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Evaluating the Environmental Criticality of Massive Objects in LEO for Debris Mitigation and Remediation

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Abstract

Approximately 95% of the mass in Earth orbit is currently concentrated in about 6700 intact objects, of which nearly 80% are abandoned and more than 90% cannot be maneuvered. The intact objects abandoned in low Earth orbit (LEO) above 650 km, i.e. with an average residual lifetime of more than 25 years, represent the main potential mass reservoir for the generation of new detrimental orbital debris in case of mutual collisions with the existing debris environment, taking into account that an 800 g impactor may be sufficient, in principle, to shatter a 1000 kg spacecraft or rocket stage. Since the 1980's, several mitigation measures were promoted and agreed at the international level in order to prevent the occurrence of new breakups in space and put under control the accumulation of mass abandoned in orbit, but unfortunately the level of compliance with such guidelines, requirements or standards is still far from satisfactory. Moreover, the appearance on the scene of space activity of new private and government actors from a growing number of countries makes the proper management of the circumterrestrial space a task of increasing complexity, taking also into account the rapid emerging of new potential applications, disrupting technologies and operational approaches quite different from the past. In this rapidly evolving environment, it might be useful to have a simple and flexible instrument for evaluating the potential criticality for the environment of massive objects placed or abandoned in LEO. With this goal, in the last few years, a particular effort was devoted to the development of various "criticality indexes", then applied for evaluating many families of rocket bodies and selected spacecraft. In this paper, with the underlining ambition to be simple, intuitive and relevant, from an environmental point of view, a couple of the most complete indexes were coherently applied in order to assess the potential criticality of the most massive objects abandoned in LEO. The results obtained are presented here in detail, also highlighting how these ranking approaches might be used both for debris mitigation, for instance to choose an appropriate disposal orbit for either spacecraft or upper stages to be dismissed at the end-of-life, and for debris remediation, as a guide in the selection of the most relevant targets for active debris removal, if and when such missions will become practicable.

Keywords: space debris, criticality index, intact objects, low Earth orbit, mitigation, remediation ranking.

1. Introduction

The long-term simulations of the orbital debris environment carried out during the last 40 years have identified the abandoned mass in orbit as the main driver of collisional fragments and impact probability growth over several decades, potentially jeopardizing the practical utilization of some of the most popular orbital regimes, particularly in low Earth orbit (LEO) [1,2]. For this reason, a "25-year rule", i.e. the prescription of limiting to less than 25 years the post-mission orbital presence of spacecraft and orbital stages in LEO, was firstly suggested inside the National Aeronautics and Space Administration (NASA), later on endorsed by the Inter-Agency Space Debris Coordination Committee (IADC), and finally adopted by several national and international standards [3]. The aim of the rule was averting the accumulation of intact spacecraft and orbital stages, in order to retard as much as possible a rapid growth of artificial debris and collision rates triggered by mutual collisions and catastrophic breakups [4,5].

Presently there are approximately 7500 metric tons of mass in orbit around the Earth, of which about 95% concentrated in almost 6700 intact spacecraft and orbital stages [6]. Among them, nearly 80% are abandoned and more than 90% cannot be maneuvered. Those left above ~ 650 km, i.e. with a typical residual lifetime of more than 25 years, represent the main potential mass reservoir for the generation of new detrimental orbital debris in case of mutual collisions with the existing debris environment, taking into account that an 800 g impactor may be sufficient, in principle and on average, to deeply shatter a 1000 kg spacecraft or rocket stage. Just considering the most massive objects abandoned in LEO, the 9000 kg second stages of the Zenit-2 launcher, it has been pointed out that there is a 1/4000 probability per year of a collision involving two of them, leading to an immediate doubling of the cataloged debris population in LEO [7].

A possible approach for gauging the latent long-term environmental impact of an orbiting object, avoiding thousands of complex simulations built on rather uncertain scenario assumptions and forecasts [8], is to formulate a "criticality index" grounded on simplified credible assumptions and characterized by much faster, and easier to implement, computations. An intuitive and simple to understand meaning, if possible, would add further practical value to the definition, which may represent, for instance, a good starting point for the assessment of the post-mission disposal options for a spacecraft or an orbital stage, or for a preliminary analysis of environmental criticality and prioritization of intact targets for active debris removal (ADR). An appropriately defined criticality index may be therefore beneficial both for mitigation and remediation debris evaluations.

During the last decade, several criticality/ranking indexes have been proposed [9-17]. In this paper, the definition presented in [18-20] was adopted. A simplified version of it, particularly suited for analyzing relatively homogeneous sets of objects, had been previously and extensively used for the relative ranking in between and among the main families of rocket bodies [21,22]. However, being this work devoted to both spacecraft and orbital stages, the use of the complete index defined in [18-20] was deemed more appropriate.

