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Using the Flux of Debris to Assess the Criticality of the Environment in Low Earth Orbit

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Abstract

In this paper we introduce a new index for evaluating the propensity of a volume of space in low Earth orbit (LEO) to catastrophic collisions, that is to accidental collisions leading to the complete destruction of intact objects. The proposed index is therefore not intended to assess the criticality of individual objects or missions, but rather to estimate the global impact of space activities on a given region of space. Moreover, the new index was conceived to be objective, as simple as possible, built from easily accessible data, as well as smoothly reproducible by third parties. Named "volumetric collision rate index", it was developed starting from the analytical equations that express the collision rate as a function of the fluxes of intact objects and cataloged debris pieces. The application of reasonable simplifying assumptions and approximations finally allowed to define a dimensionless index that explicitly depends only on the spatial densities of intact objects and cataloged debris pieces. It was therefore applied to the LEO environment, analyzing its evolution from mid-2008 to mid-2020, a crucial period characterized by an impressive change of space activity patterns, with the launch of lots of small satellites and mega-constellations. We also discuss how the index can be further improved, taking into account the maneuverable satellites that do not contribute to the collision rate and the increasing number of cubesats, which in many respects would be more similar to debris, finally presenting a preliminary analysis in this direction.

Keywords: space debris, cataloged objects, environmental criticality indexes, catastrophic collision rate.

1. Introduction

The next decade will be crucial in deciding the long-term sustainability of space activities in LEO, at least as we conceive them now. In fact, despite the recommendation and partial application of specific mitigation measures, over the last twenty years, the situation around the Earth has continued to worsen and the growth in the number of debris shows no signs of decreasing. To aggravate the situation, an incredible number of new satellites will be launched over the course of the 2020s, such as to equal or even multiply by ten those launched over the previous six decades.

This rapidly changing launch pattern will represent an unprecedented challenge for the preservation of the environment, that is maintaining it safe, sustainable and open to use by all countries. The need to devise and apply new and more effective rules of behavior, applicable to contain the orbital debris problem and to space traffic management as well, has never been more pressing and urgent.

As the COVID-19 pandemic reminded us, the adverse evolution of phenomena with an intrinsic component of exponential development must be contrasted well before, and not after, the "exponential explosion", and since the so-called Kessler Syndrome would be in practice an exponential debris increase driven by the destruction of intact objects by fragments of previous collisions, there is a clear need to have indicators, easy to use and based on objective quantitative data, to assess the criticality level of the situation through the LEO protected region well before it is too late to intervene.

For this reason, continuing an effort that has been going on for almost a decade now, and which has seen the development, analysis and application of various criticality indexes for mitigation and remediation applications, we further developed this line of research, focusing the attention on intact objects and cataloged debris pieces. The new criticality index was then applied in fine detail to the whole LEO region during the period 2008-2020, highlighting its evolution over an interval of time characterized by great changes in the launch pattern.

Concluding the work are a discussion of the results obtained, an evaluation of how the index can be further improved with a first example of implementation, and an assessment of the current criticality through the LEO protected region.

2. Volumetric collision rate index

To quantitatively assess the criticality of the debris environment, it is obviously possible to simulate thousands of scenarios, of varying complexity, capable of exploring the space of possibilities with certain levels of confidence. This requires appropriate software tools, with very complex simulation setups, and with complete and reliable models able to take into account all relevant sources and sinks of space objects.

However, since these approaches are rather expensive and time consuming, depend on many initial assumptions and uncertain forecasts about the future and, despite their great complexity, they are still affected by significant uncertainty [1], the use of simplified alternative methods, such as the development of criticality indexes based on plausible inferences, is increasingly frequent to evaluate the conditions of the debris environment or the environmental footprint of individual objects [2-21].

We embarked on this line of research in 2013, developing several indexes of varying complexity for different applications, such as the ranking of individual space objects for active debris removal, the evaluation of the environmental criticality of mega-constellations and large numbers of small satellites, and the criticality assessment, both of single space objects and of significant portions of the LEO environment as a whole [22-35].

