simulations were carried out are indicated in Table 1 with their study case number.

Table 1
Mean altitudes and inclinations considered for new constellations, or sub-constellations, consisting of more than 80 satellites in nearly circular LEO orbits (as of September 2019).

Study Case	Altitude (km)	Inclination (°)
	335.9	42
	340.8	48
	345.6	53
	550	53
	600	97.7
1	800	98.6
2	1000	99.5
	1056	54
3	1110	53.8
	1130	74
4	1200	87.9
	1275	81
5	1325	70
6	1400	90

2.2. Radius vector dispersion of the failed satellites

Another important issue for our analysis was to obtain an evaluation of the radius vector dispersion of the constellation satellites eventually failed at, or around, the operational altitude. Of course, this information was not yet available for the planned large constellations, still to be deployed. However, some useful clues were found through the knowledge and study of a few constellations that have been in orbit for a relatively long time, namely Globalstar (with an inclination of 52°), Iridium (with an inclination of about 86°) and Orbcomm (mostly with inclinations of 45° and 47°). Normally, most of the satellites completed their nominal or extended mission and were finally de-orbited or re-orbited at the end-of-life, clearing the operational height. For some satellites, nevertheless, this was not possible, either due to failures during the mission or exhausted propellant. Therefore, a few dead spacecraft remained close to the operational altitudes of the constellations.

Figs. 1–3 show the apogee vs. perigee altitude, computed with respect to the mean equatorial radius of the Earth, for the satellites belonging, respectively, to the Globalstar, Iridium and Orbcomm constellations. The plots are centered around the nominal heights and therefore do not include most of the spacecraft de-orbited or re-orbited at the end-of-life. Moreover, the active satellites are clearly distinguished from the non-functional ones.

In the region of interest, only three abandoned Globalstar satellites were present (Fig. 1). They were scattered in an altitude band of 20 km, while the active satellites were distributed in less than 30 km, but nearly all concentrated in less than 20 km as well. In the Iridium case (Fig. 2), approximately 20 non-functional satellites shared the volume of space used by the active spacecraft. The inactive satellites were scattered in an altitude band of less than 50 km, even though mostly (~70%) concentrated in less than 30 km. The active satellites were distributed as well in 50 km, but largely clustered in less than 25 km. In the Orbcomm case (Fig. 3), the picture is a little more complicated, because two sub-constellations were deployed (first and second-generation), plus several test and replenishment spacecraft using different families of orbits. Anyway, looking at the non-functional spacecraft in the lower left area of Fig. 3, all but one were spread in an altitude band of nearly 40 km. Concerning the functional satellites, the three main groups were clustered, instead, in approximately 15 km. Therefore, in view of the observed distribution of the operational constellation satellites, either functioning or not, a radius vector dispersion between 15 km and 50 km might be reasonably assumed for the new constellation spacecraft failed or abandoned in their operational orbits.

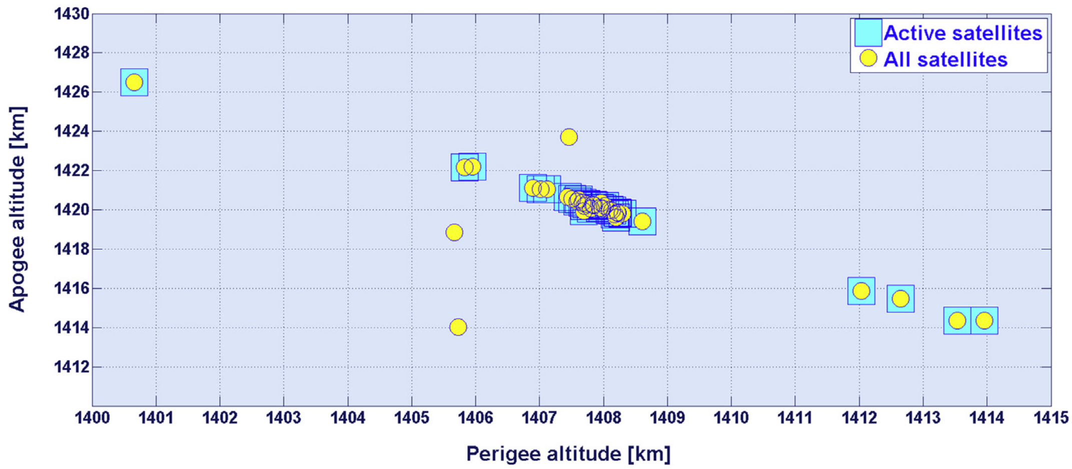

Fig. 1. Apogee vs. perigee altitude (w.r.t. the mean equatorial Earth radius) of the Globalstar satellites around the nominal altitude of the constellation (September 5, 2019).

2.3. Spread of the orbital planes

Constellation satellites are usually arranged in a suitable number of evenly spaced orbital planes. Then, taking a snapshot of the active satellites at any given time, their right ascensions of the ascending and descending nodes will be clustered at certain values, separated by regular angular intervals in the equatorial plane. However, uncontrolled non-functional satellites are subject to minor differential perturbations, for instance in the nodal precession rate, which progressively lead to a plane drift with respect to the operational constellation planes.

For circular orbits, or orbits with the same eccentricity, a small difference Δa between the semi-major axis of a non-functional spacecraft and that of the operational orbit will cause a nodal drift proportional to $\cos i$, where i is the inclination of both orbits. The spread of the orbital planes can be accordingly quite fast at low or medium inclinations, while it takes much longer for high inclinations or nearly polar orbits. Anyway, after an interval of time depending on the Δa values and on i, the non-functional satellites tend to distribute themselves in a spherical shell around the Earth, with the exclusion of two spherical caps centered on the geographical poles and with angular radii of $|90° - i|$. As an example, Fig. 4 shows the situation for the Iridium constellation, with $i \approx 86°$. The operational planes are clearly identified by the active satellites, while the non-functional spacecraft display a significant dispersion between the operational planes, even when the semi-major axes are close to the nominal one, despite the nearly polar inclination of the constellation.

