2nd IAA Conference on Space Situational Awareness (ICSSA)

Washington D.C., USA

IAA-ICSSA-20-00-17
THE LOW LEO PROTECTED REGION: NEW CHALLENGES FROM LARGE SATELLITE CONSTELLATIONS

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Keywords: *Space Debris, Low LEO Region, Large Satellite Constellations*

ABSTRACT

Since the definition of a Low Earth Orbit (LEO) protected region, up to the altitude of 2000 km, at the beginning of the 2000s, most of the attention of the space debris mitigation community was focused on heights greater than 600 km. In such orbital regimes, in fact, the average residual lifetimes of inert satellites and rocket bodies are typically greater than 20 years and the highest concentrations of functional satellites and space debris were historically found. The low LEO region, below 600 km, is however extremely important for space applications. In fact, since the last Apollo mission to the Moon, in December 1972, all human spaceflight was carried out there, the International Space Station, the planned large Chinese space station, the Indian crewed program and possible human tended private havens are making or will make use of this region of space, and also absolutely critical missions, like the Hubble Space Telescope, are orbiting below 600 km.

In recent years there was a dramatic increase in the launch rate of small satellites and cubesats in low LEO, boosting the number of potentially risky objects to be tracked and monitored. But the most dramatic development currently going on is the deployment of large satellite constellations, with almost 10,000 spacecraft planned only in low LEO in the coming years. Even though any failed satellite of the planned mega-constellations will decay from orbit in less than 25 years, therefore formally complying with current international space debris mitigation guidelines, it is realistic to expect a relatively high number of failures, considering the experimental nature of spacecraft tested in space, and in great numbers, for the first time. The short- and medium-term consequences for the satellite operations in low LEO might therefore be far from negligible.

The aim of this paper is therefore to present a preliminary review of the new challenges to be faced by spacecraft and space operations below 600 km, in the coming years, due to the deployment of large constellations of small satellites.

1. INTRODUCTION

The nearly spherical shell which goes from the Earth's surface to 2000 km in height is widely regarded as the Low Earth Orbit (LEO) Protected Region since the beginning of the 2000s [1] [2]. However, most of the attention of the space debris mitigation community was paid so far to heights greater than 600 km, because at such altitudes the average residual lifetimes of inert satellites and rocket bodies become typically higher than 20 years (Fig. 1), leading to a long-term accumulation of dead objects if appropriate disposal maneuvers to reduce the residual lifetime are not carried out [1] [2]. For this reason, coupled with the advantages and popularity of sun-synchronous orbits, the highest concentrations of functional satellites and cataloged space debris were found, historically, between 600 and 1000 km, followed by a secondary peak between 1400 and 1500 km, mainly due to a few constellations of communication satellites operated for decades.

