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Institute of Information Science and Technologies

The impact of space activities in Low Earth Orbit

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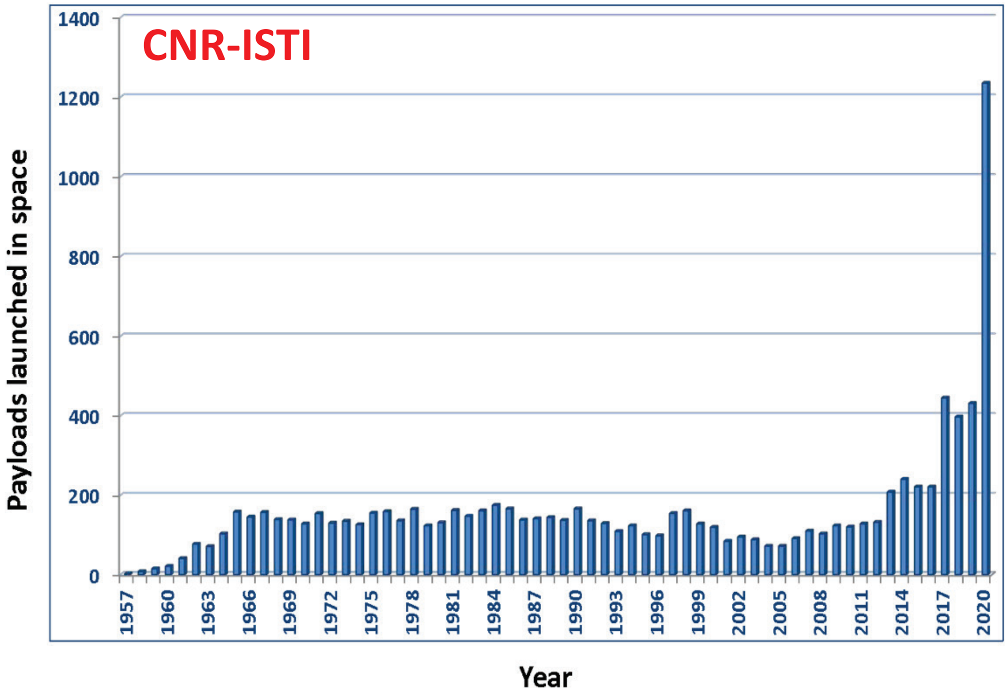
Introduction

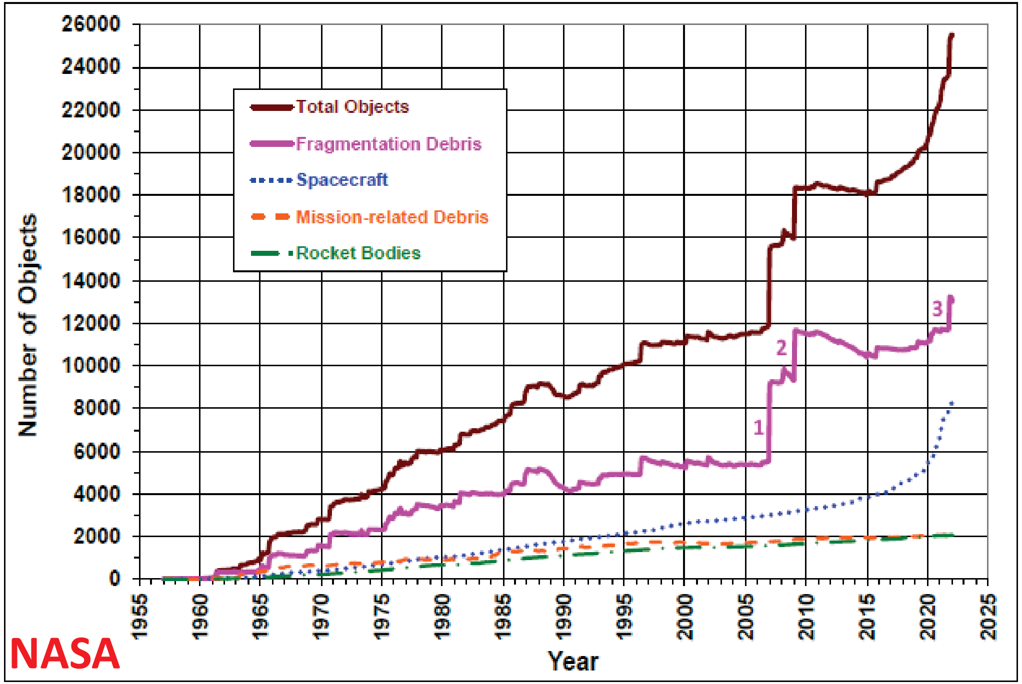
- The quality and quantity of launch traffic in LEO has changed a lot since 2013 and will change even more in the coming years
- The main drivers of this change are small satellites and mega-constellations, deployed in response of emerging needs and applications, with the support of dynamic technological innovation
- The IADC Space Debris Mitigation Guidelines – and other sets of national and international recommendations – were, however, conceived having in mind a quite different launch traffic structure and near-Earth orbital environment
- New recommendations, approaches and solutions are needed to address the environmental impact of these new space activities