Then, looking at the consequences of failed or abandoned new constellation satellites over more than several years, a fairly even distribution of the ascending nodes of no longer maneuverable spacecraft might be considered a reasonable assumption, also bearing in mind that the combinations of possible specific initial conditions, as well as unpredictable, would be practically infinite.

3. Evaluating the impact of large constellations

The deployment of large constellations in LEO, beyond the specific functions they will perform, will have a profound and durable impact on space activities and operations. A not necessarily complete list of possible sectors affected entails:

1. The improvement of space surveillance and situational awareness;
2. The need for much more effective and reliable conjunction assessment;
3. The implementation of dependable maneuvering for collision avoidance and end-of-life disposal;
4. The adoption of a strong reduction of the residual lifetime of decommissioned spacecraft;
5. The evaluation of the possible interference with astronomical and radio-astronomical observations, and with standard operations of other space systems;
6. The application of enhanced levels of protection from impact damages caused by micrometeoroids and small non-trackable orbital debris, to prevent the failure of constellation satellites from launch

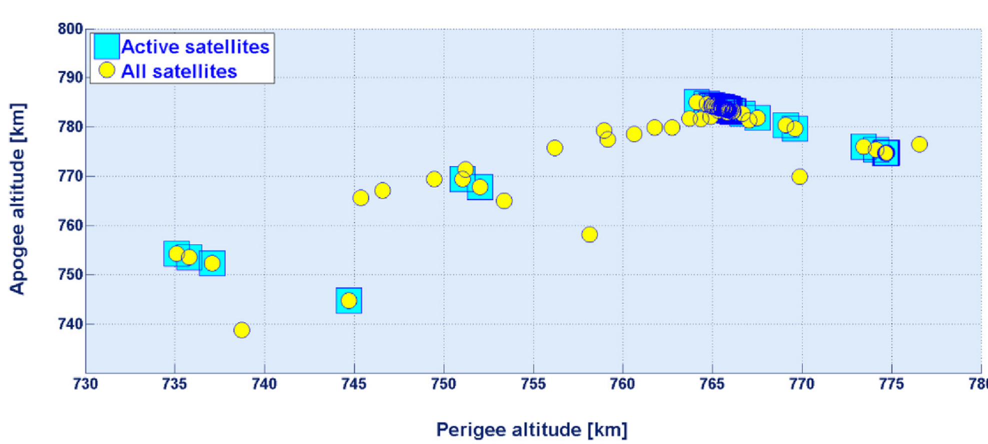

Fig. 2. Apogee vs. perigee altitude (w.r.t. the mean equatorial Earth radius) of the Iridium satellites around the nominal altitude of the constellation (September 5, 2019).

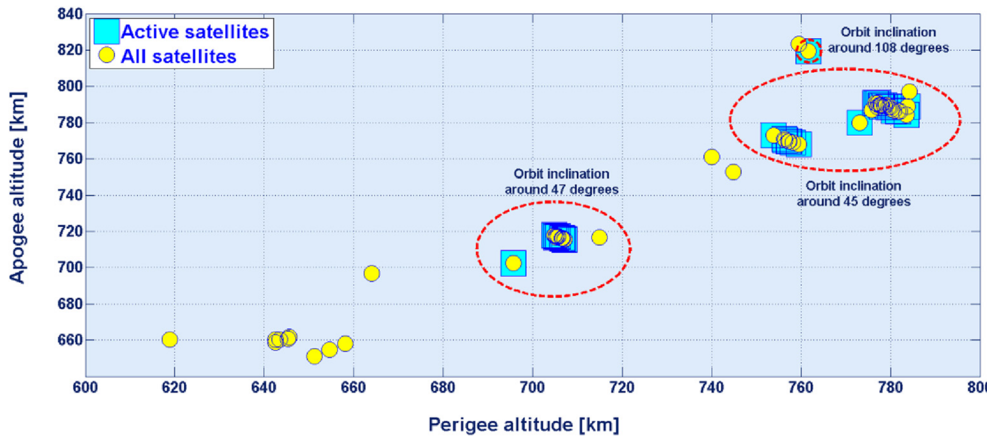

Fig. 3. Apogee vs. perigee altitude (w.r.t. the mean equatorial Earth radius) of the Orbcomm satellites around the nominal altitudes of the sub-constellations (September 5, 2019).

to disposal;

7. The prevention of the build-up of a huge number of disposed constellation satellites crossing the low LEO region, typically below 500 km, characterized by crewed missions, permanent human presence and high value spacecraft;
8. The possible significant increase of the total casualty expectancy on the ground if the disposed constellation satellites reenter uncontrolled and are not adequately designed for demise.

Another noteworthy aspect is represented by the potential detrimental effects that large constellations might have on the LEO debris environment. Only this last point was specifically addressed in this study.