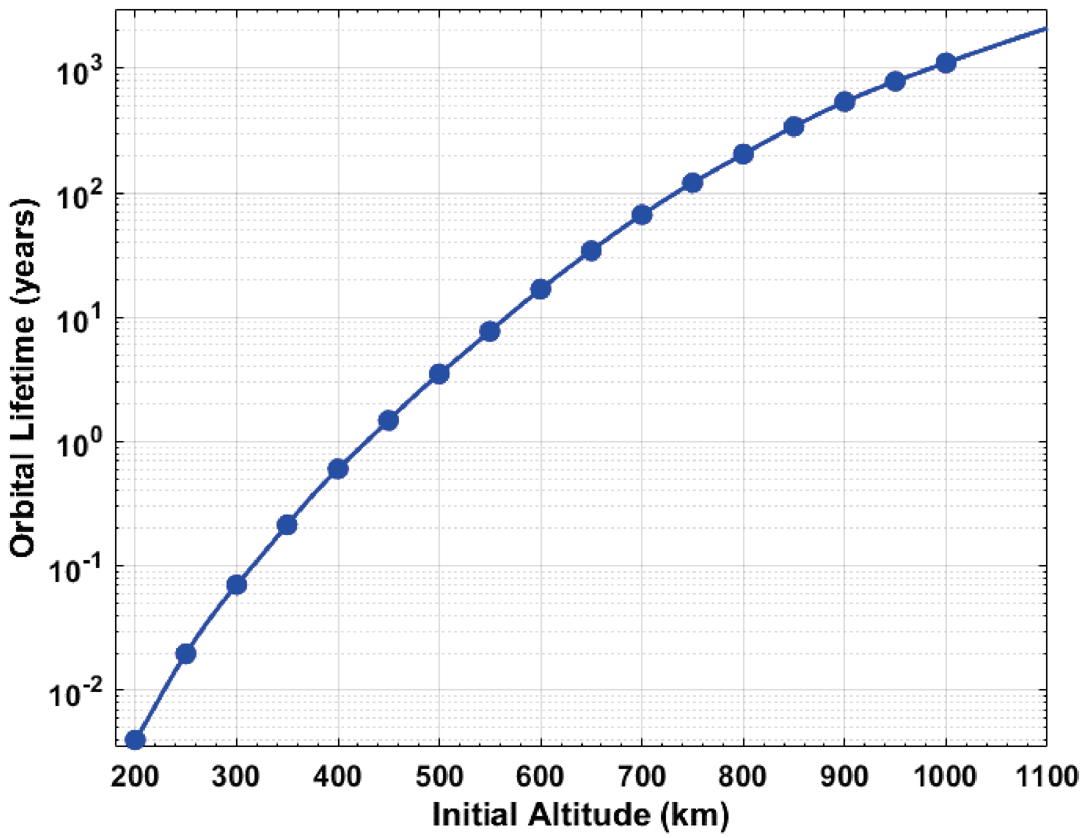

Fig. 1. Orbital lifetime in circular orbit for the average intact object abandoned in LEO (area-to-mass ratio = 0.012 m^2/kg; solar flux at 10.7 cm = 125 standard flux units; geomagnetic activity = quiet)

The "low LEO" region, below 600 km, even though historically characterized by smaller cataloged object densities, chiefly due to the reduced lifetimes caused by thermospheric drag, is nonetheless extremely important for space applications. In fact, since the last Apollo mission to the Moon, in December 1972, all human spaceflight was carried out there, the International Space Station (ISS), the planned large Chinese space station and the Indian crewed program are making and will make use of this region of space, and also absolutely critical scientific missions, like the Hubble Space Telescope (HST), are in low LEO. Even though generally considered less critical, from the orbital debris point of view, the low LEO region is now facing new and rapidly evolving challenges, that will need to be addressed in order to guarantee the continuation of its practical and safe use.

The recent years have seen several relevant developments. Among them, there was a resurgence of “live” anti-satellite weapon (ASAT) tests, i.e. leading to the actual destruction of the intended target. In fact, after a world-wide moratorium of more than 20 years, following the end of the Cold War, the successful (but badly conceived, from the orbital debris point of view) Chinese test carried out on 11 January 2007, at the altitude of about 865 km, was followed by the American test of 20 February 2008 and by the Indian test of 27 March 2019. Luckily, the latter two were carried out at low altitude, i.e. at 247 km and 264 km, respectively, so most of the fragments produced by the destruction of the targets reentered the atmosphere in several months, cleaned by the relatively intense thermospheric drag.