However, first of all we should ask ourselves: How could an “acceptable” or “sustainable” space debris environment be defined around the Earth?

Space debris: the evolution

- Since the late 1970s, Kessler pointed out that an unchecked growth of abandoned objects around the Earth might lead to a collisional chain reaction
- The first mitigation measures, to avoid accidental explosions of upper stages, were implemented in the 1980s
- The first version of the IADC Space Debris Mitigation Guidelines was approved in 2002
- For about 20 years, the first mitigation measures, coupled with the end of the Cold War, have effectively put under control the growth of fragmentation debris, while satellites, upper stages and operational debris have grown slowly and linearly

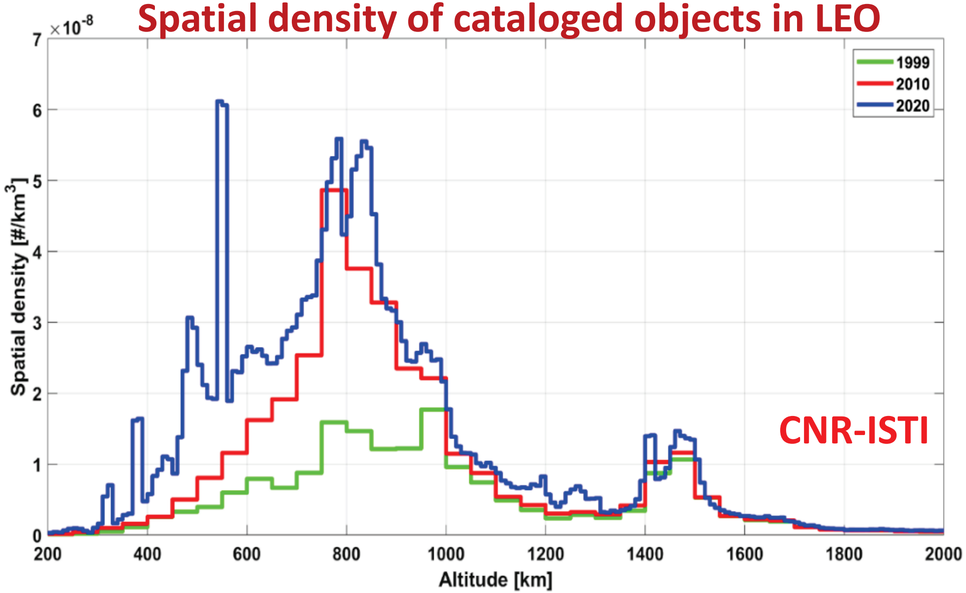


The situation has worsened a lot during the last 15 years, with more than a doubling of the number of objects accumulated in space over the previous 50 years, due to 3 catastrophic collisions in LEO (2 intentional [1 and 3] and 1 accidental [2]), and to the soaring number of spacecraft (small satellites and large constellations)

Space debris: the current situation

- The objects officially cataloged by the US Space Force, ~ 25 500, are currently only 56% of those tracked, ~ 45 300, with typical sizes > 5 cm in low LEO
- Of these, 5700 are active satellites, less than 13% of the tracked objects
- Generally, impact with an object > 10 cm is required to produce catastrophic fragmentation of a spacecraft or upper stage
- However, debris > 1 mm can damage critical satellite components, while debris > 5 mm can put a satellite out of service