In this paper we introduce a new index for evaluating the predisposition of an altitude shell in LEO space to catastrophic collisions, that is to accidental collisions leading to the complete destruction of intact objects, these being the events that can determine an uncontrolled growth of space debris even in the absence of new launches [36,37]. This index is therefore not intended to assess the criticality of individual objects or missions, but rather to estimate the global impact of the complex of space activities on a given region of space. Moreover, the new index was conceived to be objective (that is not based on discretionary or declaratory aspects which then may not be realized), as simple as possible, built from easily accessible data, as well as easily verifiable and reproducible by third parties.

In order to comply with these requirements, several reasonable simplifying assumptions were adopted. First of all, the population of cataloged orbital debris was schematized as consisting of two populations of objects: intact objects, i.e. spacecraft and upper stages, identified in the following by the subscript I, and debris pieces, i.e. breakup fragments and mission related objects, identified by the subscript D [38,39]. The accidental collision rate among cataloged objects CR in a LEO altitude shell h_i can then be expressed as follows:

$$CR(h_i) = CR_{I-I}(h_i) + CR_{D-I}(h_i) + CR_{D-D}(h_i) \qquad (1)$$

where the three terms in the right-hand side of the equation represent, respectively, the collision rates between intact objects, between debris pieces and intact objects, and between debris pieces. Taking into account that CR_{D-D} is smaller than the other two terms by an amount between one and two orders of magnitude, and that the fragments eventually generated by a collision between debris pieces would be anyway below the threshold needed for the catastrophic breakup of intact objects, Eq. (1) may be rewritten neglecting the third term of the right-hand side:

$$CR(h_i) \approx CR_{I-I}(h_i) + CR_{D-I}(h_i) \qquad (2)$$

If the considered region of space has a volume V, and r represents the mean radius of the objects approximated as spherical, ρ the mean object density and v_R the mean relative velocity between cataloged objects ($v_R \approx 10$ km/s in LEO [40]), then the collision rates can be expressed as follows [41]:

$$CR_{I-I} = 2\pi r_I^2 \rho_I v_R (\rho_I V - 1) \qquad (3)$$

$$CR_{D-I} = \pi (r_D + r_I)^2 \rho_D v_R \rho_I V \qquad (4)$$

Being the number of intact objects $N_I = \rho_I V \gg 1$ and r_I greater than r_D by one order of magnitude, Eqs. (3) and (4) can be simplified in the following way:

$$CR_{I-I} \approx 2\pi r_I^2 v_R \rho_I^2 V \qquad (5)$$

$$CR_{D-I} \approx \pi r_I^2 \rho_D v_R \rho_I V \qquad (6)$$

Substituting Eqs. (5) and (6) into Eq. (2), we thus obtain:

$$CR \approx \pi {r_I}^2 v_R \rho_I V (2\rho_I + \rho_D) \qquad (7)$$

The volumetric collision rate, that is the collision rate per unit volume, can therefore be expressed as:

$$CR/V \approx \pi {r_I}^2 v_R \rho_I (2\rho_I + \rho_D) \qquad (8)$$

At this point, assuming that $\pi {r_I}^2 v_R$ might be considered roughly constant through the LEO region and over time, or at least slowly varying, and by a significantly lower fraction, compared with the spatial density of intact objects and cataloged debris pieces, the criticality of the environment with respect to the occurrence of accidental catastrophic collisions could be evaluated with a Volumetric Collision Rate Index (I_{VCR}) characterized by the following property:

$$I_{VCR} \propto \rho_I (2\rho_I + \rho_D) \qquad (9)$$

Since spatial densities are usually expressed in km^{-3} and are very small, in order to have a dimensionless and handy (i.e. not too tiny) quantity, the Volumetric Collision Rate Index was finally defined as follows:

$$I_{VCR} \equiv \rho_I (2\rho_I + \rho_D) \times 10^{16} \qquad (10)$$

where the 10^{16} factor, in km^6, was introduced to ensure that the values of the index fell in a more acceptable range. The logarithmic version of the index is instead given by the following expression:

$$LI_{VCR} \equiv \log_{10}[\rho_I(2\rho_I + \rho_D)] + 16 \qquad (11)$$

It has the advantage of having all the index values compressed between –4 and +1, during the period considered in this paper.