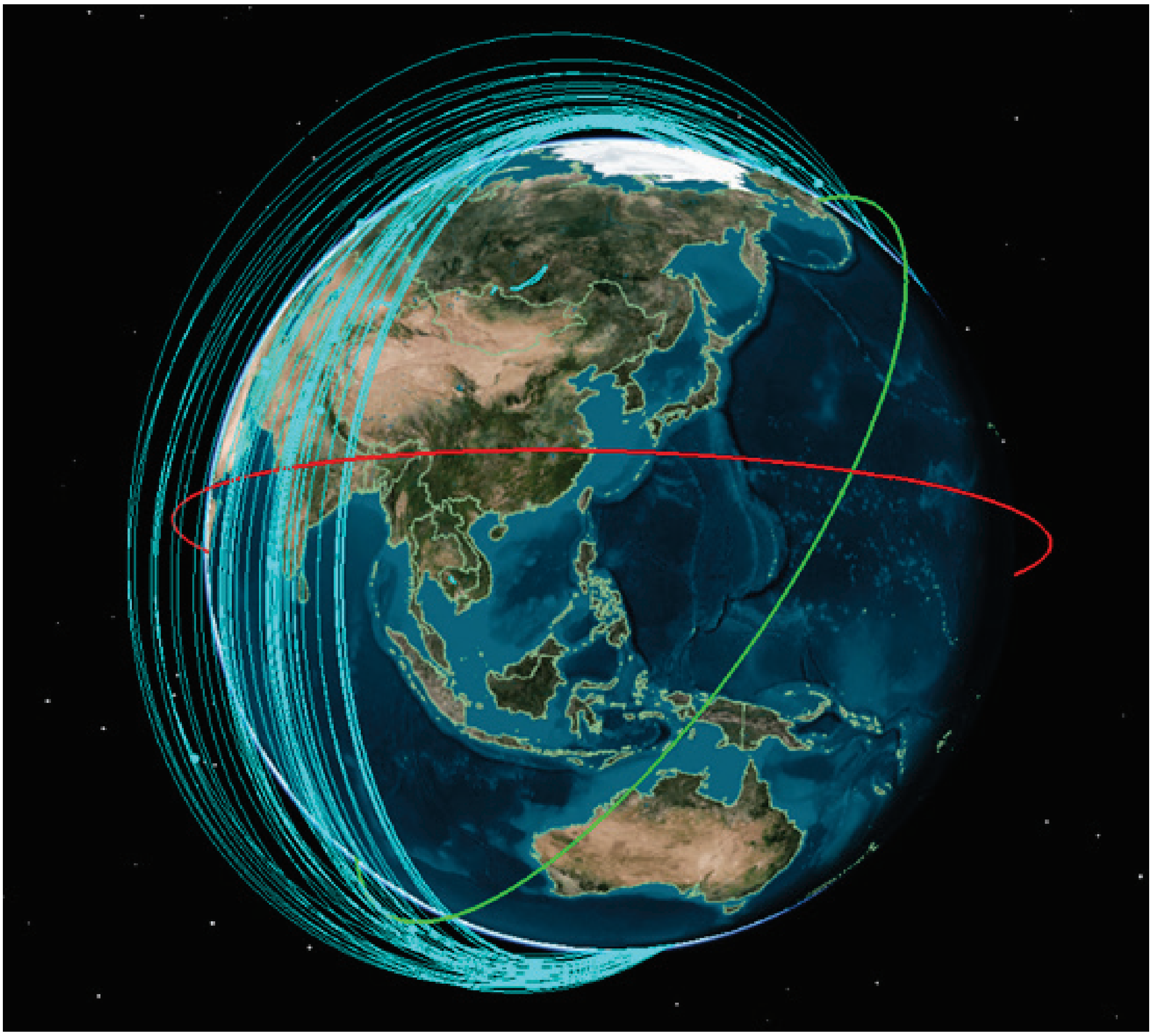

Fig. 2. Distribution of the cataloged fragments of the Indian ASAT test on 27 May 2019 (light blue) obtained with the STK 11.6.0 tool by Analytical Graphics; the orbit of the ISS is shown in green and that of the HST in red

However, during the days and weeks following the tests, the collision risk in low LEO increased moderately, affecting the operations in orbit. Regarding the American test of 2008, for instance, the lift off from the Vandenberg Air Force Base of a classified reconnaissance spacecraft atop an Atlas V rocket, initially slated for 29 February 2008, was delayed for at least two weeks. The impact risk for the ESA's Jules Verne Automated Transfer Vehicle, launched towards the ISS from Kourou, in French Guiana, on 9 March 2008, increased by a factor of two at the beginning of the cruise phase, although the background debris flux was moderate and the risk level decreased quickly. The cumulative risk increase for the ISS was equivalent to approximately 2-3 days of exposure to the pre-event space debris environment [3]. Concerning the Indian test of 2019 (Fig. 2), several tens of cataloged fragments crossed the altitude of the ISS immediately after the target breakup (they were 21 at end of November 2019), and at least one year was needed to have the situation coming back to the pre-test conditions, due to the low minimum of the solar activity cycle.