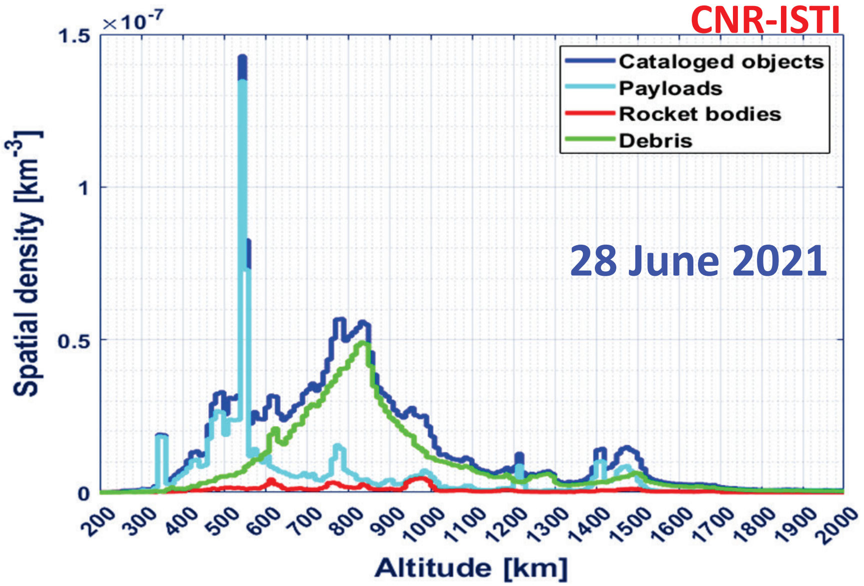
Spatial density of cataloged objects in LEO



- According to the ESA's MASTER model, there are ~ 900,000 orbital debris in the 1-10 cm size range and ~ 128 million orbital debris in the 1-10 mm size range
- The impacts of debris ≤ 1 mm – and in some cases up to 1 cm – can be dealt with appropriate shielding, while those with tracked objects can be addressed – when possible – with collision avoidance maneuvers
- The large population of untracked debris between 1 mm and 10 cm represents a growing concern for space operations
- But a long-term uncontrolled evolution of the debris environment (the so-called Kessler Syndrome) would depend on mutual collisions between objects larger than 10 cm

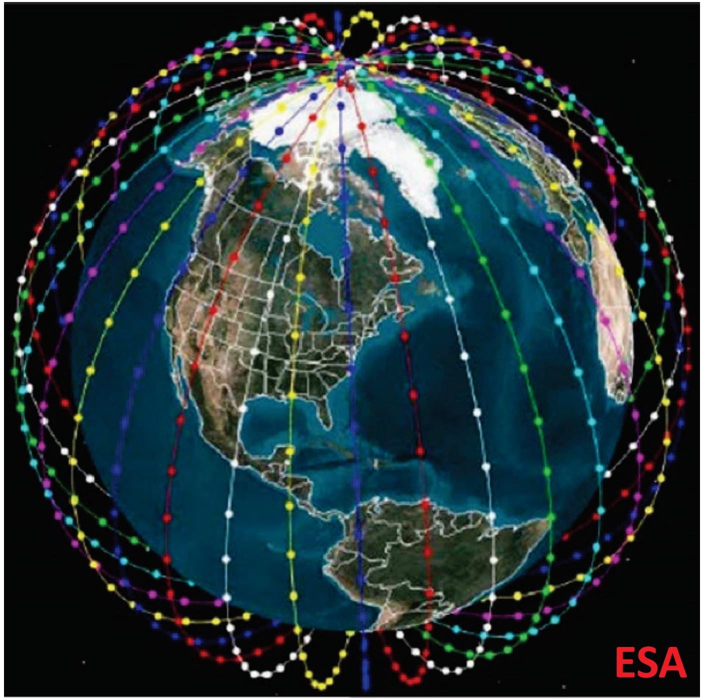
Space debris: the problem

- Even where the density of objects is maximum, there is – on average – a large separation (~ 200 km) between one object and another: therefore, "space" is not a problem
- The problem is a consequence of orbital dynamics: high relative velocities (10 km/s – on average – in LEO), and geometry of high inclination orbits, leading to converging trajectories at high latitudes
- Objects can then be very close in "time" (seconds or tens of seconds) even if they are far away in space (tens or hundreds of km)
- The differential effects of orbital perturbations may then foster close approaches and, possibly, collisions