Finally, if the volumetric collision rate $CR/V \ll 1$, a condition certainly valid in LEO with the measurement units usually adopted in practice, also the probability of catastrophic collisions per unit of volume P_{CV} can be considered, with a good approximation, proportional to the volumetric collision rate index, that is:

$$P_{CV} \propto I_{VCR} \leftrightarrow CR/V \ll 1 \qquad (12)$$

3. Evolution of the situation in LEO from 2008 to 2020

The new index, as defined in the previous section, was applied to the LEO environment from 2008 to 2020. Specifically, the LEO region was divided into altitude shells, 50 km thick, and for each of them the volumetric collision rate index was computed, as a function of time, spanning the transition from old to new space activity patterns.

The results obtained are summarized in Fig. 1, in which I_{VCR} is plotted in logarithmic scale, and in Fig. 2, in which the index is plotted in linear scale. First of all, the index did nothing but grow systematically in almost any altitude shell, from mid-2008 to mid-2020. Below 400 km and at some higher heights, as between 1700 and 1750 km, the trend was less systematic, alternating decreasing and increasing phases, but at the end the growth prevailed everywhere above 300 km. It should also be pointed out that the worst accidental collision ever, the one involving the Iridium 33 and Cosmos 2251 satellites, on 10 February 2009 at an altitude of 789 km, occurred precisely in the altitude range, between 750 and 800 km, at which corresponded, before the event, the maximum value of the volumetric collision rate index and a probability of catastrophic collision equal to 20% of the overall one in LEO, estimated with Eq. (12).

Significant changes due to the new patterns of space activities began to manifest themselves from the second half of the 2010s, with a significant acceleration since 2017. As shown in Fig. 3, which compares the volumetric collision rate index computed in mid-2020 with that obtained in mid-2008, the most dramatic changes occurred in low LEO, between 350 and 600 km, where I_{VCR} increased more than 10 times, peaking between 70 and 80 times the initial value. Elsewhere the growth was mainly by about a factor of two, ranging between maximum values of 5-6 times and practically no increase, such as between 1400 and 1450 km.

From the point of view of the long-term evolution of the debris environment, it is certainly important that the most massive growth was recorded below 600 km, where the action of atmospheric drag can effectively sweep away, in a reasonably short time, any collisional debris before it can collide with other objects. However, the increases of I_{VCR} registered above 600 km, even if much smaller in relative terms of those below, are anyway quite significant and worrying in absolute terms, in particular between 600 and 1000 km, where already high collision probabilities have increased, in just a dozen years, by factors between 1.4 and 6, again estimated using Eq. (12).

Above 1000 km, I_{VCR} increases of more than a factor of two were found between 1050 and 1350 km, and above 1700 km. On the other hand, where the collision rate was already maximum back in mid-2008, i.e. between 1400 and 1500 km, the growth of I_{VCR} was restrained: less than 1% between 1400 and 1450 km, and about 30% between 1450 and 1500 km.

According to how the volumetric collision rate index was defined, a "criticality condition" might be associated with $I_{VCR} \geq 1$. For example, applying this criterion to LEO in mid-2020, it was estimated with Eq. (12) that 95% of the "a priori" catastrophic collision probability among cataloged objects – i.e. assuming no evasive maneuvers and relative orbit keeping for active spacecraft – was associated with the altitude shells in which $I_{VCR} \geq 1$, that is between 450 and 1000 km, and between 1400 and 1500 km. Back in mid-2008, the heights in which $I_{VCR} \geq 1$ accounted instead for 75% of the total collision probability in LEO. This "criticality condition" is particularly relevant above 600 km, for the long-term impact on the debris environment previously mentioned, but high values of I_{VCR} can be "critical" even in low LEO, adversely affecting the operations of satellites having to manage an increased collision probability with advanced conjunction analysis and avoidance maneuver capabilities.

