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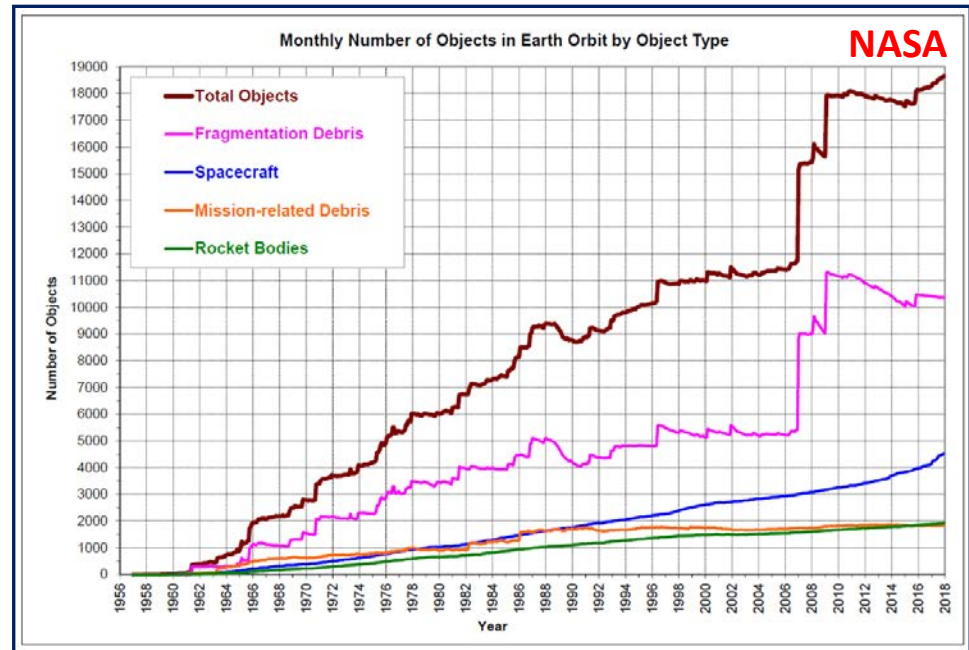
Evaluating the Environmental Sustainability of Large Satellite Constellations in Low Earth Orbit

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Introduction

- The quality and quantity of launch traffic in LEO changed a lot in the last five years and will change even more dramatically in the coming years and decades
- The main drivers of this change are small satellites and large constellations, deployed in response of emerging needs and applications, with the support of vigorous innovation and technological development
- The IADC Mitigation Guidelines were, however, conceived having in mind a quite different launch traffic structure and evolution

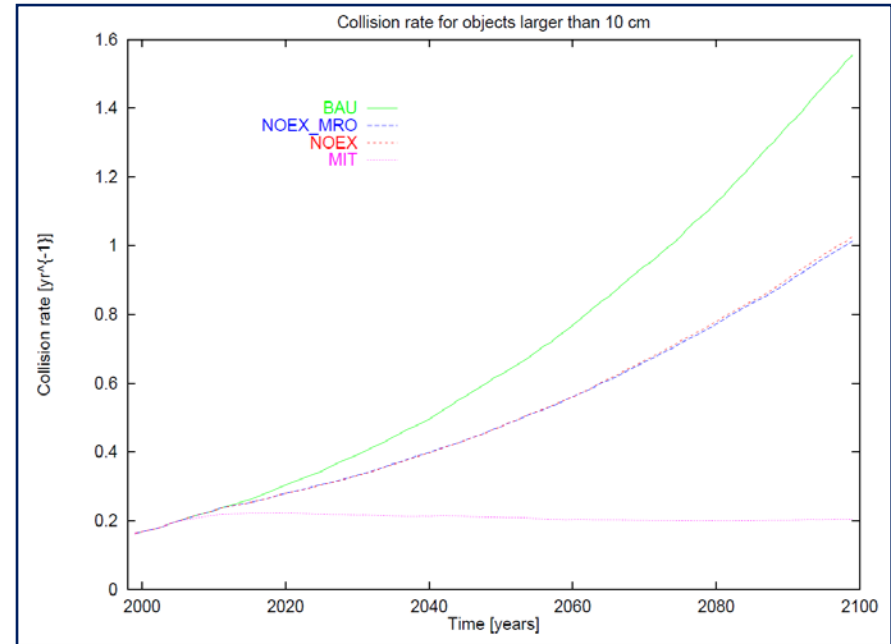


The question then arises whether the current IADC Mitigation Guidelines are still adequate for a plentiful of small satellites and several large constellations