Nonetheless, the effects of the two ASAT tests with kinetic warheads carried out below 300 km were limited in size and time. During the second decade of the third millennium, the real change of the landscape below 600 km was triggered by a dramatic surge in the launch rate of small satellites and cubesats, in particular since 2014. But the most noteworthy development currently going on is the recent (26 April 2019) decision by the US Federal Communications Commission (FCC) to grant SpaceX permission to deploy the first segment of the company's Starlink mega-constellation for broadband global internet access into much lower orbits than originally planned. The regulatory commission, in fact, approved the SpaceX proposal to fly 1584 of its Starlink satellites at an altitude of 550 km, with an inclination of 53°, instead of at 1150 km as originally planned.

The first 60 Starlink satellites were launched on 23 May 2019, half of the constellation will be deployed by March 2024 and completion will be attained in March 2027. These new spacecraft will add up to the Kepler Communications internet-of-things constellation, planning 140 nanosatellites at an altitude of 575 km and inclination of 99° by the end of 2022, and to the Planet Labs multiple satellite constellations Flock, designed for Earth observation, already consisting, at the end of November 2019, of 232 nanosatellites in orbit between 450 and 600 km, with an inclination of 97°. Adding to these figures three additional SpaceX V-band constellations authorized by the FCC, consisting of 2493 (altitude of 336 km, inclination of 42°), 2478 (altitude of 341 km, inclination of 48°) and 2547 satellites (altitude of 346 km, inclination of 53°) – of which one half to be deployed by November 2024 and the remaining by November 2027 – the total number of spacecraft below 600 km attributable only to SpaceX, Planet Labs and Kepler Communications might reach the astonishing value of almost 9500 in less than eight years.

These staggering numbers will change forever the way operations are carried out in low LEO orbit, including those involving astronauts, with an increased burden on public and private operators, not only to maintain the proper configuration of the constellations, but also to prevent accidental collisions with other satellites, either functioning or not, or orbital debris. The situation will be further complicated by the fact that some of the active satellites will not be able to maneuver, due to the lack of a propulsion system, to severe failures, or simply to the lack of timely and accurate information, or time to plan and execute an avoidance maneuver.

The low LEO region will also be significantly affected by the evolution of space activities above 600 km. In fact, several mega-constellations are planned at higher altitudes as well, and in order to mitigate the long-term accumulation of objects and the production of new collisional debris in high LEO, both categories being characterized by a very long orbital lifetime, the end-of-life disposal of constellation satellites in orbits able to guarantee a relatively fast reentry in the atmosphere is foreseen [4]. This procedure, highly recommended from the orbital debris mitigation point of view, in particular concerning the long-term evolution of space debris in the LEO region as a whole, may however present some temporary drawback in low LEO. For instance, the 2825 SpaceX satellites to be deployed between 1110 and 1325 km will be disposed, at the end-of-life, in elliptical orbits of 300×1075 km, characterized by a residual lifetime of 5 years with a solar flux at 10.7 cm of 70 standard flux units, or of 2 years with a flux of 110 standard flux units. This means that, during the operation of mega-constellations in high LEO, a significant number of disposed satellites will cross at any time the low LEO region as well, in a dynamic balance between new end-of-life disposals and atmospheric reentries.