The analysis presented in the following considered all the unclassified intact objects fully resident in LEO, i.e. with a mean altitude ≤ 2000 km, with a perigee height ≥ 650 km and with a mass ≥ 1000 kg, as of 3 May 2017. This included 165 spacecraft, with a total mass of about 325 metric tons, and 434 rocket bodies, with a total mass of about 801 metric tons. Together, with 1126 metric tons, accounted for 40% of the total mass of intact objects in LEO, including the International Space Station, and 47% excluding the permanent human habitat [23]. The analysis was also extended to constellation satellites with an individual mass < 1000 kg, but characterized by a mean altitude > 900 km. The constellations considered, in order of decreasing total mass, were the following: Parus, Globalstar, Strela 3, Strela 1M, Tsiklon, Tsikada, Sfera, Yaogan†, and Gonets. In total, 737 spacecraft, with a total mass of about 208 metric tons.

In conclusion, all the objects included in the study had a combined mass of 1334 metric tons, i.e. 47% of the total mass of intact objects in LEO, including the International Space Station, and 56% excluding it. Moreover, most of the ignored mass orbited below 650 km, so was not relevant for the long-term evolution of the debris environment, due to the cleaning effect of thermospheric drag. Therefore, the selection criteria adopted should have sorted out almost all, if not all, the most critical objects in LEO potentially able to play an adverse role on the long-term evolution of the debris environment.

†The Yaogan satellites listed here were those with mass < 1000 kg; the other ones with mass exceeding one metric ton were instead included in the general analysis.

2. Criticality index setup

The criticality index (R) adopted in this study was already introduced and described in detail elsewhere [18-20]. However, in order to improve the readability of the paper, review all the assumptions made and pointing out the small fine tunings introduced, the definition is recalled in the following.

Starting from the idea that a higher criticality index should be associated with a greater potential for adverse effects on the LEO debris environment, its building began with the product of two functions, f and g, the first one depending on the probability of catastrophic fragmentation P_c due to orbital debris collision, and on the number of new "projectiles" N_p resulting from the breakup, the second one characterizing the long-term impact on the environment as a function of the lifetime of the new cloud of fragments, of the volume of space involved, and of the interaction with the pre-existing debris distribution:

$$R = f \cdot g \tag{1}$$

Taking into account that the condition $P_c < 0.1$ generally applies and that the typical "critical projectiles" are ~ 20 times smaller than the targets, the probability of catastrophic collisional fragmentation can be expressed, in terms of the flux of debris $F(t)$ able to destroy the target object, of the average cross-section A of the latter, and of the interval of time t considered, as follows:

$$P_c \approx \int F(t) \cdot A \cdot dt \tag{2}$$

However, being the time evolution of $F(t)$ affected by significant uncertainties [8], and the computation of the integral for each specific target object quite cumbersome, also because the flux of debris leading to a catastrophic fragmentation, i.e. with masses $\geq m_D(M)$, is a function of the target mass M, orbit inclination i and altitude h as well, it was decided of including in the definition just the current flux $F = F\left[h, i, m_D(M)\right]$, either provided by a debris model or estimated using a catalog. This led to:

$$P_c \sim F\left[h, i, m_D(M)\right] \cdot A \cdot L_T \tag{3}$$

where L_T is the object residual lifetime, approximated as the product between the object mass-to-area ratio M/A and a "normalized" mean lifetime function $l(h)$:

$$L_T \cong l(h) \cdot \frac{M}{A} \tag{4}$$

Fig. 1 shows the mean lifetime function $L_{T0}(h)$ computed for an average intact object in LEO, as could be found in mid-2013 [8,12,24], with $M_0 = 934$ kg and $A_0 = 11$ m^2. The "normalized" mean lifetime function $l(h)$ can be therefore written in the following way:

$$l(h) = L_{T0}(h) \cdot \frac{A_0}{M_0} \tag{5}$$

leading to:

$$P_c \sim F\left[h, i, m_D(M)\right] \cdot l(h) \cdot M \tag{6}$$

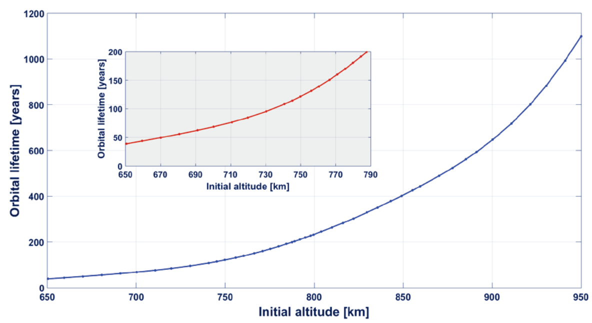

Fig. 1. Mean orbital lifetime, as a function of the initial altitude in nearly circular orbit, of an average intact object