- Before answering this question, the following two issues must be addressed
 1. How an “acceptable” and “sustainable” orbital debris environment should be defined
 2. How “enough simple” and “practical to use” criteria for evaluating the environmental impact of new systems, and their compatibility with the debris environment sustainability goals, might be identified
- After a brief look back at the past for the first issue, the following of this presentation will be devoted to some possible criteria for assessing the environmental impact of new space systems

Looking at past scenarios and forecasts

- 20 years ago, an ESA funded study was carried out with the SDM 2.0 software tool to investigate the long-term evolution of the orbital debris environment and the potential beneficial effect of IADC-like mitigation guidelines [1][2]
- Traffic quality and quantity, and on-orbit explosion rates and patterns, were those prevailing and projected at the turn of the century, but 5 constellations were simulated as well, including one large constellation at 1375 km
- For the purposes of this presentation, the following results should be highlighted
- In the business-as-usual “unmitigated” scenario, the average collision rate among LEO objects greater than ~ 10 cm was expected to grow from below 0.2 yr^{-1} , in 2000, to 0.5 yr^{-1} around 2040, to 1.0 yr^{-1} after 2070, and to 1.6 yr^{-1} in 2100
- Such “unmitigated” evolution was expected to result in a progressively increasing trend, and in about 70 collisions among objects greater than ~ 10 cm in one century: as such, it was considered unacceptable
- The rigorous implementation of the IADC mitigation guidelines would have led to a stabilization of the average collision rate between 0.2 yr^{-1} and 0.3 yr^{-1} , 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



Criteria to assess the environmental impact

- A possible simple criterion for evaluating the environmental impact of a new set of non-maneuverable satellites (deployed, lost or abandoned in LEO) might be the comparison of the additional collision rate due to their presence ($CR_{0-0} + CR_{0-B}$) with the current overall collision rate among the objects of the background (CR_{B-B})
- For instance, the Collision Rate Percentage Increase (CRI) was proposed at the 7th European Conference for Aeronautics and Space Sciences (EUCASS), in 2017 ^{[3][4]}

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

- Another criterion was proposed by the ESA Space Debris Office at the 1st IAA Conference on Space Situational Awareness (ICSSA), in 2017 ^[5]: the Environment Capacity
- The definition of the available “capacity” of the environment is a task that may be accomplished in many ways, ranging from relatively simple to quite complex approaches
- Concerning the aspect of capacity (or loss of capacity) evaluation, or, to put it in other words, of assessing the potential impact of new satellite systems on the current capacity load of the environment, one option would be the use of one (or more) of the several criticality/ranking indexes developed by the community in recent years to assess the environment criticality of space objects, or to rank them for active debris removal

Example of use of CRI

- The current average collision rate in LEO among the background (B) objects greater than ~ 10 cm is ^[6]