4. Discussion and further refinements

The volumetric collision rate index, if applied in the simplest and most direct way, as outlined in Section 3, can overestimate the environmental criticality, especially in this revolutionary phase of space activity. In fact, with the deployment of mega-constellations, active spacecraft account for a large fraction of intact objects (see Fig. 4), but do not contribute so much to the catastrophic collision probability, being controlled and maneuverable. Moreover, small satellites like cubesats are cataloged as intact objects, but from the collisional point of view they should be considered more as debris pieces, if not maneuverable, both for the orbital behavior and for the consequences of any impacts.

As a first step in trying to account for these facts, not having available for the moment a detailed list of all the cubesats and maneuverable spacecraft, and wanting to safeguard the simplicity of the approach in this first application, all active satellites were subtracted from the count of intact objects. In this way, all the maneuverable

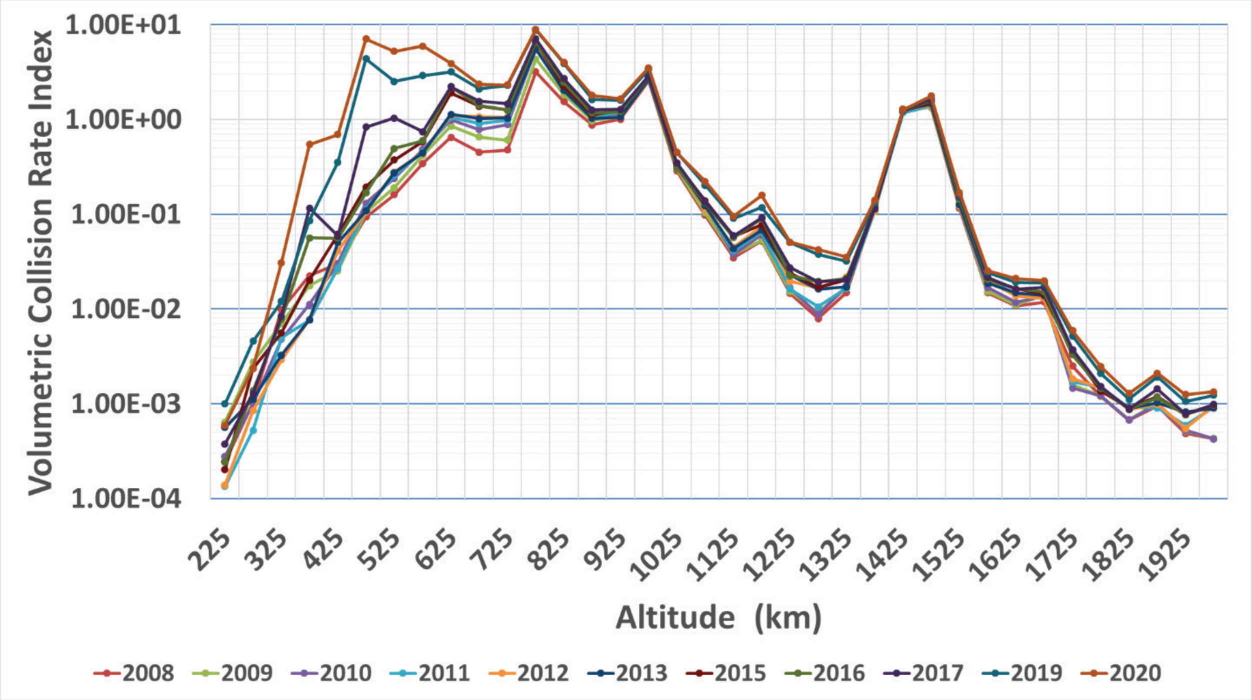

Fig. 1. Evolution of the volumetric collision rate index in LEO, averaged over 50 km altitude bins, from 2008 to 2020 in logarithmic scale (the altitude is counted from the mean equatorial Earth's radius)