- In addition, the kinetic energy associated with collisions of debris > 10 cm is so large that it can cause the complete disintegration of spacecraft or upper stages, producing hundreds or thousands of other fragments > 10 cm
- These fragments might then cause other catastrophic collisions of the same type
- Unfortunately, natural orbital perturbations alone, in particular atmospheric drag, are not very effective in removing large debris and abandoned intact objects above 600 km, where the orbital lifetimes of the latter exceed 20 years, growing exponentially at greater heights
- This leads to a progressive accumulation of large debris and abandoned intact objects above 600 km

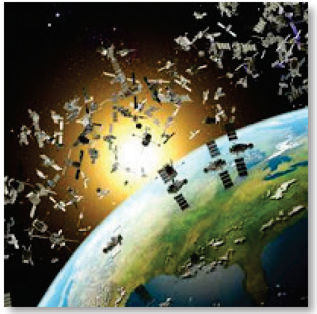
Sustainability



- A “sustainable” circumterrestrial environment must guarantee the long-term peaceful use of space for the benefit of all humanity
- This concept, although difficult to translate into technical specifications, is somehow related to some form of “maximum possible exploitation” of a certain region of space
- But such a “maximum possible exploitation” depends on technological capabilities, in particular by the feasibility and cost-effectiveness of debris mitigation, space situational awareness and active debris removal
- Therefore, significant technological advances in each of these areas would allow more satellites to operate in a given region of space
- However, if the number of debris and abandoned intact objects continues to grow, especially above 600 km, such advances would only buy some time, but sooner or later the risk of an unsustainable situation would have to be faced
- Even below 600 km, where the long-term accumulation of abandoned intact objects and debris is not possible, due to atmospheric drag, the launch of many thousands of new spacecraft, and the perigee lowering of thousands more satellites from higher altitudes for lifetime reduction, might place an unsustainable technical and economical burden on operations
- Such developments could also have adverse effects on the safety and operations of human spaceflight

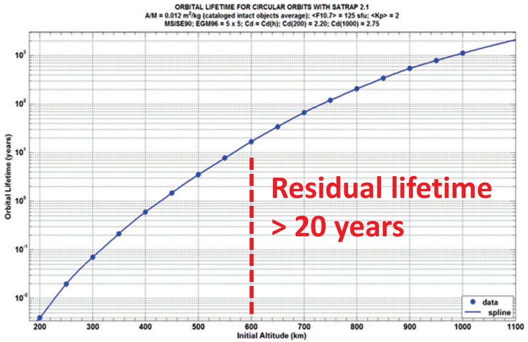
How to define an acceptable debris environment

HOW THE LONG-TERM SUSTAINABILITY OF SPACE ACTIVITIES AROUND THE EARTH CAN BE ENSURED?