$$CR_{B-B} \approx 0.2 \text{ yr}^{-1}$$

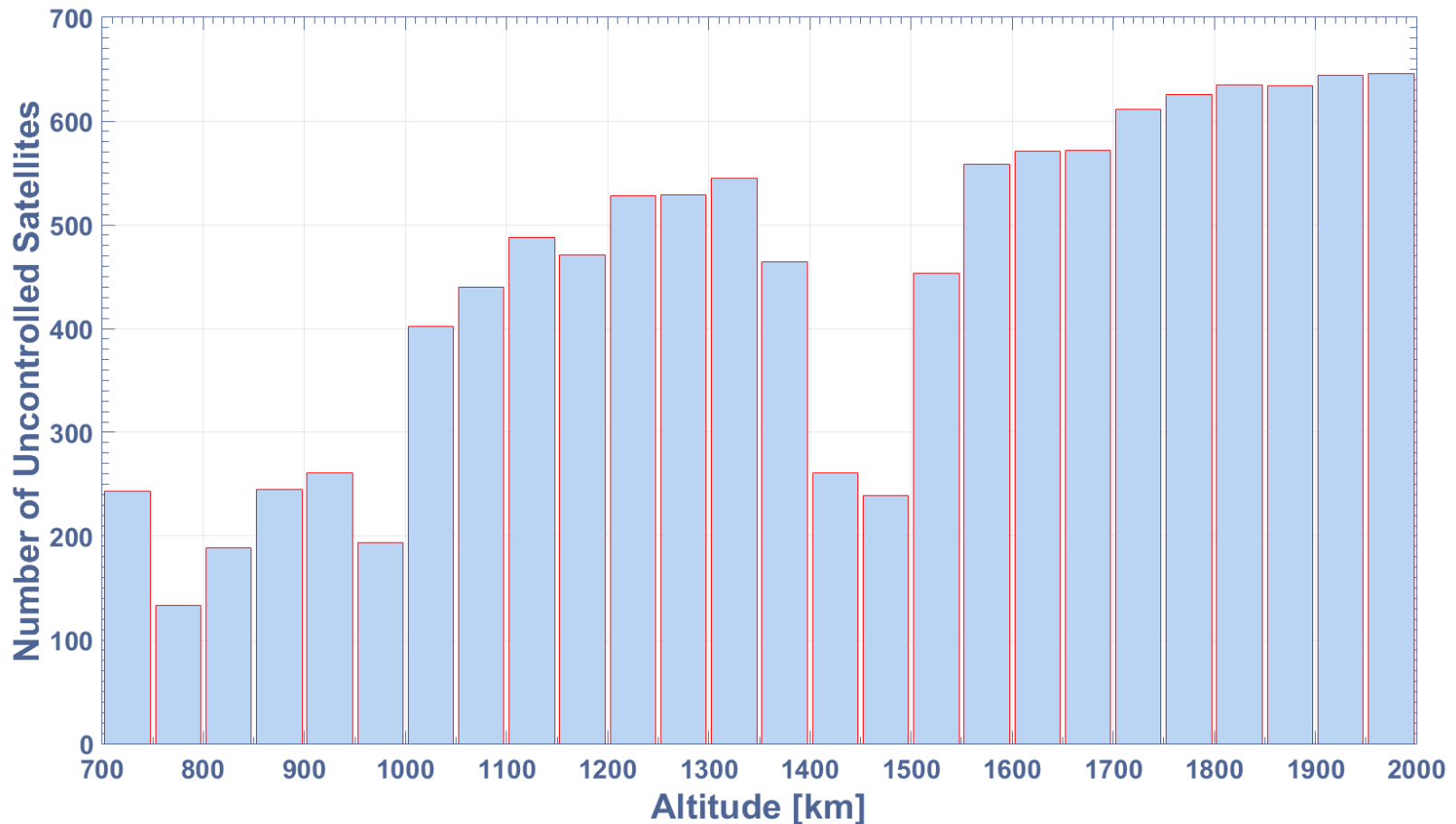
- *One possible question is: «How many new satellites (O) must be lost or abandoned in space in order to increase the average collision rate by 10%?», i.e.*

$$CR_{O-O} + CR_{O-B} \approx 0.02 \text{ yr}^{-1} \Rightarrow \text{CRI} \approx 10\%$$

- The computations for this numerical example were carried out using the analytical approach presented at the EUCASS Conference in 2017 ^{[3][4]}
- The satellites were supposed to have an average cross-sectional area of $\approx 3 \text{ m}^2$, the orbits were nearly polar and the interaction volume had a thickness of 50 km
- In fact, even assuming an initial small eccentricity of the order of 0.001, the long-period evolution of the orbital radius vector would display a significant overall excursion of about ± 25 km, dominated by the odd zonal harmonics of the geopotential (i.e. J_3, J_5, J_7 , etc.), with further smaller contributions from the tiny eccentricity, radiation pressure, the remaining terms of the geopotential, and luni-solar third body attraction

Additional satellites leading to $CRI \approx 10\%$

Number of simulated uncontrolled satellites able to increase the collision rate in LEO by 10%, among objects ≥ 10 cm, as a function of the release altitude
Results obtained with the EUCASS-2017 analytical approach



Consequences of the results

- Even altitude bands currently relatively empty might reach average collision rates of the order of 10% of the present overall value among cataloged objects in LEO, with the addition of a number of uncontrolled satellites from 600 to 700
- Below 1500 km, the same result can be reached with a number of uncontrolled satellites from 200 to 550
- For very large constellations with several thousand spacecraft, possibly including a huge number of successfully de-orbited satellites crossing LEO for reducing the residual lifetime, post-mission disposal must be extremely reliable, compared with current standards, in order to prevent a sizable increase of the collision rate
- The details would depend on the specific characteristics of each constellation, which should be properly modeled, but a post-mission disposal success rate around 90% might not be sufficient to prevent a significant collision rate increase