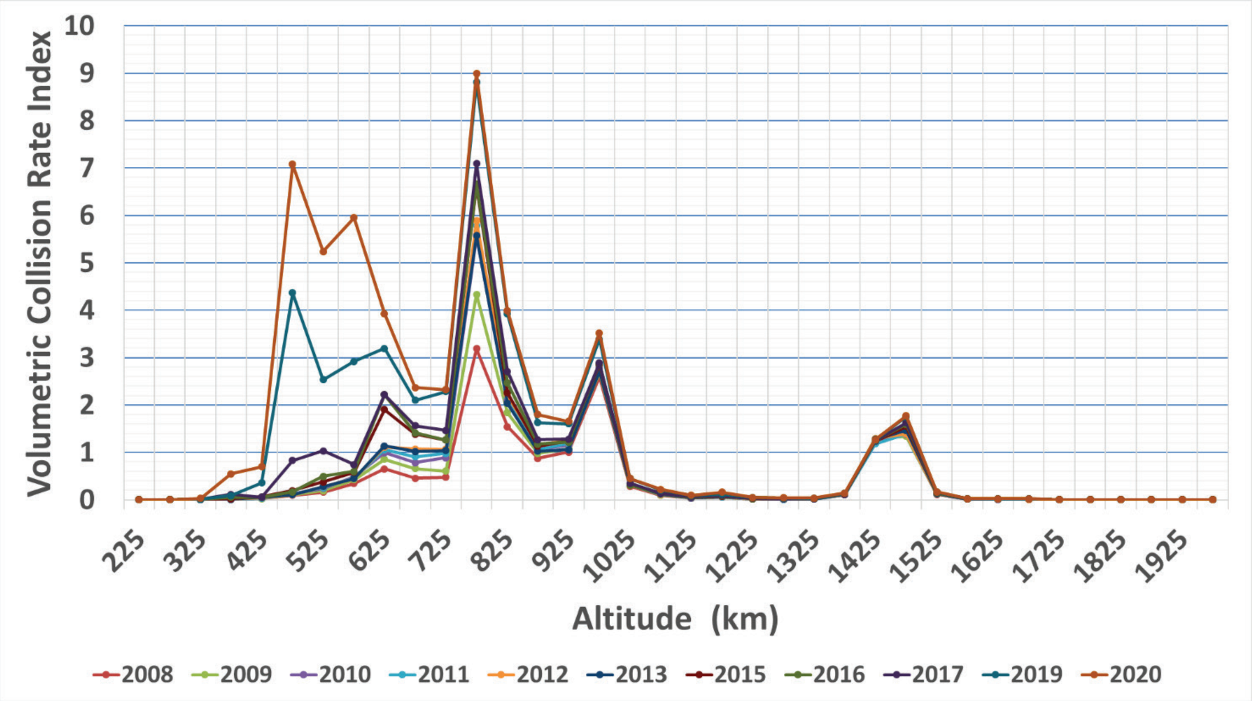

Fig. 2. Evolution of the volumetric collision rate index in LEO, averaged over 50 km altitude bins, from 2008 to 2020 (the altitude is counted from the mean equatorial Earth's radius)