In order to quantify the number of new "projectiles" resulting from a hypothetical disrupting collision, the NASA standard breakup model was used [25,26]. In it, the cumulative number of fragments N_p generated in a catastrophic collision and larger than a given characteristic size is proportional to the cumulative mass of the target object and the impacting debris, raised to the 0.75th power. It should be however pointed out that, in most of the cases, the cumulative mass would be in practice very close to the target mass, being the latter generally much larger (by 3 orders of magnitude in LEO) than the impactor's one. As a result, $N_p \propto M^{0.75}$, leading to the following expression for the f function:

$$f \equiv P_c \cdot M^{0.75} \sim F\left[h, i, m_D(M)\right] \cdot l(h) \cdot M^{1.75} \tag{7}$$

Regarding the definition of the g function, the first step was the evaluation of the long-term impact on the environment of the new debris cloud resulting from a potential catastrophic collision. It was therefore introduced the concept of collisional debris cloud decay of 50% of the catalogable fragments (*CDCD*50). Given a collisional cloud of fragments with sizes $d \geq 10$ cm, released around a certain mean altitude, its *CDCD*50 represents the time needed for the orbital decay of 50% of the pieces due to air drag. In other words, *CDCD*50 is the cloud half-life. Fig. 2 shows *CDCD*50 as a function of the mean breakup altitude in nearly circular orbit. It was calibrated studying the area-to-mass distribution and orbital evolution of the cloud of cataloged fragments resulting from the catastrophic collisional destruction of the Cosmos 2251 satellite, on 10 February 2009 [27].

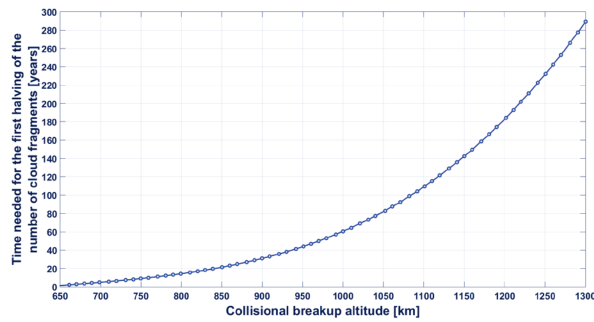

Fig. 2. First halving time of the number of catalogable debris generated by a catastrophic collision (CDCD50), as a function of the breakup altitude in nearly circular orbit

Coming to the volume of space affected by the potential breakup and to the interaction of the resulting fragment cloud with the pre-existing debris distribution, the choice fell on the ratio between the flux of debris able to induce a catastrophic fragmentation, i.e. with masses $\geq m_D(M)$, at the target mean altitude h and orbital inclination i, and the flux at the same altitude, but for $i = 0°$. This z function was therefore defined in the following way:

$$z\left[h, i, m_D(M)\right] \equiv \frac{F\left[h, i, m_D(M)\right]}{F\left[h, i = 0°, m_D(M)\right]} \tag{8}$$

Such approximately bell shaped function in LEO peaks around polar inclinations and has minima for equatorial, or nearly equatorial, orbits, either direct or retrograde. [18-20].

Then, the g function can be defined as follows:

$$g \equiv CDCD50(h) \cdot z\left[h, i, m_D(M)\right] \tag{9}$$

completing the intended set up of the criticality index R, which becomes:

$$R \equiv F(h, i, m_D) \cdot l(h) \cdot M^{1.75} \cdot CDCD50(h) \cdot z(h, i, m_D) \tag{10}$$

3. Normalized and dimensionless criticality index

For practical applications, it was highly desirable deriving a criticality index R_N both normalized and dimensionless. Therefore, the average intact object in LEO, as of mid-2013 [12,24], was used for defining a reference object, with $M_0 = 934$ kg, placed into a circular sun-synchronous orbit with $h_0 = 800$ km and $i_0 = 98.5°$. The normalized and dimensionless criticality index R_N was then defined in the following way:

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

$$\times \frac{CDCD50(h)}{CDCD50(h_0)} \cdot \frac{z[h,i,m_D(M)]}{z[h_0,i_0,m_D(M_0)]} \quad (11)$$

where it was set:

$$l(h)/l(h_0) \equiv 1 \text{ when } h > h_0 \quad (12)$$

and:

$$\frac{CDCD50(h > 1250\text{km})}{CDCD50(h = 1250\text{km})} \equiv 1 \quad (13)$$

These conditions, corresponding, in the case of Eq. (12), to an orbital lifetime equal or greater than about 230 years for the target object (see Fig. 1), and, in the case of Eq. (13), to a half-life equal or greater than about 230 years for the possible debris cloud (see Fig. 2), 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.