As a further example, the 20 Italian satellites and 1 upper stage in LEO have a combined CRI $< 0.1\%$ ^[7]

Example of use of criticality index

- Since 2013, several criticality indexes were developed at ISTI/CNR for various purposes, e.g. the ranking of upper stages and spacecraft for active debris removal, the assessment of the environment criticality of the Italian objects in LEO, and the pre-launch evaluation of the potential environmental impact of new systems, including mission and disposal scenarios
- For the goals of this presentation, the **criticality index RN-F-ISTI-2014** was adopted ^{[8][9][10]}, being considered the most appropriate for the indented application
- It was built starting from the product of two functions \Rightarrow
- f depends on the probability of catastrophic fragmentation due to orbital debris collision, and on the number of new effective “projectiles” resulting from the breakup
- g characterizes the long-term impact on the environment as a function of the lifetime of the new cloud of fragments, the volume of space involved, and the interaction with the pre-existing debris distribution
- Having defined f and g , a **criticality index R_N** “**normalized**” and “**dimensionless**” was derived ^{[8][9][10]}
- The adopted “**yardstick**” was an object with $M_0 = 934$ kg and $A_0/M_0 = 0.012$ m²/kg, placed into a circular **sun-synchronous orbit** with $h_0 = 800$ km and $i_0 = 98.5^\circ$
- The chosen values for M_0 and A_0/M_0 were the estimated averages for abandoned intact objects in LEO in mid-2013, when the criticality index was developed

A rectangular box with a dark blue background featuring a faint image of a satellite in orbit. The equation $R = f \cdot g$ is written in a large, bold, yellow font in the center of the box.
$$R = f \cdot g$$

Normalized and dimensionless criticality index

- In summary, the **criticality index** R_N (RN-F-ISTI-2014), **normalized** and **dimensionless**, referred to an object of 934 kg placed into a circular sun-synchronous orbit at 800 km, is defined as follows:

$$R_N \equiv \frac{F[h, i, m_D(M)]}{F[h_0, i_0, m_D(M_0)]} \cdot \frac{l(h)}{l(h_0)} \cdot \left(\frac{M}{M_0}\right)^{1.75} \cdot \frac{CDCD50(h)}{CDCD50(h_0)} \cdot \frac{z[h, i, m_D(M)]}{z[h_0, i_0, m_D(M_0)]}$$

It was set $\frac{l(h)}{l(h_0)} \equiv 1$ when $h > h_0$



It corresponds to an orbital lifetime equal or greater than about 230 years for the target object