3.1. Collision rate increase

In order to assess the potential detrimental effects on the LEO debris environment of constellation satellites – either lost, abandoned or non-maneuverable close to their operational altitudes, i.e. before an appropriate end-of-life disposal could be implemented – a simple criticality index, named *collision rate percentage increase* (*CRI*), had been previously defined [3,4], and was herein adopted and applied. In *CRI* the additional average collision rate due to new lost, abandoned or non-maneuverable constellation satellites, both among themselves (CR_{0-0}) and with the pre-existing background of cataloged objects (CR_{0-B}), is compared with the current overall collision rate in LEO among the background cataloged objects (CR_{B-B}):

$$CRI\,[\%] = 100(CR_{0-0} + CR_{0-B})/CR_{B-B} \tag{1}$$

The current collision rate among non-maneuverable cataloged objects in LEO was assumed to be [13]:

$$CR_{B-B} \approx 0.2\ year^{-1} \tag{2}$$

3.2. A desirable upper limit of CRI

Considering that most mitigation measures developed and applied over the last 20 years had as their main goal a long-term stabilization of the debris environment in LEO, a desirable upper limit of *CRI* in the near future should be such to guarantee this objective. As an example, a study carried out in 1999–2000, with the launch traffic forecasts of that time and assuming a strict adherence with the IADC mitigation recommendations then under discussion [1], found a near-stabilization of the LEO debris population, of 10 cm or more, around 2100, with an asymptotic collision rate in between 0.22 and 0.24 per year, and an expected cumulative number of collisions, always among objects greater than 10 cm, less than 25 [14]. This means that, for simulations carried out in 2000, an increase in the collision rate in LEO between 10% and 20% of the current value (i.e. ≈ 0.2 per year) was considered a desirable and reachable goal of the worldwide mitigation effort by the end of the century.

A doubling of the current (2019) collision rate between orbital debris greater than 10 cm by 2045 would have led, instead, to more than 50 collisions by 2100, with an asymptotic collision rate of one per year [14]. But such outcome, corresponding to a partially mitigated scenario (on-orbit explosion prevention), was considered unsatisfactory

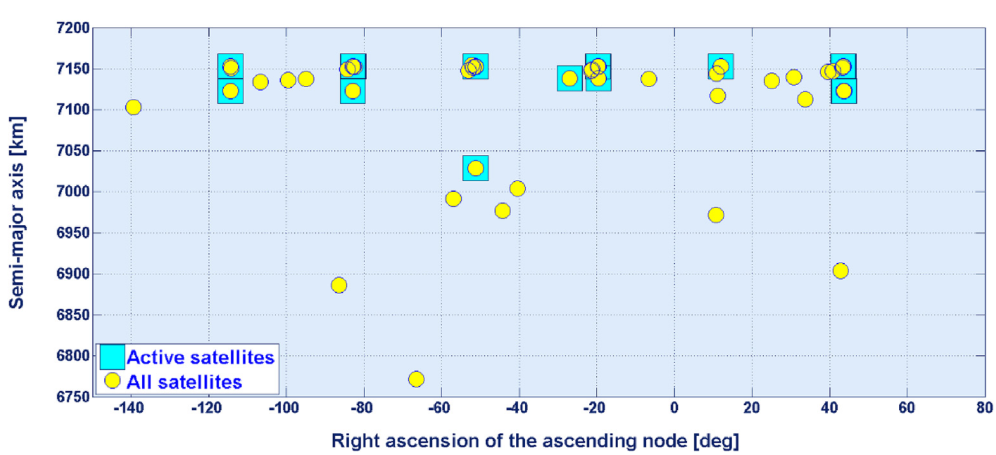

Fig. 4. Semi-major axis vs. right ascension of the ascending node of the Iridium satellites (September 5, 2019).

at that time, and it was just to avoid similar trends of debris growth that further mitigation guidelines were evaluated, recommended and (unfortunately still partially) implemented [1].

3.3. CRI trend due to additional inactive satellites

For a given spread in radius vector of the lost, abandoned or non-maneuverable constellation satellites, and an assigned orbital debris background, the following relationships *approximately* apply [3,4]:

$$CR_{0-0} \propto N^2 \tag{3}$$

and

$$CR_{0-B} \propto N \tag{4}$$

where N is the number of constellation satellites either lost, abandoned or non-maneuverable. Therefore, when N is below a certain threshold, which obviously varies case by case, $CR_{0-B} \gg CR_{0-0}$ and CRI is roughly proportional to N, while when N is large enough, $CR_{0-B} \ll CR_{0-0}$ and CRI is roughly proportional to N^2. This means that a small number of failed constellation satellites will typically cause a linear increase of the criticality index CRI, while a large number of failures will lead to a quadratic growth, sign of a clear prevalence of the intra-constellation conjunctions compared with those between failed constellation satellites and debris background. The latter situation can also occur for relatively small values of N if the new constellation is deployed at an altitude in which the debris background is particularly low, as between 1200 km and 1400 km (see Figs. 5 and 6), and the failed satellites are narrowly concentrated in terms of radius vector dispersion, but generally the trend of CRI will be intermediate between that of Eq. (3) and that of Eq. (4) when N is between several tens to several hundred.

3.4. Towards a partial mitigation scenario

The deployment and operation of large constellations, due to the large number of spacecraft involved, will represent a big challenge for the current mitigation measures [1,2], conceived when the payload launch rates, the typical satellite masses and the orbits used were distinctly different. Adjustments will surely be necessary to adapt to a rapidly changing situation. But to do this in a sensible way one must first obtain quantitative results capable of offering a realistic picture of the problems one may face and specific indications on the issues on which it may be most urgent to intervene. This study was just a further step in that direction.