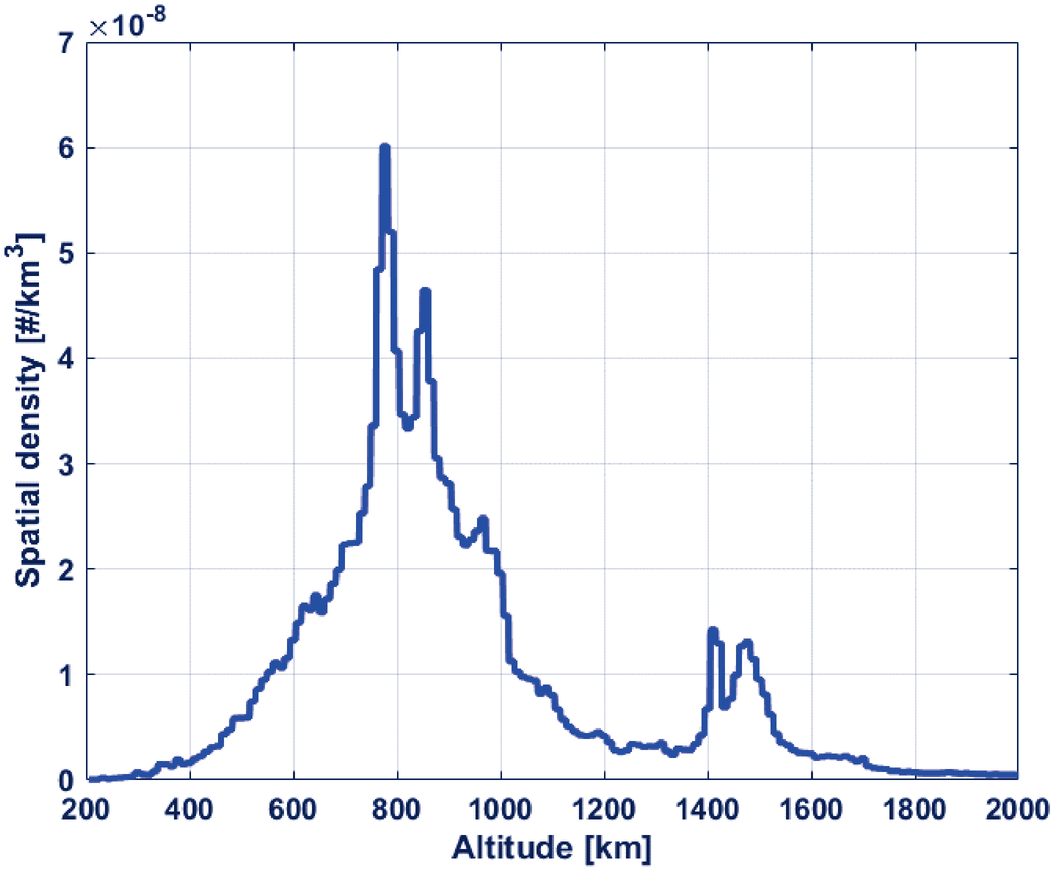

Fig. 3. Spatial density of cataloged objects in LEO on 20 April 2010

2. CATALOGED OBJECTS BELOW 600 KM

The big change already occurred in low LEO during the last decade can be immediately appreciated just by comparing two plots, representing the spatial density of cataloged objects in LEO on 20 April 2010 (Fig. 3) and on 26 November 2019 (Fig. 4). While above 700 km the density distribution pattern remained, in fact, roughly the same, both qualitatively and quantitatively, the changes at lower altitudes were significant, driven by the launch of many satellites, which created several new density peaks.