and

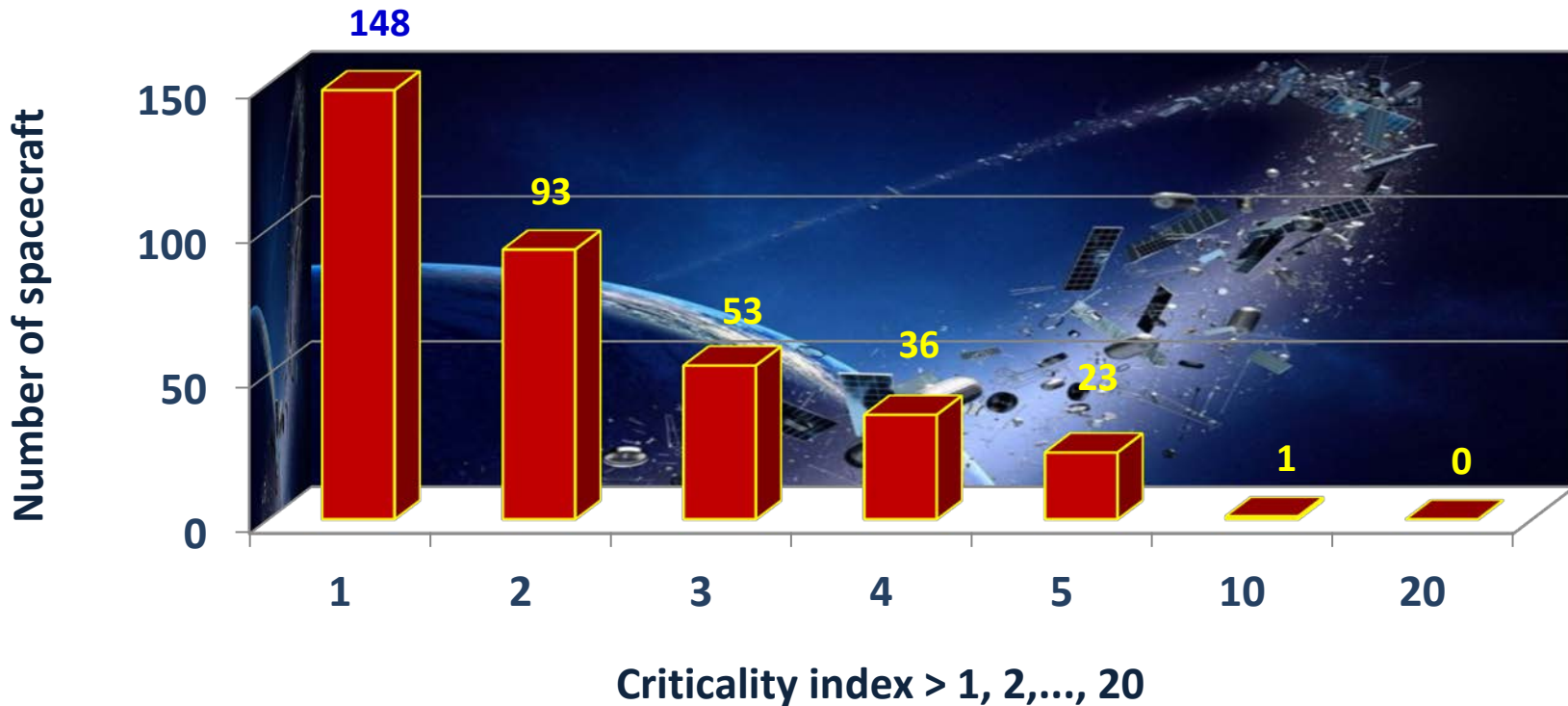
$\frac{CDCD50(h > 1250 \text{ km})}{CDCD50(h = 1250 \text{ km})} \equiv 1$



It corresponds to a half-life equal or greater than about 230 years for the possible debris cloud

- Such conditions were introduced to avoid of giving too much weight, in relative terms, to objects with very long lifetimes, much longer, in fact, than any reasonable temporal horizon for the current modeling, technology and social projections
- Moreover, having adopted for the index definition a normalized and dimensionless ratio instead of an absolute value, R_N is nearly independent from the specific assumptions used to build the $l(h)$ and the $CDCD50$ functions