In any case, following the previous discussion, an acceptable result, from the orbital debris mitigation point of view, might perhaps be obtained only if the combination of large constellation operations, other space activities and debris mitigation requirements would be able to limit the growth of the average collision rate in LEO, among objects greater than 10 cm, to less than 50% (i.e. to a total amount of less than 0.3 collisions per year) during the next 25 years. A stabilization at the current level would be, of course, preferable, but probably impossible at this point, so a “reasonable” compromise should be reached, taking into account the technical feasibility, the economic viability and the long-term preservation of the LEO Protected Region [1]. A further relaxation of that requirement, however, would mean throwing away all the work done in recent decades in the field of mitigation, resigning to a LEO region abandoned to ephemeral private interests and transformed into an extremely difficult environment to manage within a few decades.

4. Simulation setup

The six study cases identified in Table 1 were analyzed in detail, being representative of all combinations of heights and inclinations relevant to assess the medium- and long-term negative effects on the orbital debris environment.

4.1. Sets of failed constellation satellites

For each study case, corresponding sets of failed constellation satellites, each comprising 100, 300, 500 and 1000 non-maneuverable spacecraft, were generated, assuming three different spacecraft masses, i.e. 150 kg, 250 kg and 500 kg, well representative of the range currently considered for the new systems, either under deployment or planned. Moreover, two radius vector dispersion intervals Δr were specifically considered, based on the knowledge of the existing commercial constellations (see the discussion in Section 2.2): Δr = 15 km and Δr = 50 km. However, it should also be stressed that the simulation outputs and the available analysis tools allowed a fast and accurate scaling of the results to any other satellite number, satellite mass and Δr. The nodal distribution of the simulated non-maneuverable constellation satellites could be user defined, as well as the other orbital parameters defining the constellation. For the simulations described in this paper, an even distribution of the nodes was adopted (see the discussion in Section 2.3).

4.2. Collision rate estimate

Concerning the estimation of the collision rates CR_{0-0} and CR_{0-B}, the Space Debris Impact Risk Analysis Tool (SDIRAT) was used [15,16], coupled with an ad hoc post-processing routine to obtain the desired output as a function of the number of non-maneuverable constellation satellites, of the spacecraft mass, and of the dispersion interval of the radius vector. As input populations, SDIRAT used the cataloged objects, as of September 5, 2019, and the simulated sets of failed constellation satellites, generated with an external routine according to the study cases identified in Table 1 and further detailed in Section 4.1. Regarding the background debris population in LEO, i.e. the cataloged objects, Figs. 5 and 6 show the density distribution as a function of the height above the mean equatorial radius of the Earth.

4.3. Collisional cross-section

In order to compute the collisional cross-sectional area among the abandoned constellation satellites, and between those satellites and the orbital debris background, all objects were simulated as spheres. The mutual cross-sectional area applicable to a generic couple of objects, for instance 1 and 2, was then obtained by means of the formula $\pi(r_1 + r_2)^2$, where r_1 and r_2 represented the respective radii of the two interacting objects. For the constellation satellites, the applicable radii as a function

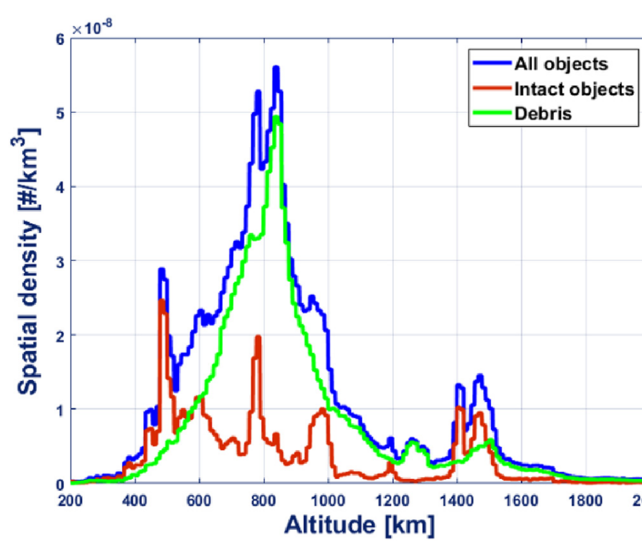

Fig. 5. Spatial density in LEO of cataloged objects, intact objects and debris (September 5, 2019).

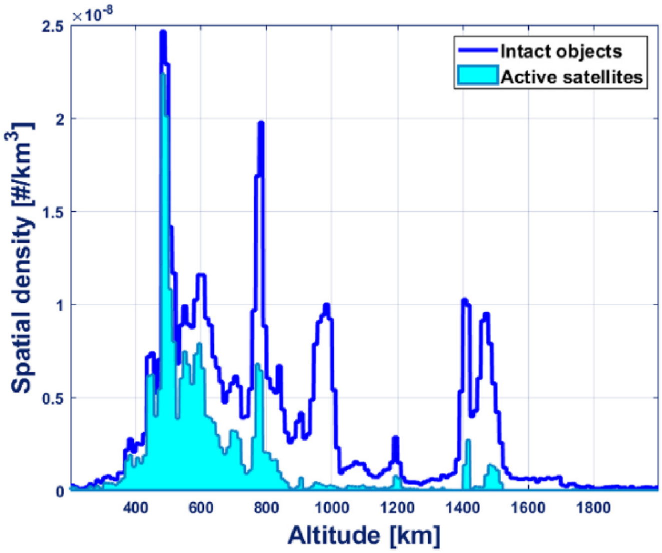

Fig. 6. Spatial density in LEO of intact objects and active satellites (September 5, 2019).

of the considered masses, i.e. 150 kg, 250 kg and 500 kg, were obtained with the classical formula [17]:

$$M = 62.013 \cdot A^{1.13} \tag{5}$$

where M is the satellite mass, in kg, and A is the average cross-section, in m^2. The values found are shown in Table 2. For comparison, it can be noticed that the mean radius of intact objects in LEO was about 1.21 m, while that of debris was about 0.26 m [18].