4. Study targets and assumptions

As anticipated in Section 1, the study considered all the unclassified intact spacecraft and orbital stages fully resident in LEO, as of 3 May 2017, with a perigee height ≥ 650 km and with a mass ≥ 1000 kg. In addition, it also analyzed the constellation satellites with an individual mass < 1000 kg and a mean height > 900 km.

The debris mass $m_D(M)$ able to produce the catastrophic breakup of a target object of mass M was estimated by assuming a mean relative velocity of 10 km/s [28,29] and a specific fragmentation energy of 40 000 J/kg [30]. The flux of orbital debris having mass $\geq m_D(M)$, i.e. $F[h,i,m_D(M)]$, was computed using the SDIRAT tool [29,32], applied to the MASTER-2009 population model [31].

All the computations were repeated using the catalog of the unclassified orbital objects issued by the US Strategic Command on 3 May 2017. In that case, the flux, $F_{cat}(h,i)$, was again computed with SDIRAT, using the population of all cataloged objects, irrespective of their masses. This led to the estimation of the criticality index R_{Ncat}:

$$R_{Ncat} \equiv \frac{F_{cat}(h,i)}{F_{cat}(h_0,i_0)} \cdot \frac{l(h)}{l(h_0)} \cdot \left(\frac{M}{M_0}\right)^{1.75} \times$$

$$\times \frac{CDCD50(h)}{CDCD50(h_0)} \cdot \frac{z_{cat}(h,i)}{z_{cat}(h_0,i_0)} \quad (14)$$

The reasons for computing also an index like R_{Ncat} were the following:

1. Large space objects, made of two or more nearly structurally independent modules, or having pressurized tanks, just to highlight a couple of examples, might suffer a catastrophic breakup even if hit by debris with mass $< m_D(M)$ [24];
2. Collisions among cataloged objects are anyway relevant events;
3. The debris catalog is updated daily, while a population model requests years to be developed and validated;
4. If the ranking order obtained with R_N is basically the same obtained with R_{Ncat}, the latter is much easier and straightforward to compute.

5. Criticality of spacecraft

The values of R_N and R_{Ncat} obtained for the 165 spacecraft in LEO with perigee height ≥ 650 km and mass ≥ 1000 kg are summarized in Figs. 3-12. R_N (MASTER) is always plotted in brown, R_{Ncat} (CATALOG) is always plotted in blue. The satellites with a "*" superscript were still functioning when the analysis was carried out, so their criticality indexes were applicable to the operational orbit, in case of no de-orbiting at the end-of-life.

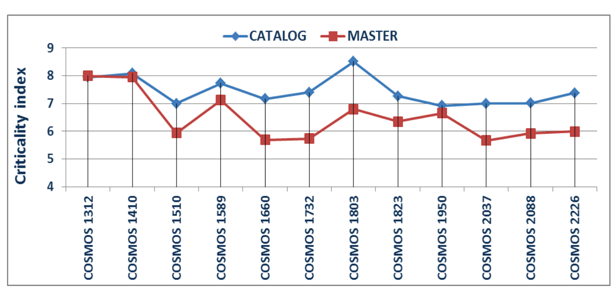

Fig. 3. Criticality index of the Russian Geo-IK geodesy satellites ($M = 1500$ kg)

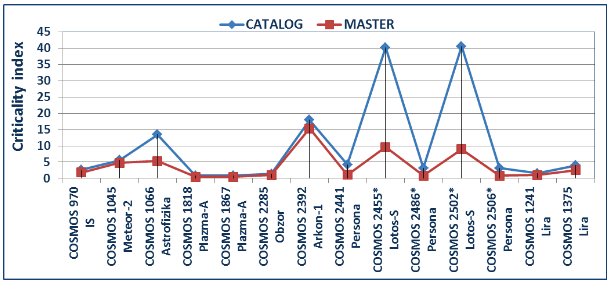

Fig. 4. Criticality index of heterogeneous Cosmos satellites, with mass up to 7000 kg (Cosmos 2441, 2455 and 2502)