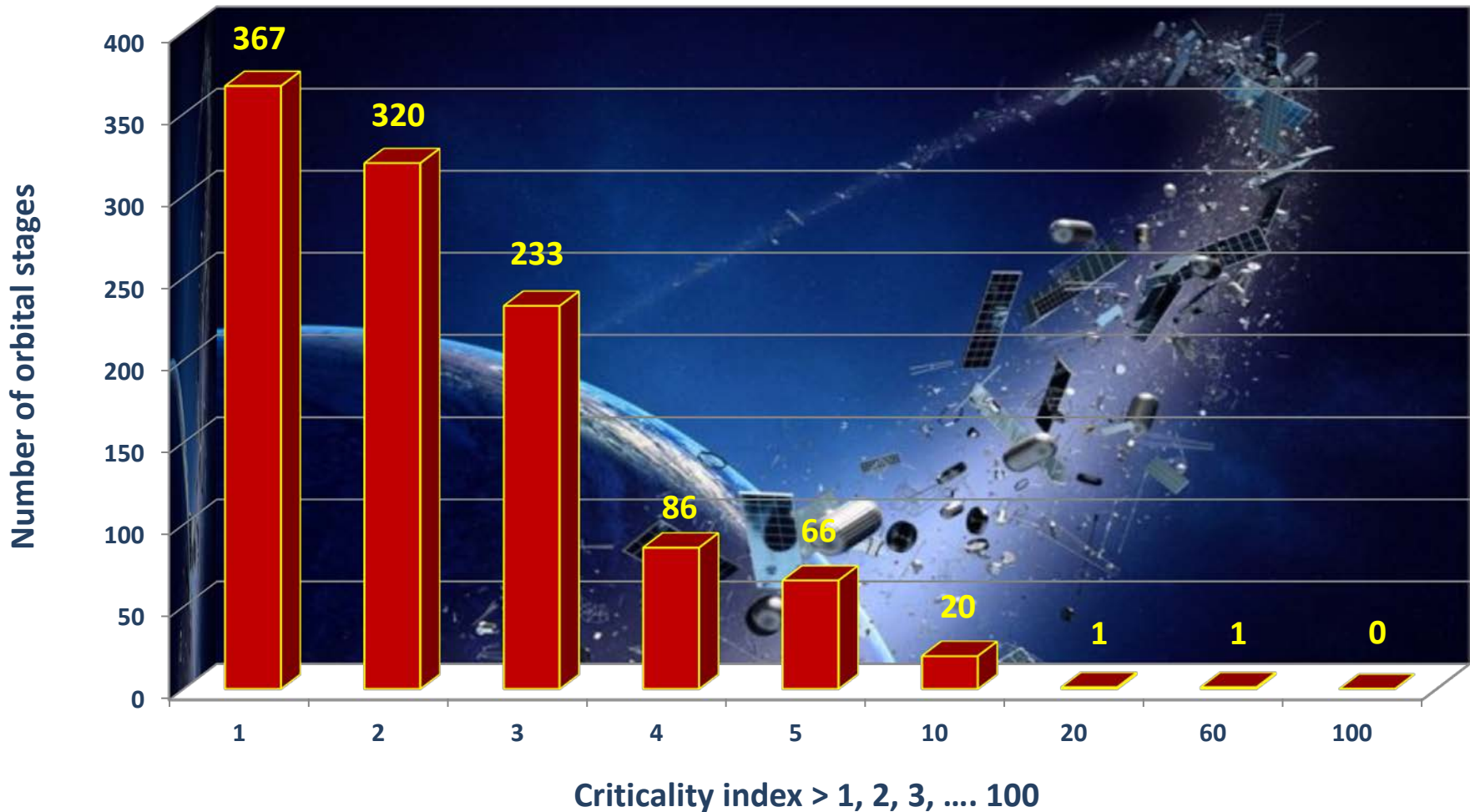
Criticality of spacecraft



- Among the abandoned spacecraft, the most critical objects resulted to be Cosmos 2392 (Arkon-1), the Geo-IK geodesy satellites, several meteorological Meteor satellites (Cosmos 1045 and Meteor 3-1, 3-2, 3-4, 3-5, 3-6, 3M, and M), Midori 2 (ADEOS 2), Envisat, Cosmos 1066 (Astrofizika), ARGOS and the Tselina-2 satellites ^{[11][12]}

Criticality of orbital stages

- The most critical rocket bodies resulted to be the 20 SL-16 Zenit second stages with $R_N > 10$ [11][12]



Overall criticality in LEO

- Computing the criticality index R_N (RN-F-ISTI-2014) for the overall cataloged population in LEO leads to:

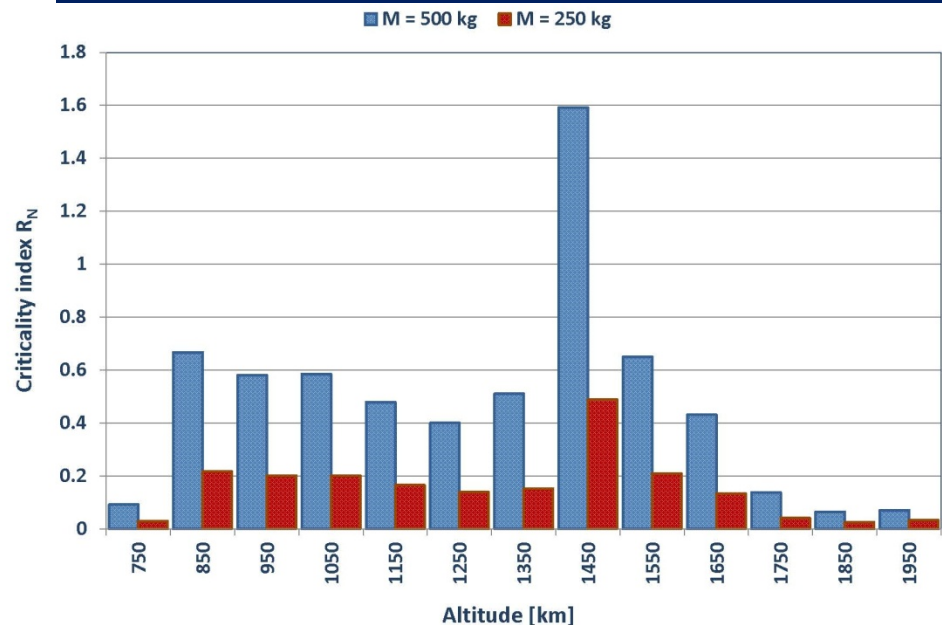
Total R_N in LEO ~ 3000

- As an example, the total R_N of the Italian satellites and rocket bodies in LEO is ≈ 2 [7]
- One single satellite, LARES ($h \approx 1450$ km, $i \approx 70^\circ$), accounts for $\approx 90\%$ of the criticality



- Concerning the possible impact of new satellites lost or abandoned in LEO, as an example, the “marginal” criticality index R_N was evaluated for spacecraft with a mass of 250 kg and 500 kg, as a function of the release altitude
- For 250 kg satellites, $R_N \approx 0.2$ from 800 km to 1400 km, with a maximum of 0.5 around 1450 km
- For 500 kg satellites, $0.4 < R_N < 0.7$ from 800 km to 1400 km, with a maximum of 1.6 around 1450 km

Marginal criticality index of new satellites added in LEO



Criticality of additional satellites

As an example, the additional criticality index R_N was evaluated for a new set of abandoned satellites (N_0), with $h \approx 1350$ km, $i \approx 80^\circ$, and interaction volume thickness ≈ 50 km

■ Two types of spacecraft were considered

a) Mass = 250 kg

b) Mass = 500 kg

■ a) Results for 250 kg lost or abandoned satellites

	Fraction of current total criticality in LEO
■ $N_0 = 100 \Rightarrow$ Total additional $R_N \approx 24$	0.8 %
■ $N_0 = 300 \Rightarrow$ Total additional $R_N \approx 128$	4.3 %
■ $N_0 = 400 \Rightarrow$ Total additional $R_N \approx 207$	6.9 %
■ $N_0 = 500 \Rightarrow$ Total additional $R_N \approx 305$	10.2 %
■ $N_0 = 600 \Rightarrow$ Total additional $R_N \approx 421$	14.0 %



■ b) Results for 500 kg lost or abandoned satellites

■ $N_0 = 100 \Rightarrow$ Total additional $R_N \approx 85$	2.8 %
■ $N_0 = 200 \Rightarrow$ Total additional $R_N \approx 221$	7.4 %
■ $N_0 = 250 \Rightarrow$ Total additional $R_N \approx 314$	10.5 %
■ $N_0 = 300 \Rightarrow$ Total additional $R_N \approx 422$	14.1 %
■ $N_0 = 550 \Rightarrow$ Total additional $R_N \approx 1186$	39.5 %



■ At $h \approx 1350$ km, the marginal criticality index was close to the mean from 700 km to 2000 km

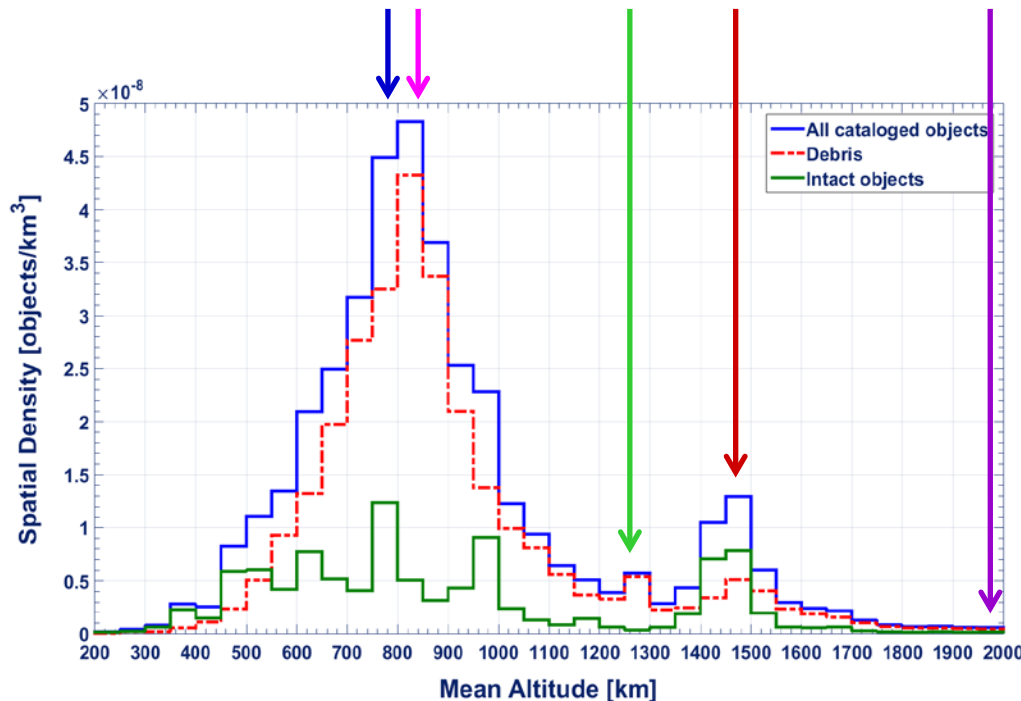
Big vs. small satellites impact trade-off