5. Criticality assessment

According to the simulation setup and tools described in Section 4, the collision rate percentage increase *CRI*, as defined in Eqs. (1) and (2), was therefore evaluated, for each of the six sets of orbital elements identified in Table 1, as a function of the number N and mass M of the lost, abandoned or non-maneuverable constellation satellites, taking into account as well the dispersion of their radius vectors Δr. The results obtained with Δr = 15 km are summarized in Tables 3–8 and in Fig. 7, while those found with Δr = 50 km are summarized in Tables 9–14 and in Fig. 8. However, as already pointed out, these results can be easily scaled to other radius vector dispersions, spacecraft masses and numbers of lost, abandoned or non-maneuverable satellites.

As expected, the criticality index *CRI* increases with the number of satellites and spacecraft mass, both leading to a growth of the collisional cross-section. Moreover, a greater spatial dilution of the satellites, i.e. a larger value of Δr, or placing the constellation in a region of space with a lower orbital debris background, e.g. at 1110 km or at 1325 km, lead to a significantly smaller value of *CRI* for a given spacecraft mass and number of non-maneuverable satellites. However, apart from these quite obvious qualitative aspects, what mattered, in this case, were the quantitative estimates of how many objects are sufficient to produce a certain negative effect on the orbital debris environment in LEO. If, for example, we were interested in knowing

Table 2
Masses, average cross-sections and radii of the simulated constellation satellites.

Mass (kg)	Cross-Section (m^2)	Radius (m)
150	2.185	0.840
250	3.434	1.046
500	6.342	1.421

Table 3
Collision rate percentage increase (*CRI*) in LEO for the constellation # 1, with Δr = 15 km, as a function of the number N and mass M of the lost, abandoned or non-maneuverable satellites.

Altitude = 800 km, Inclination = 98.6°, Δr = 15 km			
N	*CRI* (%)		
	M = 150 kg	*M* = 250 kg	*M* = 500 kg
100	6.6	9.1	14.8
300	30.7	44.2	75.4
500	69.2	101.6	177.3
1000	226.9	340.4	607.8

Table 4
Collision rate percentage increase (*CRI*) in LEO for the constellation # 2, with Δr = 15 km, as a function of the number N and mass M of the lost, abandoned or non-maneuverable satellites.

Altitude = 1000 km, Inclination = 99.5°, Δr = 15 km			
N	*CRI* (%)		
	M = 150 kg	*M* = 250 kg	*M* = 500 kg
100	4.0	5.6	9.1
300	22.1	32.3	56.0
500	53.1	79.0	139.7
1000	187.2	283.5	511.2

Table 5
Collision rate percentage increase (*CRI*) in LEO for the constellation # 3, with Δr = 15 km, as a function of the number N and mass M of the lost, abandoned or non-maneuverable satellites.

Altitude = 1110 km, Inclination = 53.8°, Δr = 15 km			
N	*CRI* (%)		
	M = 150 kg	*M* = 250 kg	*M* = 500 kg
100	1.3	2.0	3.5
300	8.6	13.0	23.4
500	22.0	33.6	61.0
1000	83.1	127.8	234.0

Table 6
Collision rate percentage increase (*CRI*) in LEO for the constellation # 4, with Δr = 15 km, as a function of the number N and mass M of the lost, abandoned or non-maneuverable satellites.

Altitude = 1200 km, Inclination = 87.9°, Δr = 15 km			
N	*CRI* (%)		
	M = 150 kg	*M* = 250 kg	*M* = 500 kg
100	2.4	3.6	6.4
300	18.8	28.7	52.4
500	51.3	79.0	144.7
1000	199.6	308.4	567.1

how many abandoned satellites of a single constellation would be sufficient to increase the total collision rate in LEO by 10% – a decidedly significant amount, considering what was said in Section 3.4 and the fact that several constellations are currently planned –, the answer can be found in Fig. 9, with Δr = 15 km, and in Fig. 10, with Δr = 50 km.

In the regions of space already most crowded with debris, as around the height of 800 km, about one hundred more non-maneuverable satellites in the considered mass range would be sufficient to increase the current collision rate in LEO by ~10%, while a number between 500

Table 7
Collision rate percentage increase (*CRI*) in LEO for the constellation # 5, with Δr = 15 km, as a function of the number *N* and mass *M* of the lost, abandoned or non-maneuverable satellites.

Altitude = 1325 km, Inclination = 70.0°, Δr = 15 km			
N	*CRI* (%)		
	M = 150 kg	*M* = 250 kg	*M* = 500 kg
100	1.2	1.8	3.3
300	9.1	13.9	25.3
500	24.1	37.0	67.7
1000	94.5	145.8	267.8

Table 8
Collision rate percentage increase (*CRI*) in LEO for the constellation # 6, with Δr = 15 km, as a function of the number *N* and mass *M* of the lost, abandoned or non-maneuverable satellites.

Altitude = 1400 km, Inclination = 90.0°, Δr = 15 km			
N	*CRI* (%)		
	M = 150 kg	*M* = 250 kg	*M* = 500 kg
100	3.0	4.3	7.2
300	19.3	28.7	51.1
500	49.6	75.0	135.1
1000	186.6	285.6	520.7

and 1000 would double it. In the less crowded LEO regions, as around 1110 km and 1325 km, a number of abandoned satellites between approximately 200 and 500 would instead be needed to boost the overall collision rate by ~10%.