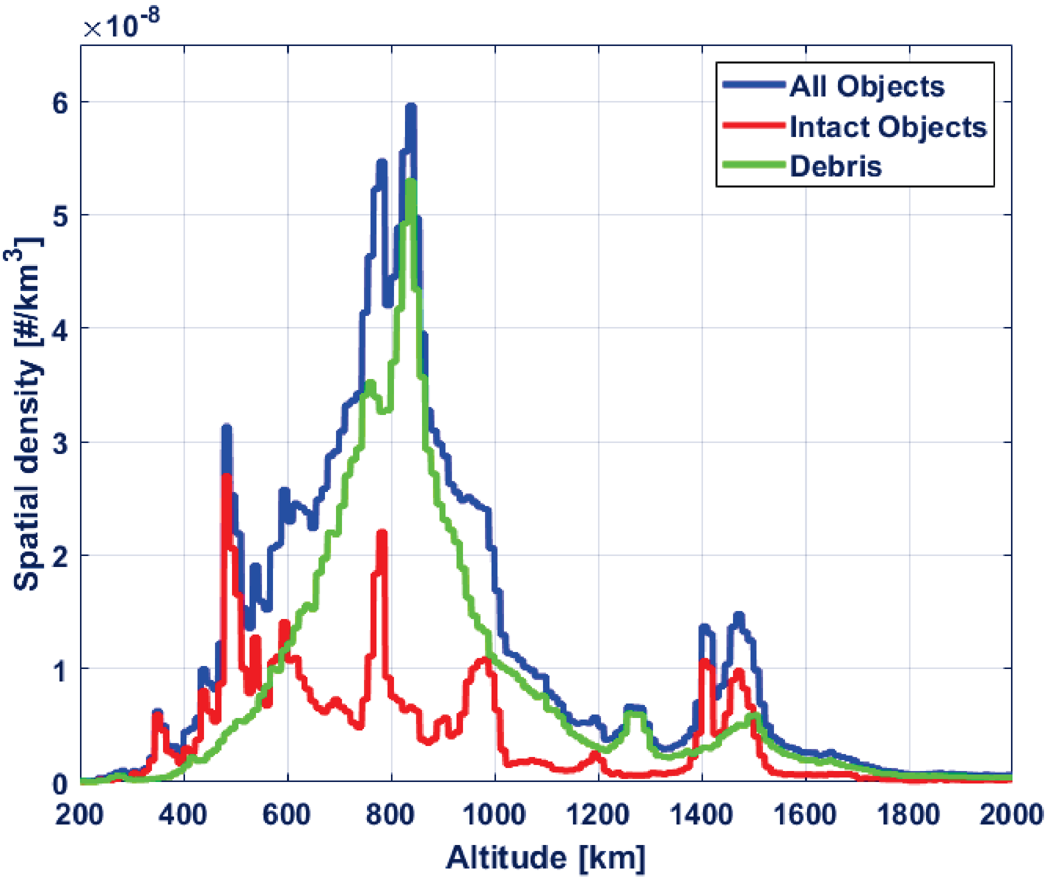

Fig. 4. Spatial density of cataloged objects (blue), intact satellites and rocket bodies (red), and debris (green) in LEO on 26 November 2019

At the end of 2010 there were ≈ 920 cataloged objects below 600 km. At the end of November 2019 their number had become equal to ≈ 1844, consisting of ≈ 1304 intact objects and ≈ 540 debris. The number of cataloged objects resident below 600 km then doubled in just under 9 years and in the next decade it is destined to increase at least tenfold compared to the value it had at the end of 2010.

These numbers also allow to put in a different perspective the relative impact of the Indian ASAT test conducted on 27 March 2019. After the event, 125 fragments were cataloged, of which 26 still in orbit on 26 November 2019, corresponding to 1.4% of the cataloged objects below 600 km (they were already less than 3% on 21 June 2019). Moreover, from 1 January 2018 to 27 November 2019, India alone launched 109 small satellites, for several countries, below 600 km. This latter figure was comparable with the cataloged debris produced by the ASAT test, but the orbital lifetime and the mass of the new satellites were significantly greater. In low LEO is therefore emerging a situation of growing complexity and concern for space access and operations, also because most of the nanosatellites launched there are not able to perform orbital maneuvers, being then equivalent to “true” debris from the impact risk point of view.

The small spacecraft of the Starlink constellation, on the other hand, are maneuverable and will be disposed at the end-of-life, lowering the perigee to 300 km while maintaining the apogee around 550 km. After this first “active” phase, taking a few weeks, a “passive” orbital decay phase will follow, with a duration – from several weeks to months – depending on solar activity [5]. But even during the “passive” decay phase, the Starlink satellites will continue to perform conjunction avoidance until the high atmospheric torques encountered at low altitudes will cause the loss of attitude control [5].

These procedures, together with the deployment approach, in which the new satellites are launched at an altitude of about 350 km, thoroughly checked and then progressively raised to the operational altitude of 550 km, were clearly devised for orbital debris mitigation. However, as widely demonstrated in general by several decades of space operations, and in particular by the initial operations of Starlink, satellites may fail and do so in not negligible amounts. For instance, just five weeks after the first launch, 3 out of 60 Starlink satellites, that is 5%, had already failed, and any new failed satellite, even though originally maneuverable, becomes a debris.