- The substitution one-by-one of large satellites with smaller ones would be advantageous from a debris mitigation point of view
 - However, for a given total mass deployed in space, fewer more massive satellites would be better than many more less massive ones
 - The breakeven point would depend on the design details of the satellites and on the background debris environment at the deployment altitude
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- Using the EUCASS-2017 approach, and assuming the classical relationship $M = 62.013 A^{1.13}$ (where M is measured in kg and A in m^2)^[13], the following cases were simulated^{[3][4]}
 - Given 100 satellites with $M = 1000$ kg, lost or abandoned in LEO
 - How many satellites with $M = 100$ kg, deployed at the same altitude, would be able to match the additional average collision rate, among themselves and with the background objects ≥ 10 cm, of the original 100 satellites?
 - How many satellites with $M = 10$ kg, deployed at the same altitude, would be able to match the additional average collision rate, among themselves and with the background objects ≥ 10 cm, of the original 100 satellites?

Big vs. small satellites results

Mean altitude [km]	Number of satellites with M = 1000 kg	Number of satellites with M = 100 kg	Number of satellites with M = 10 kg
775	100	298 (× 3.0)	535 (× 1.8)
825	100	376 (× 3.8)	860 (× 2.3)
1275	100	328 (× 3.3)	902 (× 2.8)
1475	100	248 (× 2.5)	407 (× 1.6)
1975	100	278 (× 2.8)	737 (× 2.7)

← Number of new uncontrolled satellites (of 100 kg and 10 kg) needed to induce, in five selected altitude bands, the same additional average collision rate, with objects ≥ 10 cm, as 100 abandoned spacecraft of one metric ton



■ In the cases analyzed, with a reduction of the average satellite mass by a factor 10 (one order of magnitude), the original collision rate increase (CRI) of the new satellites is recovered with substitution ratios from 1.6 to 3.8

■ For example, at 1275 km, 9 metric tons of 10 kg uncontrolled satellites, or 33 metric tons of 100 kg uncontrolled satellites, lead to the same collision rate increase (CRI) of 100 metric tons of 1000 kg uncontrolled spacecraft

Conclusions

- The rapid change in the quality and quantity of launch traffic, initiated in 2014 and destined to increase in the coming years and decades, requires a rethinking of the space debris mitigation guidelines, basically conceived twenty years ago having in mind a pattern of space activities which remained substantially unchanged for 55 years
- Taking as example the debate concerning “Climate Change”, it is not possible (for philosophical and scientific reasons) to define a “Climate Optimum”, but several climatic trends, and their consequences, may be simulated, analyzed and discussed, in terms of local and global sustainability
- Regarding the circumterrestrial space, an “optimal” space debris environment clearly exists (with no debris and no collision risk), but this realization is pointless
- As for Climate Change, specific (additional) actions (i.e. mitigation guidelines and standards, national and international regulations, remediation activities, etc.) should be driven by a broad international agreement on the environmental goals to be met, in terms of acceptable and sustainable launch traffic trends, on-orbit operations, disposal success rates, reentry risk control
- A widely shared definition of an “acceptable” and “sustainable” orbital debris environment is neither easy nor indisputable, and it might take a long time to be reached
- We hope, with this presentation, to have offered some useful clues and insights for the on-going discussion on these topics

References [1]

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