IT IS NECESSARY TO DEFINE AN ACCEPTABLE ORBITAL DEBRIS ENVIRONMENT

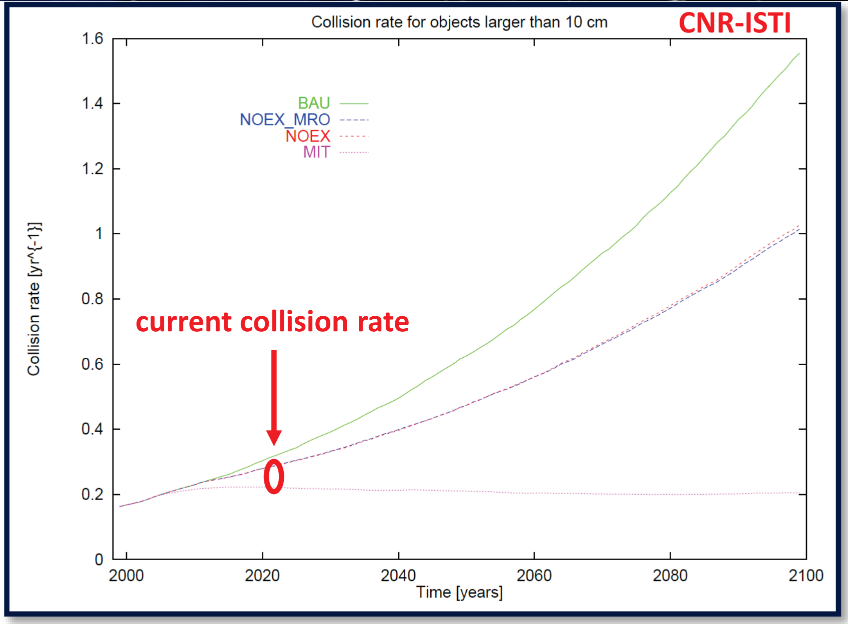
What is the limit that cannot be exceeded, and that mitigation and remediation measures should allow us not to cross?



- Reaching a broad consensus on the acceptability or sustainability of a given circumterrestrial environment can be very complex, since it relies upon technical, economic, political and legal aspects, which can change considerably over time
- Reductionist approach: Since the Kessler Syndrome is the outcome of a collisional chain reaction, the frequency of accidental collisions between objects > 10 cm can be taken as a measure of the "health" of the environment
- The evolution scenarios investigated more than 20 years ago, which led to the first IADC mitigation guidelines, have already implicitly defined, both qualitatively and quantitatively, orbital debris environments considered at that time desirable, tolerable or unacceptable, in terms of the accidental collision rate or of the number of catastrophic collisions expected during a certain time interval

A reductionist definition of sustainability

- As an example, at the end of the 1990s, an ESA funded study was carried out in Pisa to investigate the long-term evolution of the orbital debris environment and the potential beneficial effects of IADC-like mitigation measures
- Launch traffic and on-orbit explosions, in quality, quantity and orbital distribution, were those prevailing and projected at the turn of the century, but five constellations were simulated as well, including one large constellation at 1375 km
- The following results should be highlighted:
  - In the business-as-usual "unmitigated" scenario, the annual average collision rate among LEO objects > 10 cm was expected to grow from below 0.2 (2000), to 0.5 (2040), to 1.0 (2070), and to 1.6 (2100)

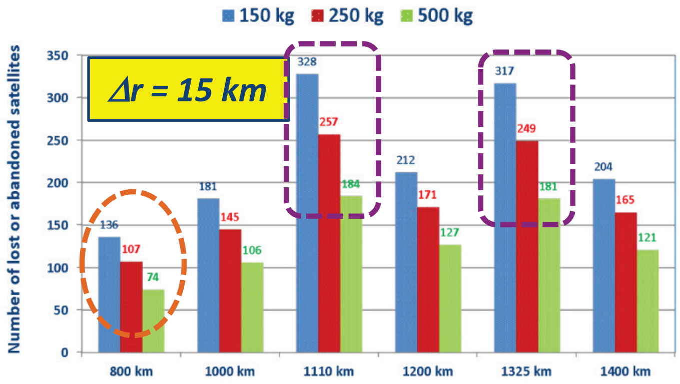


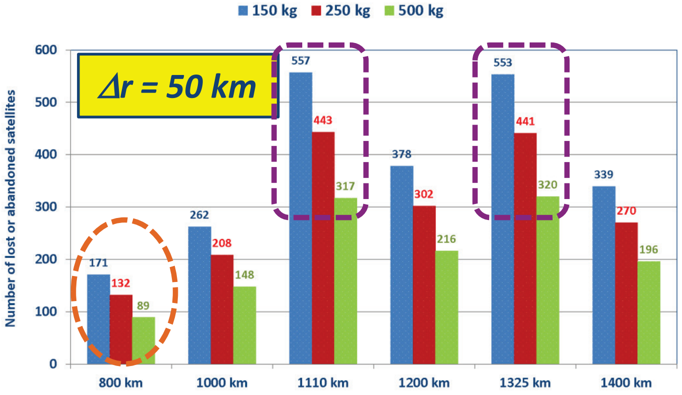
  - Such "unmitigated" evolution (green line in the plot) was expected to result in about 70 collisions among objects > 10 cm in one century: as such, it was considered unacceptable at that time (more than 20 years ago)
  - The rigorous implementation of the IADC mitigation guidelines (magenta line in the plot) would have led to a stabilization of the average collision rate between 0.2 and 0.3 per year, and to 20-25 collisions in one century
  - Such conditions, like those characterizing the current status of the debris environment, were considered acceptable and bearable, at least in the medium term