Therefore, in the coming decade, a significant increase of the collision risk in low LEO should be expected mainly as a consequence of the following components:

1. The great number of non-maneuverable nanosats launched below 650 km;
2. The failed satellites of the mega-constellations launched there;
3. The disposed satellites of the mega-constellations launched in high LEO, either failed or with reduced maneuverability/operability;
4. A greater number of disposed satellites not belonging to mega-constellations, in order to comply with space debris mitigation guidelines or standard.

Certainly, as shown in Fig. 1, the orbital lifetimes of intact objects, that is spacecraft and rocket bodies, will be typically less than 20-30 years, and in many cases much lesser. For the Starlink satellites, as an example, the disposed constellation satellites will reenter the atmosphere in less than 1.5 years, the satellites failed in the operational orbit will decay in less than 5 years, and those failed after the launch in the lower deployment orbit will take less than 1 year to decay, considering in all three cases the worst-case assumptions [5]. Regarding the disposed satellites of mega-constellations launched in high LEO, their reentry might take several years with low solar activity and cold thermosphere conditions.

But unfortunately these relatively fast decays, comparted with the values found in high LEO, will not be able to compensate the very high number of new satellite launches expected below 600 km, as demonstrated by the experience of the last decade, which has seen a doubling of the population of cataloged objects. Therefore, even assuming the wide adoption of the space debris mitigation measures outlined above, by the end of the 2020s a collision probability increase between 50% and 100% might be expected, among non-maneuverable cataloged objects below 600 km, considering a reasonable failure rate of maneuverable satellites of 10-15%. Of course, the situation could be even worse if an accidental catastrophic collision will occur in the meantime, in particular between two intact objects, or in case of an ill-conceived ASAT test.

3. AVERAGE CONJUNCTION RATE AND HUMAN SPACE ACTIVITIES

At the end of November 2019, the cataloged object population between 300 and 600 km implied an average debris flux of $\sim 1.5 \times 10^{-7}$ km^{-2}s^{-1}. This translated in approximately 1 close approach per day at less than 100 m and in about 100 close approaches per day at less than 1 km. These values were still $\approx 1/4$ of those encountered where the cataloged debris density was highest, i.e. between 750 and 850 km, but were growing faster in the absence of accidental collisions.

The situation below 600 km is therefore still manageable, but will get worse quickly if the increase of small, micro- and nanosatellites will proceed unchecked and substantially unregulated. In particular, special attention should be paid to the evolution of human space activities in low LEO, in order to avoid adverse operational consequences on space operations (e.g. too frequent collision avoidance maneuvers) and safety (e.g. collisions).

Circular orbits below 550 km are particularly attractive for human spaceflight. Even if still very close to the Earth's surface, are in fact just on the border of the deep "energy well" or "barrier" that each payload must exceed to reach space from our planet. In energetic (or ΔV) terms, a low Earth orbit is further from the surface of our planet than it is from the surface of the Moon or Mars. Moreover, orbits below 550 km guarantee a good protection from solar and cosmic radiation, due to the shielding effect of the magnetosphere, and avoid most of the South Atlantic Anomaly, i.e. the low point of the inner Van Allen belt. Orbits above 300-350 km, on the other hand, allow the practical compensation of atmospheric drag by propulsion for sufficiently long periods of time.

These and several other reasons, some including safety aspects as well, like the possibility of quickly returning to Earth in the event of serious emergencies, concur in making the region below 550 km very attractive for human spaceflight and human-tended activities. In addition to the ISS and Tiangong operations, the coming years will see the deployment of a new large Chinese space station, the debut of the Indian crewed spacecraft, and the missions of several private companies active in orbital and sub-orbital operations, human-tended facilities and habitable modules. Even looking at much more distant exploration destinations, such as high Earth orbits, the Moon, near Earth asteroids or Mars, the low LEO region might still play a fundamental role, acting as a parking volume to assemble and check carefully the large and complex spacecraft needed for human expeditions in deep space. A better attention to this important region is therefore well deserved, in order to leave open all the possibilities of future human access to space.