Assuming an appropriate, and currently quite optimistic [19], post-mission disposal success rate of 90%, these results show that at a height of 800 km no more than about 1000 constellation satellites could be deployed over the years in order to limit the total collision rate increase in LEO to less than 10%. In much less crowded regions, depending on the constellation spacecraft mass and radius vector dispersion, the overall deployment might not exceed a number of satellites between 2000 and 5000, considering the same ceiling for the collision rate increase.

Table 9
Collision rate percentage increase (*CRI*) in LEO for the constellation # 1, with Δr = 50 km, as a function of the number *N* and mass *M* of the lost, abandoned or non-maneuverable satellites.

Altitude = 800 km, Inclination = 98.6°, Δr = 50 km			
N	*CRI* (%)		
	M = 150 kg	*M* = 250 kg	*M* = 500 kg
100	5.4	7.3	11.4
300	19.6	26.9	43.6
500	38.0	53.3	88.1
1000	102.6	147.7	252.1

Table 10
Collision rate percentage increase (*CRI*) in LEO for the constellation # 2, with Δr = 50 km, as a function of the number *N* and mass *M* of the lost, abandoned or non-maneuverable satellites.

Altitude = 1000 km, Inclination = 99.5°, Δr = 50 km			
N	*CRI* (%)		
	M = 150 kg	*M* = 250 kg	*M* = 500 kg
100	3.0	3.9	6.0
300	11.9	16.4	26.6
500	24.7	34.8	58.3
1000	73.6	107.4	186.1

Table 11
Collision rate percentage increase (*CRI*) in LEO for the constellation # 3, with Δr = 50 km, as a function of the number *N* and mass *M* of the lost, abandoned or non-maneuverable satellites.

Altitude = 1110 km, Inclination = 53.8°, Δr = 50 km			
N	*CRI* (%)		
	M = 150 kg	*M* = 250 kg	*M* = 500 kg
100	0.7	1.1	1.8
300	3.6	5.3	9.2
500	8.3	12.4	21.9
1000	28.4	43.0	77.4

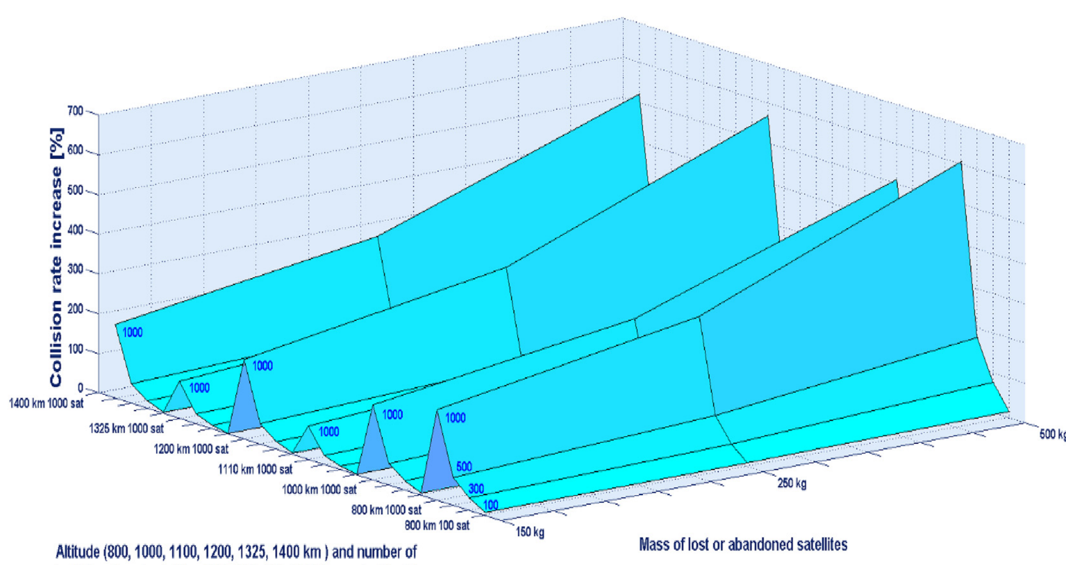

Fig. 7. Collision rate increase in LEO for the six constellations considered (Table 1), with Δr = 15 km, as a function of the number and mass of the lost, abandoned or non-maneuverable satellites.

Table 12
Collision rate percentage increase (*CRI*) in LEO for the constellation # 4, with $\Delta r = 50$ km, as a function of the number *N* and mass *M* of the lost, abandoned or non-maneuverable satellites.

Altitude = 1200 km, Inclination = 87.9°, Δr = 50 km			
N	*CRI* (%)		
	M = 150 kg	*M* = 250 kg	*M* = 500 kg
100	1.0	1.5	2.6
300	6.6	9.9	17.7
500	17.0	25.9	46.7
1000	63.2	96.8	176.7

Table 13
Collision rate percentage increase (*CRI*) in LEO for the constellation # 5, with $\Delta r = 50$ km, as a function of the number *N* and mass *M* of the lost, abandoned or non-maneuverable satellites.

Altitude = 1325 km, Inclination = 70.0°, Δr = 50 km			
N	*CRI* (%)		
	M = 150 kg	*M* = 250 kg	*M* = 500 kg
100	0.6	0.8	1.4
300	3.4	5.1	9.0
500	8.3	12.6	22.6
1000	30.5	46.7	84.9

Table 14
Collision rate percentage increase (*CRI*) in LEO for the constellation # 6, with $\Delta r = 50$ km, as a function of the number *N* and mass *M* of the lost, abandoned or non-maneuverable satellites.