Impact of mega-constellations above 600 km

- **How many abandoned satellites of a single constellation would be sufficient to increase the total collision rate in LEO by 10%?**

Number of failed, abandoned and non-maneuverable satellites able to increase by 10% the total collision rate in LEO among objects > 10 cm, as a function of constellation altitude, spacecraft mass and radius vector dispersion





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- **In the regions of space already most crowded with debris, as around the height of 800 km, ~ 100 more non-maneuverable satellites would be sufficient to increase the current collision rate in LEO by ~ 10%, while a number between 500 and 1000 would increase it by ~ 100%**

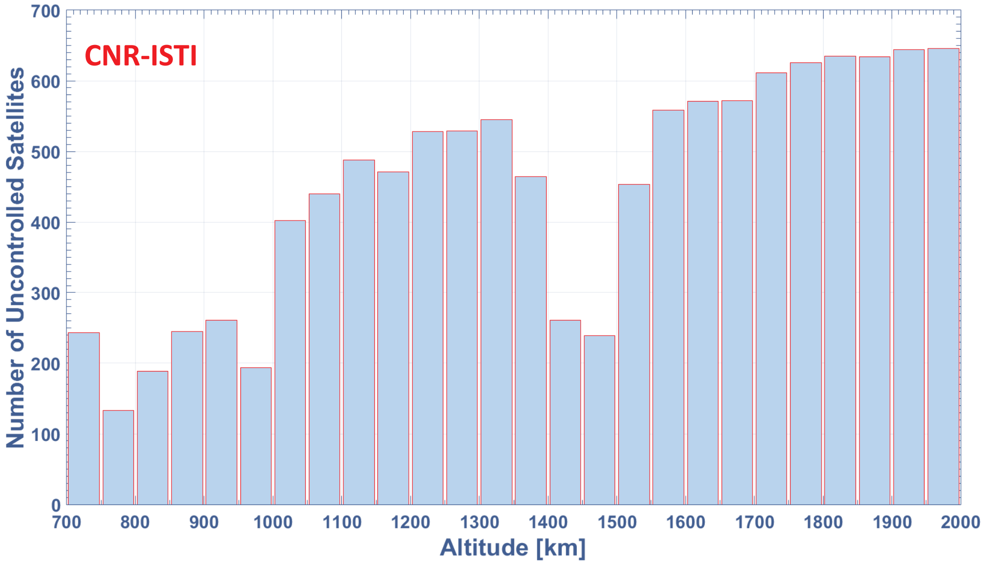
- **In the less crowded LEO regions, as around 1110 km and 1325 km, a number of abandoned satellites between 200 and 500 would instead be needed to boost the overall collision rate by ~ 10%**

LONG-LASTING EFFECTS (DECADES, CENTURIES OR MORE) ABOVE 600 KM, TRANSIENT EFFECTS (YEARS) BELOW

Impact of mega-constellations above 600 km

- Assuming 6000 new satellites between 800 and 1400 km, a long-term increase of the total collision rate in LEO by 20-30% might be expected, assuming spacecraft de-orbiting at the end-of-life 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
- If disposed on lower elliptical orbits, the collision rate increase would be moved to low LEO (< 600 km), unless the satellites do not continue to be maneuvered until their reentry in the atmosphere