4. IMPACT ON ASTRONOMY

In the 1970s and in the 1980s – consider, for instance, the original raison d'être of the Panel on Potentially Environmentally Detrimental Activities in Space (PEDAS) of the Committee on Space Research (COSPAR) –, among the main concerns raised by space activities there were the adverse consequences for ground- and space-based astronomy, from satellite trails crossing the fields of long exposure photographic plates, still used by ground observatories, to space nuclear reactors disturbing the gamma ray detectors of astrophysical spacecraft. Since mid-1980s, the space debris problem overshadowed the impact on astronomy, but the advent of mega-constellations, in particular in low LEO, could bring back again at the center of the scene the negative consequences on the observation of the sky.

These concerns re-emerged powerfully after the first launch of Starlink in low LEO, on 23 May 2019, widely supported in the media by images of astronomical targets crossed by many diagonal trails of reflected light left by constellation satellites as they passed through the telescope's field of view. On 3 June 2019, the International Astronomical Union (IAU) released a Statement on Satellite Constellations [6], followed, on 8 June 2019, by the Board of Trustees of the American Astronomical Society (AAS), which adopted a Position Statement on Satellite Constellations during the 234th meeting of the professional organization in St. Louis, Missouri [7].

The IAU statement recalled the general «principle of a dark and radio-quiet sky as not only essential to advancing our understanding of the Universe of which we are a part, but also as a resource for all humanity and for the protection of nocturnal wildlife». The AAS statement explicitly mentioned the potential negative effects: «significant disruption of optical and near-infrared observations by direct detection of satellites in reflected and emitted light; contamination of radio astronomical observations by electromagnetic radiation in satellite communication bands; and collision with space-based observatories». Both organizations recommended a collaborative effort among all the stakeholders involved to understand the problems in detail and minimize the impact of large satellite constellations on astronomy, either ground- or space-based.

More detailed analyses carried out in the meantime have shown that the situation might not be as serious as initially feared. For instance, Olivier Hainaut of the European Southern Observatory (ESO) has calculated that if 27,000 satellites were launched, then ESO's Chile telescopes would lose about 0.8% of their long-exposure observing time, concentrated near dusk and dawn [8]. However, other telescopes and research programs might be affected significantly more, as exemplified by the observation of an outburst of Alpha Monocerotid meteors, on 22 November 2019, in La Palma, on the Canary Islands. Dozens of satellites, coming from the second Starlink launch, flew in fact through the camera's field of view, much brighter than the meteors to be observed [9].

It is therefore easy to predict that in the coming decade astronomers will have to face the challenge of reviewing the operating procedures of their instruments and writing new software to process the data, filtering out a multitude of bright satellites and radio interferences. The loss of some observation time and information will probably be unavoidable: the only unknown is the exact extent of such a loss.

5. CONCLUSIONS

In the mid-2000s, the Russian delegation proposed to the Inter-Agency Space Debris Coordination Committee (IADC) the creation of a special “human spaceflight protected region” below 550 km. The proposal was motivated by the forecast, which turned out to be very accurate, of a dramatic surge in the launch rate of small satellites and cubesats in such volume of space. Unfortunately, the large majority of the IADC delegations rejected such suggestion, mentioning, among other things, the expected progresses in tracking and conjunction assessment as a way to offset the increase of small non-maneuverable satellites.

We are now at a juncture of dramatic changes, transitioning from ~ 150 to several hundred satellites launched every year around the Earth, most of them in LEO. Even if the total mass in orbit continues to grow at the current rate [10], with a doubling period of about 20 years, a much faster increase of the number of objects injected in LEO will quickly lead to a severe deterioration of the orbital debris environment if the satellite reliability, concerning avoidance maneuvers and, in particular, end-of-life disposal and removal, will remain at current levels.

Even below 600 km, where the present situation is still manageable, a very fast degradation might occur, despite the shorter orbital lifetimes, adversely affecting the current operations and future developments of crewed vehicles and habitats. A new world-wide and effective traffic management initiative is therefore necessary to focus the attention on the preservation of the orbital region below 550 km for safe, sustainable and efficient human spaceflight.

6. ACKNOWLEDGMENTS

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.

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