Altitude = 1400 km, Inclination = 90.0°, Δr = 50 km			
N	*CRI* (%)		
	M = 150 kg	*M* = 250 kg	*M* = 500 kg
100	1.7	2.3	3.6
300	8.3	11.7	19.7
500	19.0	27.7	47.8
1000	64.3	96.0	170.8

According to these results, it was estimated that the currently planned constellations between 800 km and 1400 km – consisting of ~6000 satellites as of September 2019 – would result in an increase of the total collision rate in LEO by ~20–30% during their life cycle, assuming an immediate spacecraft de-orbiting at the end-of-life with a success probability of 90% and only first-generation satellites (that is, no replacements nor second-generation spacecraft). A higher number of mega-constellations and satellites, as well as a lower probability of successful disposal, would of course impact the environment more negatively. It should also be emphasized that if the disposed satellites (several hundred or thousands of them) were not de-orbited immediately, or in a short time, but left in orbits with a residual lifetime of, for instance, 20–25 years, the collision rate in LEO would further grow, extending the problem even to lower altitudes, at least in the medium term, unless the satellites do not continue to be controlled and maneuverable until they reenter the atmosphere.

For example, by simulating 1000 disposed and uncontrolled satellites with a mass of 250 kg and elliptical disposal orbits of 300 km × 1000 km, we found an increase in the collision rate in LEO among cataloged objects by ~30%, i.e. significantly greater than that caused by the abandonment of 1/10 of those satellites in the orbits of the constellations, from 800 km upwards (see Figs. 9 and 10). But in the first case the collision rate increase would be limited to the time necessary for the orbital decay of the objects (less than 5 years in the simulated example), unless one or more catastrophic collisions involving the disposed satellites occur in the meantime, while in the latter case the collision rate increase would persist for centuries or more, affecting the long-term evolution of the environment.

A more massive use of mega-constellations, with ~10,000 or more LEO satellites above 750 km, would be compatible with environment sustainability over the medium and long term only if it were possible to increase the post-mission disposal success rate to at least 95%, and possibly to 99%. At the same time, the de-orbiting phase should be either quite short (i.e. much less than the "classical" 25 years) and/or fully controlled, in order to avoid a considerable boost in the expected collision rate even in low LEO.

6. Conclusions

A criticality index, the collision rate percentage increase *CRI*, specifically defined for easily assessing the sustainability in LEO of large constellations, was applied to six constellation configurations, ranging in altitude from 800 km to 1400 km, considering spacecraft masses of 150 kg, 250 kg and 500 kg, as well as radius vector dispersions of the lost, abandoned or non-maneuverable satellites of 15 km and 50 km around the operational orbits of the constellations. The additional collision rate in LEO among cataloged objects was estimated, for a number of abandoned constellation satellites ranging from 100 to 1000, using the SDIRAT tool, developed and maintained at ISTI-CNR to calculate the debris fluxes, new ad hoc routines, for generating the abandoned objects and processing the output of SDIRAT for *CRI* computations, and the catalog of space objects tracked by the United States Space Surveillance Network.

The results obtained, easily scalable to other radius vector dispersions, spacecraft masses and numbers of lost, abandoned or non-maneuverable satellites, clearly show that in the regions of space where the current density of cataloged debris is greater, as around the altitude of 800 km, approximately one hundred more non-maneuverable satellites in the considered mass range would be sufficient to increase the current collision rate in LEO by ~10%. In less congested LEO regions, as around 1110 km and 1325 km, a comparable collision rate increase could be achieved by a number of non-maneuverable satellites between 200 and 500. This means that assuming a collision rate increase by 10% as an impassable ceiling, together with a satellite post-mission disposal success rate of 90%, no more than about 1000 constellation satellites could be deployed over the years at the height of 800 km, while in much less crowded regions the overall deployment might not exceed a number of satellites between 2000 and 5000.

Taking into account the new planned constellations between 800 km and 1400 km – consisting of ~6000 satellites to be deployed – an increase of the total collision rate in LEO by ~20–30% might be expected during their life cycle, if an immediate end-of-life spacecraft de-orbiting were carried out with a success probability of 90%. A greater number of satellites, as well as a reduced probability of successful disposal, would hit the environment even more negatively. Moreover, if the many disposed satellites were not de-orbited immediately, or in a short time, the collision rate in LEO would further grow, at least in the medium term, unless the satellites do not continue to be controlled and maneuverable until they reenter the atmosphere. The amount of this growth will depend on the number and mass of the spacecraft involved, as well as on the disposal orbits and strategies adopted. However, 1000 satellites with a mass of 250 kg and elliptical disposal orbits of 300 km × 1000 km might increase the collision rate in LEO among cataloged objects by a further ~30%, during the few years needed to decay.

From the orbital debris mitigation point of view and including all space activities, if we were willing to endure a global increase in the collision rate in LEO, among objects greater than 10 cm, by no more than 50% during the next 25 years, it is clear that an extended and