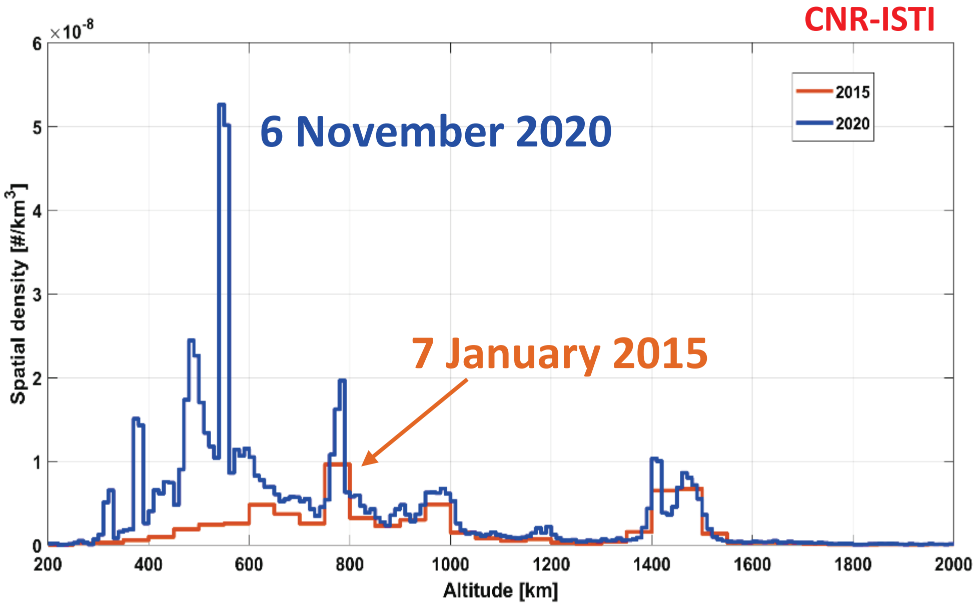
Number of uncontrolled satellites able to increase the collision rate in LEO by 10%, among objects > 10 cm, as a function of the release altitude (high inclination orbits; average cross-sectional area = 3 m^2; radius vector dispersion = 50 km)



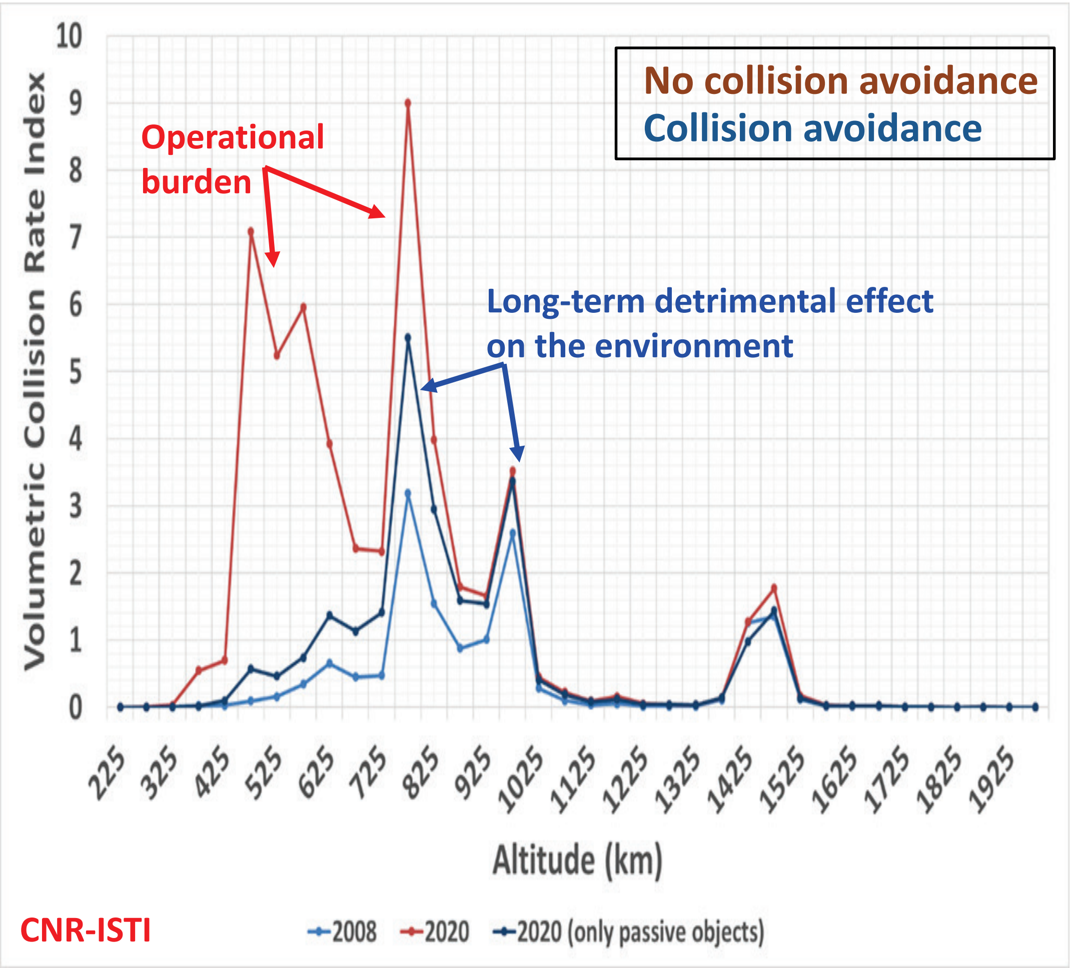
- The amount of this growth will depend on the number and physical characteristics of the spacecraft involved, and also on the disposal orbits and strategies adopted
- However, 1000 satellites with a mass of 250 kg and elliptical disposal orbits of 300 x 1000 km might increase, for a few years, the collision rate in LEO among objects > 10 cm by a further ~ 30%