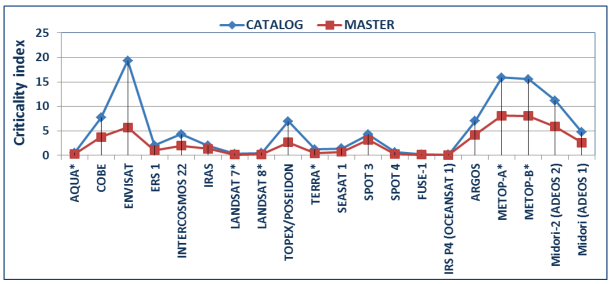

Fig. 5. Criticality index of heterogeneous satellites from Europe, United States and Japan, with mass up to 8110 kg (Envisat)

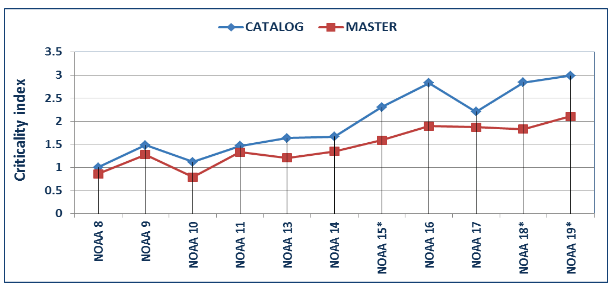

Fig. 6. Criticality index of NOAA meteorological satellites, with mass up to 1441 kg (NOAA 15)

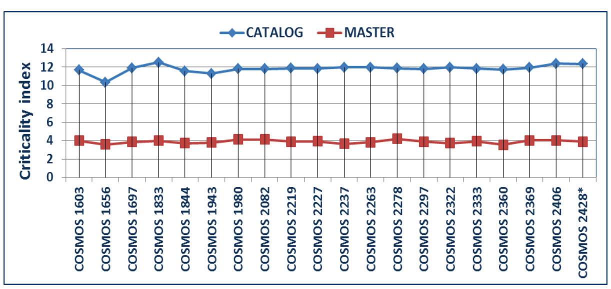

Fig. 7. Criticality index of the Russian Tselina-2 electronic intelligence satellites ($M \approx 3200$ kg)

No criticality index greater than one was obtained below 700 km, while above 800 km all the objects considered had an index close to one or greater (Fig. 12). Among the operational spacecraft, the highest values were found for the Lotos-S satellites Cosmos 2455 and 2502, and for the meteorological satellites Metop A and B, and Meteor M2 (Fig. 11). 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 (Fig. 11). $R_N > 1$ was found for 148 satellites, $R_N > 2$ for 93, $R_N > 3$ for 53, $R_N > 4$ for 36, $R_N > 5$ for 23, and $R_N > 10$ for only one spacecraft (Cosmos 2392). $R_{Ncat} > 1$ was instead found for 155 satellites, $R_{Ncat} > 2$ for 110, $R_{Ncat} > 3$ for 99, $R_{Ncat} > 4$ for 59, $R_{Ncat} > 5$ for 53, $R_{Ncat} > 10$ for 29, and $R_{Ncat} > 20$ for two operational spacecraft (Cosmos 2455 and 2502).

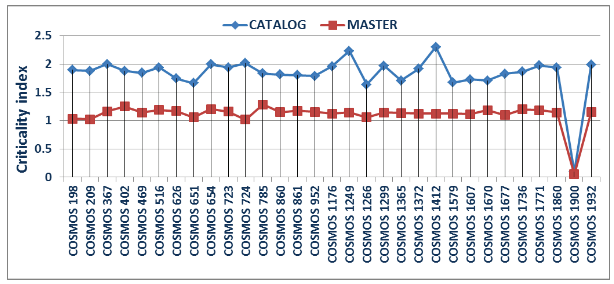

Fig. 8. Criticality index of the Russian US-A radar ocean reconnaissance satellites (RORSAT, $M = 1250$ kg)

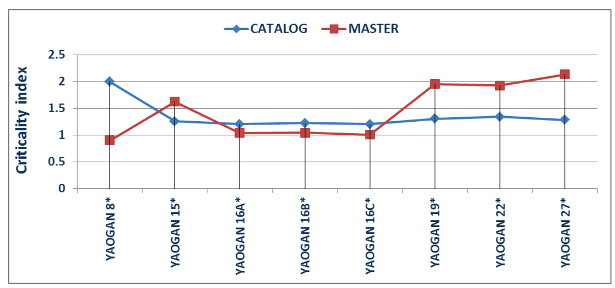

Fig. 9. Criticality index of the Chinese Yaogan reconnaissance satellites with a mass greater than one metric ton ($M = 1040$ kg)