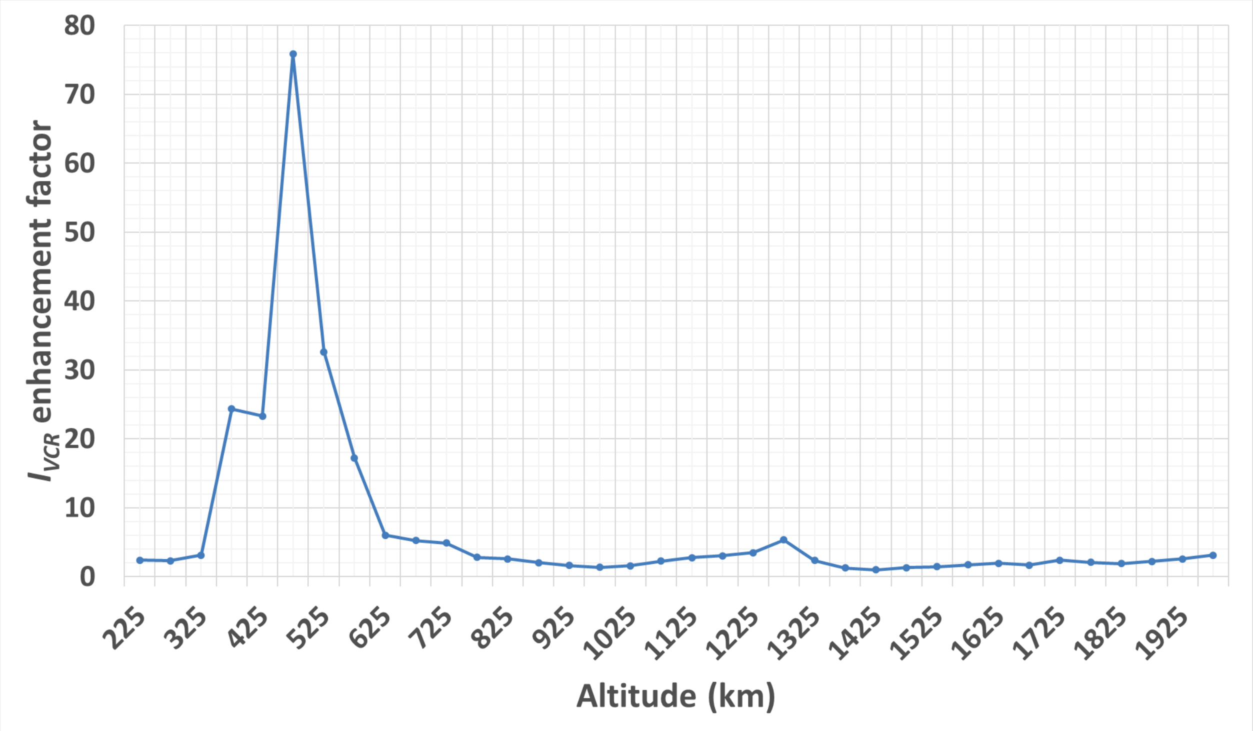

Fig. 3. The enhancement factor, plotted as a function of the altitude with respect to the mean equatorial Earth's radius, shows how many times the volumetric collision rate index multiplied in LEO from 2008 to 2020