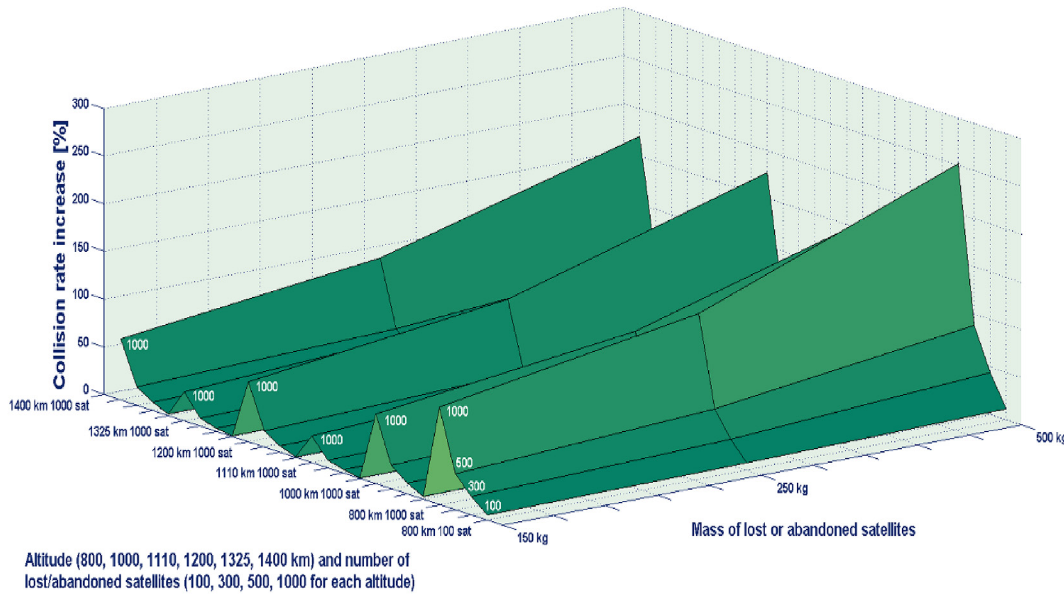

Fig. 8. Collision rate increase in LEO for the six constellations considered (Table 1), with Δr = 50 km, as a function of the number and mass of the lost, abandoned or non-maneuverable satellites.

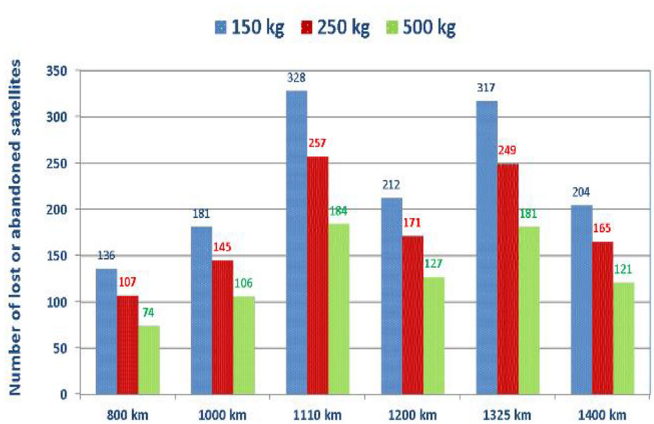

Fig. 9. Number of lost, abandoned or non-maneuverable satellites, with Δr = 15 km, able to increase by 10% the. total collision rate in LEO among cataloged objects, as a function of the constellation (see Table 1) and spacecraft mass.

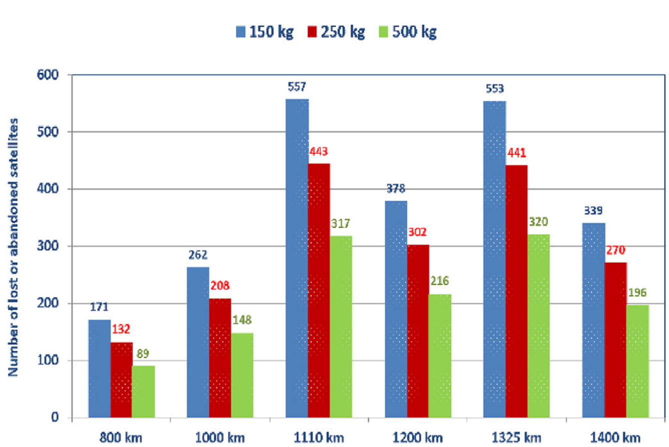

Fig. 10. Number of lost, abandoned or non-maneuverable satellites, with Δr = 50 km, able to increase by 10% the total collision rate in LEO among cataloged objects, as a function of the constellation (see Table 1) and spacecraft mass.

expanded operation of mega-constellations would be consistent with environment sustainability only if it were possible to increase the post-mission disposal success probability to at least 95%, and hopefully to 99%. At the same time, the de-orbiting phase should be either quite short or fully controlled, in order to avoid the accumulation , and therefore the continuous presence, of several hundred or thousands of non-maneuverable satellites in disposal orbits, further boosting the expected collision rate in low LEO.

These conclusions confirm and further refine the preliminary results and recommendations outlined in Refs. [3,4]. Moreover, they are also consistent with the detailed simulations carried out by NASA using the classical approach of numerically modeling the long-term evolution of orbital debris in order to address the environmental effects of large constellations and small satellites [20,21] This consistency, compared with a completely different and much more demanding method, from the point of view of simulation setup, modeling effort and execution time, was very encouraging in supporting the approach described in this paper for easy, fast and reasonably accurate preliminary assessments of the LEO environment sustainability in view of new large constellations and satellite deployments.

Last but not least, the updated Orbital Debris Mitigation Standard Practices, released by the U.S. federal government in November 2019, also incorporated, among other things, new sections to clarify and address operating practices for large constellations and small satellites [22]. Particularly relevant to the topics discussed in this paper is the recommended reliability of disposal, whose success probability should be «greater than 0.9 with a goal of 0.99 or better». This guideline nicely fits with the results of the analysis outlined in this paper and with the general indications that can be drawn from them. However, the updated Orbital Debris Mitigation Standard Practices still retain a recommendation on «orbital lifetime as short as practicable but no more than 25 years after completion of mission», a value found too high, according to our results, when several hundred or thousands of satellites are left simultaneously in disposal orbits affecting the low LEO region as well.

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