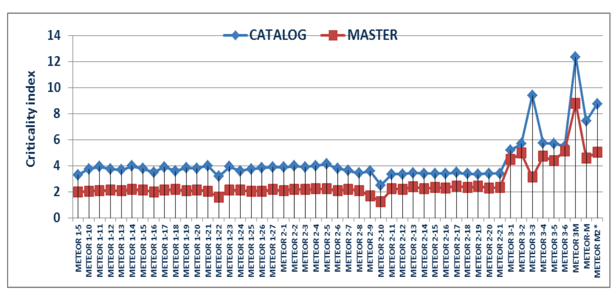

Fig. 10. Criticality index of the Russian Meteor meteorological satellites, with mass up to 2900 kg (Meteor M2)

Concerning the further 737 constellation spacecraft with an individual mass < 1000 kg and a mean height

> 900 km, the results obtained are summarized in Fig. 13. No R_N or $R_{Ncat} > 2$ was found. $R_N > 1$ was attained for 92 Parus, 24 Globalstar, 7 Tsiklon, 18 Tsikada, and 5 Sfera, i.e. 146 satellites in total, while $R_{Ncat} > 1$ was attained for 92 Parus, 11 Tsiklon, 18 Tsikada, and 7 Sfera, i.e. 128 satellites.

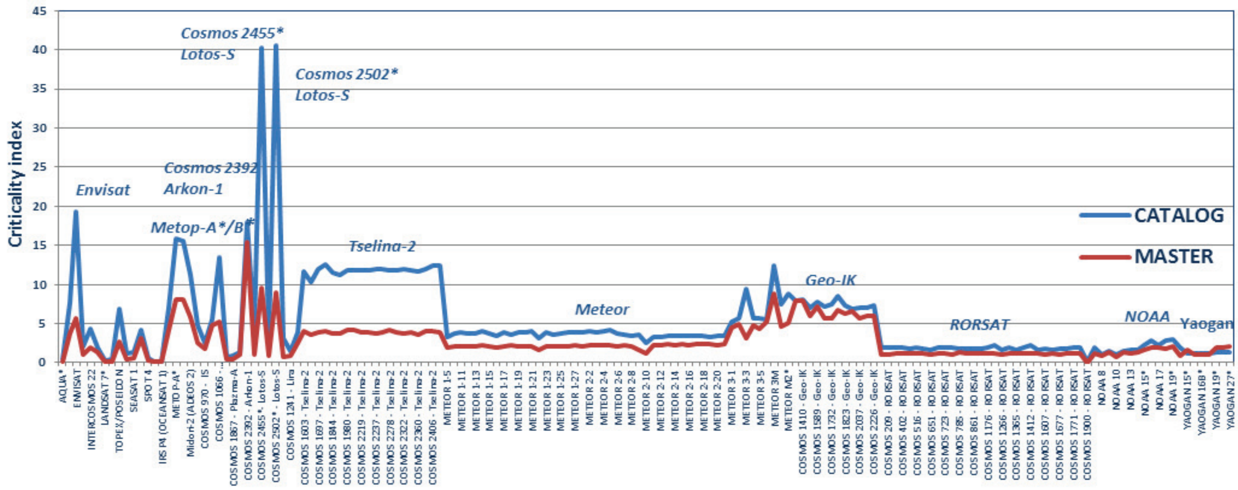

Fig. 11. Criticality index of the spacecraft in LEO with a perigee height ≥ 650 km and with a mass ≥ 1000 kg