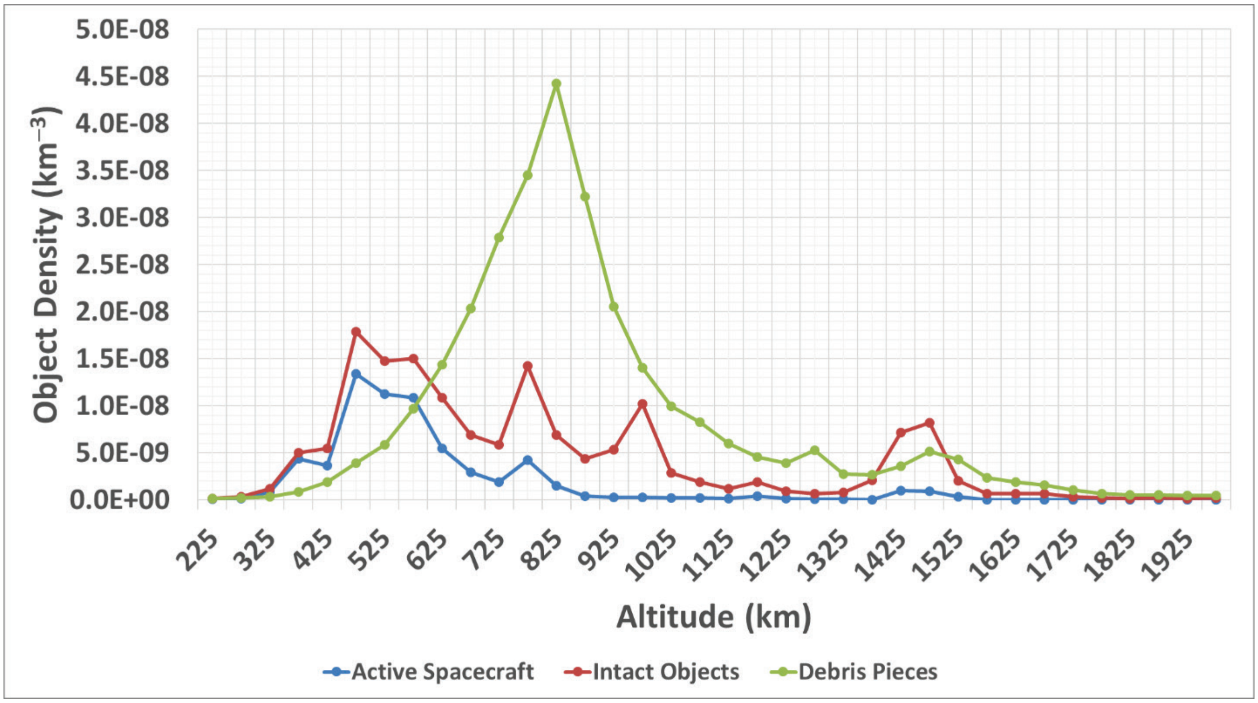

Fig. 4. Distribution in LEO, in mid-2020, of active satellites, intact objects (spacecraft + rocket bodies) and cataloged debris pieces (breakup fragments + mission related objects)

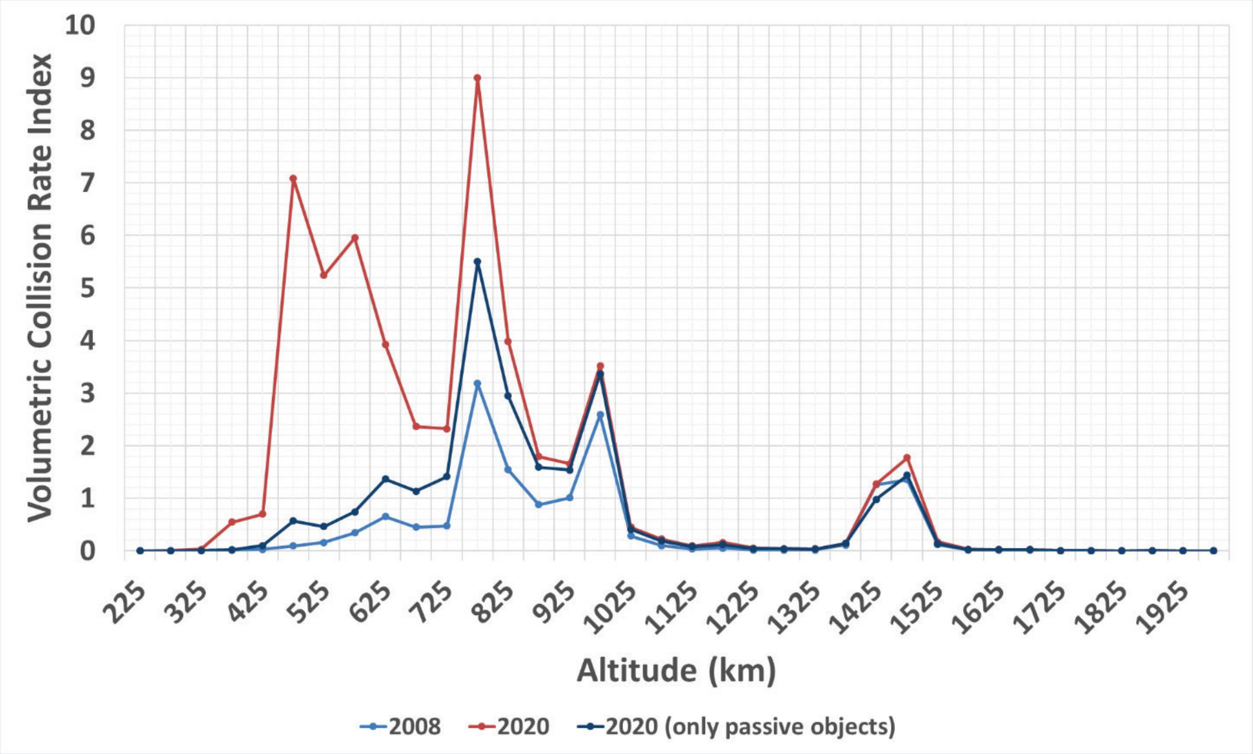

Fig. 5. Comparison of the volumetric collision rate index in LEO, averaged over 50 km altitude bins, in 2008 and 2020, in the latter case with and without the inclusion of active satellites