Impact of mega-constellations below 600 km

- Above 600 km, the main “sustainability” issue is represented by collisional cascading (long-term)
- Below 600 km, too great a growth in close approaches and accidental collisions may result in a heavy impact on operations and protection of space assets, an impact that could become technically and economically unsustainable
- The reasons of this growth are the following:
  - The great number of non-maneuverable nanosats launched
  - The failed satellites of the mega-constellations launched there
  - The disposed satellites of the mega-constellations launched above 600 km, either failed or with reduced maneuverability
  - An increasing number of disposed satellites not belonging to mega-constellations, which will comply with the space debris mitigation guidelines on residual lifetime < 25 years
- Within a decade, all of these developments could increase the frequency of close approaches and accidental collisions, below 600 km, by several times



Evolution of the collision rate in LEO (2008-2020)



- Without formation flying, collision avoidance and evasive maneuvers, the evolution of space activity would have led to an overall increase in the collision rate in LEO of more than three times
- However, it is important to remark that most of the growth was recorded below 600 km, where atmospheric drag can effectively sweep away, in a short time, any collisional debris before it can collide with other objects
- Moreover, the growth should instead have been around 60% assuming that active satellites do collision avoidance and, often, formation flying
- Taking these aspects into account, the situation has worsened more between 600 and 1000 km, a region of space quite critical for the long-term evolution of the debris environment
- Excluding active satellites, more than 75% of the probability of catastrophic collision in LEO is currently concentrated there

Conclusions

- Debris mitigation measures, gradually adopted since the 1980s, coupled with the end of the Cold War, at the beginning of the 1990s, have played a positive role over a couple of decades
- Unfortunately, during the last 15 years, their benefits have been canceled by some major fragmentation events, by prolonged periods of extremely low solar activity and atmospheric drag, and by a dramatic increase in the launch rate of satellites
- To aim for the goal of long-term sustainability of space activities, it is necessary to define an acceptable orbital debris environment
- Of course, it is not immutable, but relies upon the technical solutions available at a certain time, and on how and for what the circumterrestrial space is used
- Assuming the criteria identified more than 20 years ago to define a desirable, tolerable or unacceptable orbital debris environment, an acceptable one, at least in the medium term, should be characterized by a collision rate among objects > 10 cm as stable as possible compared to the current one, and in any case not more than 2 or 3 times higher
- Taking into account the present technological developments, and the deployment plans of mega-constellations and small satellites, the criticality threshold in LEO might be exceeded during the next ten years
- The coming decade is therefore crucial for the future of space activities in LEO, and the widespread application of the debris mitigation measures recommended since the 2000s will probably not be enough
- To counteract the negative trends, a combination of reinforced mitigation measures and operational capabilities, complemented by remediation initiatives, as the active removal of selected massive objects abandoned in critical regions of space, should be promoted and implemented

Thank you!

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