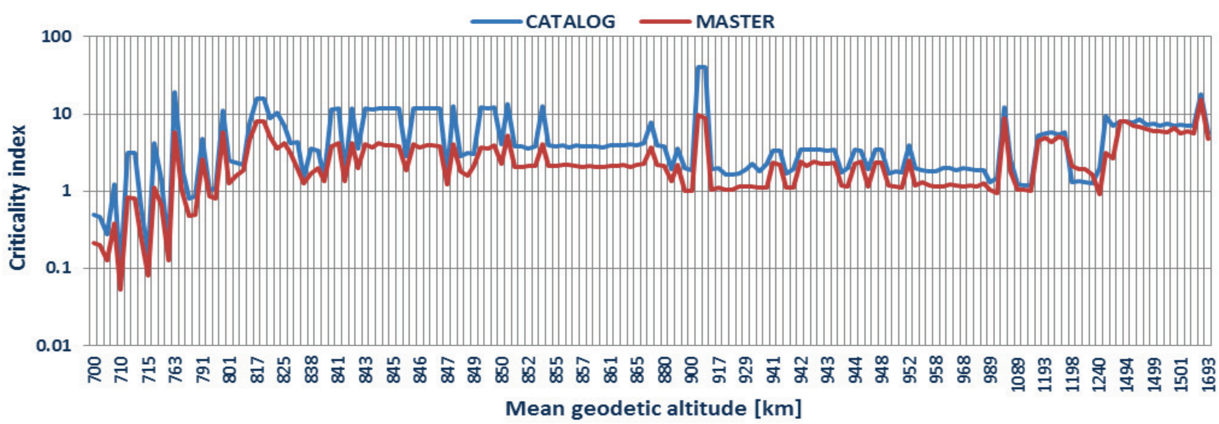

Fig. 12. Criticality index of the spacecraft in LEO with a perigee height ≥ 650 km and with a mass ≥ 1000 kg, as a function of the mean geodetic altitude

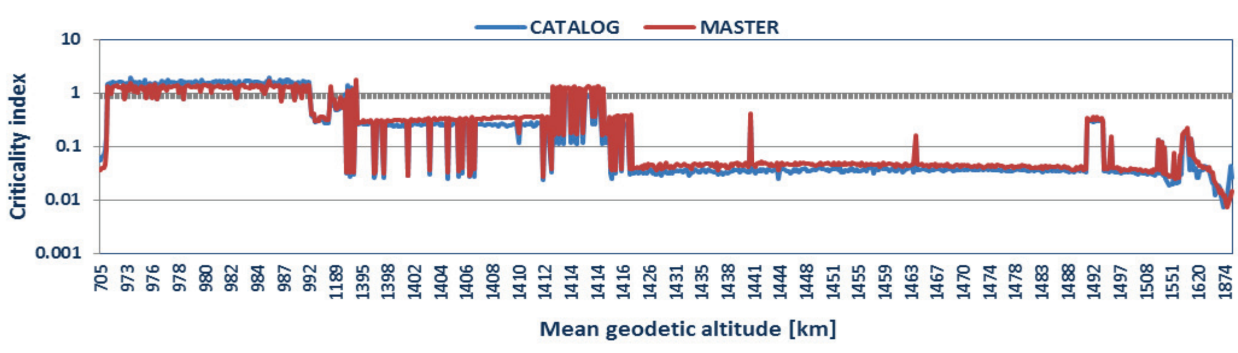

Fig. 13. Criticality index of the constellation satellites in LEO with an individual mass < 1000 kg and a mean height > 900 km, as a function of the mean geodetic altitude

6. Criticality of orbital stages

The values of R_N and R_{Ncat} obtained for the 434 orbital stages in LEO, with perigee height ≥ 650 km and mass ≥ 1000 kg, are summarized in Figs. 14-22. Again, R_N (MASTER) is always plotted in brown and R_{Ncat} (CATALOG) is always plotted in blue. For the only Japanese H-2A upper stage (M = 3000 kg) present in the region of interest when the analysis was carried out (catalog number 27601), R_N = 2.23 and R_{Ncat} = 5.97.

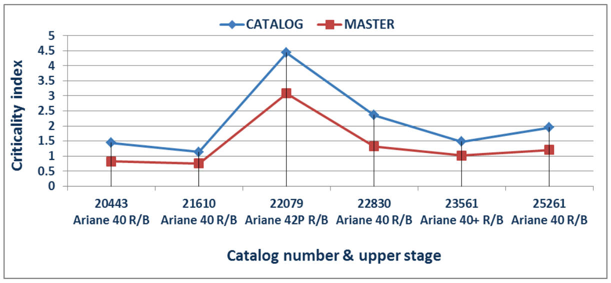

Fig. 14. Criticality index of the European Ariane 4 upper stages (M = 1800 kg)

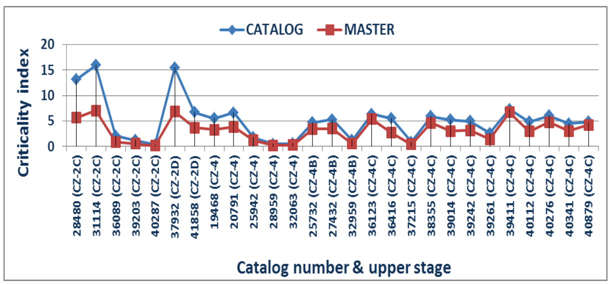

Fig. 15. Criticality index of the Chinese Long March upper stages (M = 4000 kg for CZ-2; M = 2000 kg for CZ-4)