satellites were correctly removed from the calculation, but also a certain number of non-maneuverable satellites that should have been counted instead. Concerning the cubesats, the active ones were implicitly removed from the intact objects, but not added to the debris pieces. The "dead" cubesats, on the other hand, remained in the intact objects. In any case, considering the overwhelming contribution of active and maneuverable mega-constellation satellites, and the fact that all other error sources tend to compensate each other, although not necessarily exactly, this approach was considered the easiest way to realistically assess the situation in mid-2020 and to compare it with mid-2008, when, instead, the cubesats were still very few and not many satellites were currently performing avoidance maneuvers.

The results obtained are summarized in Fig. 5. The volumetric collision rate index in mid-2008 is compared with those computed in mid-2020, with and without active spacecraft. The difference between the latter two curves is striking, witnessing the impressive impact that the launch of the satellite constellations has had in recent years in modifying the population of cataloged objects. Moreover, if the active – and today mostly maneuverable – spacecraft are removed from the index computation, the growth of I_{VCR} compared to mid-2008 remains evident, but not so dramatic as might have been expected on the basis of the large increase in satellites launched in the meantime. More specifically, while the inclusion of active spacecraft would have led to an overall increase in the collision rate in LEO of more than three times between 2008 and 2020, the growth should instead have been around 60% assuming that all active satellites do collision avoidance.

In the latter case, $I_{VCR} \geq 1$ between 600 and 1000 km, and between 1400 and 1500 km, while back in 2008 such condition was circumscribed between 750 and 850 km, 900 and 1000 km, and 1400 and 1500 km. In the dozen years since 2008 the situation has therefore worsened more between 600 and 1000 km (Fig. 4), a region of space quite critical for the long-term evolution of the debris environment and where more than 75% of the probability of catastrophic collision in LEO is currently concentrated, excluding active satellites.

In this regard, it is worth mentioning that while this article was being finalized, another accidental collision between cataloged objects was recognized, involving a small Russian fragment (1996-051Q) of the Zenit second stage used to launch Cosmos 2333 and the Chinese satellite Yunhai 1-02 (2019-063A) [42]. The collision would have occurred at 07:41:19 UTC on 18 March 2021, at a height of 773 km with respect to the equatorial Earth's radius, that is again in the altitude shell where I_{VCR} was maximum (Fig. 5) and the collision probability was approximately 20% of the overall one in LEO.

5. Conclusions

A new simple and dimensionless Volumetric Collision Rate Index (I_{VCR}) – available also in logarithmic form (LI_{VCR}) – was defined in order to estimate the global impact of space activities thorough the LEO protected region. Developed from the analytical equations for the collision rate as a function of the fluxes of two populations of orbital objects, namely intacts (i.e. spacecraft + rocket bodies) and cataloged debris pieces (i.e. breakup fragments + mission related objects), it finally explicitly depended only on the spatial densities of intact objects and cataloged debris pieces after implementing reasonable simplifying assumptions and approximations applicable to the LEO environment. The index was appropriately rescaled in order to provide numerical values in a convenient range, with "criticality" conditions corresponding to either $I_{VCR} \geq 1$ or $LI_{VCR} \geq 0$.

As an example, it was applied to the environment in LEO during the time interval from mid-2008 to mid-2020, during which a profound change of space activities occurred, due to the deployment of lots of cubesats and mega-constellations. These rather recent developments, which led to an environment characterized by a significant number of maneuverable constellation spacecraft and by numerous cubesats, both active and dead, also inspired some reflections on how the definition of the new index could be further refined to better reflect the current situation, in which maneuverable satellites generally do not contribute to the collision rate and cubesats may be considered in many respects more similar to cataloged debris pieces.

A preliminary analysis carried out along these lines showed that the catastrophic collision rate in LEO increased by about 60% from mid-2008 to mid-2020, with the worse and most detrimental growth – in the long term – between 600 and 1000 km, where more than 75% of the catastrophic collision probability is currently concentrated, excluding active satellites.

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