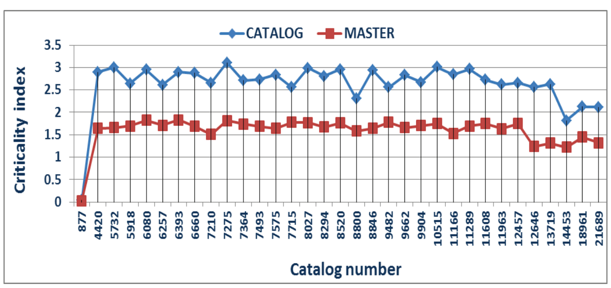

Fig. 16. Criticality index of the Russian SL-3 Vostok upper stages (M = 1100 kg)

Above 780 km, all the upper stages considered had both criticality indexes > 1 (Fig. 22). The most critical objects resulted to be the 20 SL-16 Zenit second stages (Fig. 18), with R_N > 10 and R_{Ncat} > 60. R_N > 1 was found for 367 abandoned rocket bodies, R_N > 2 for 320, R_N > 3 for 233, R_N > 4 for 86, R_N > 5 for 66, R_N > 10 for the 20 Zenit stages, and R_N > 60 for the Zenit stage with catalog number 27006. R_{Ncat} > 1 was instead found for 388 orbital stages, R_{Ncat} > 2 for 363, R_{Ncat} > 3 for 302, R_{Ncat} > 4 for 250, R_{Ncat} > 5 for 87, R_{Ncat} > 10 for 23, R_{Ncat} > 20 for the 20 Zenit stages, and R_{Ncat} > 100 for just one of these stages, again number 27006.

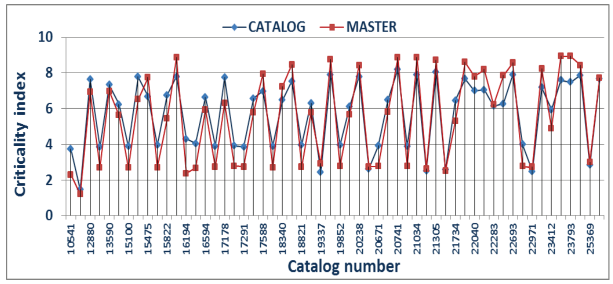

Fig. 17. Criticality index of the Ukrainian SL-14 Tsyklon-3 upper stages (M = 1407 kg)

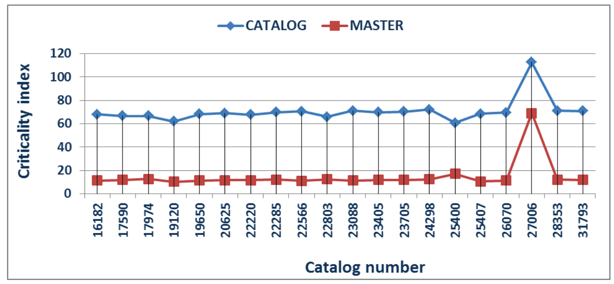

Fig. 18. Criticality index of the Russian SL-16 Zenit-2 upper stages (M = 9000 kg)

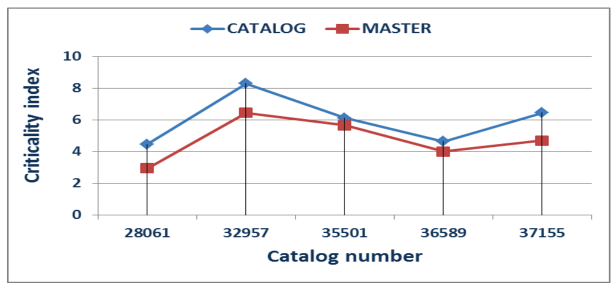

Fig. 19. Criticality index of the Russian SL-19 Rokot upper stages (M = 1600 kg)

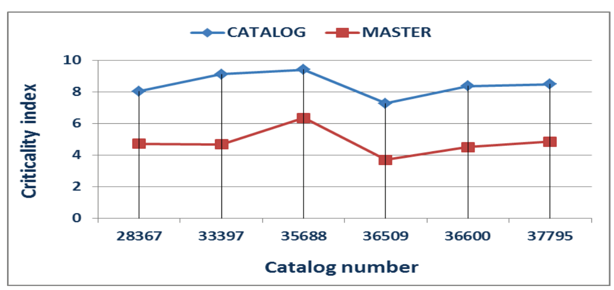

Fig. 20. Criticality index of the Ukrainian SL-24 Dnepr-1 upper stages (M = 2360 kg)

7. Remediation and mitigation applications

The assignment of a criticality index to the LEO intact objects is a first step to rank them as potential targets for active debris removal, if and when such

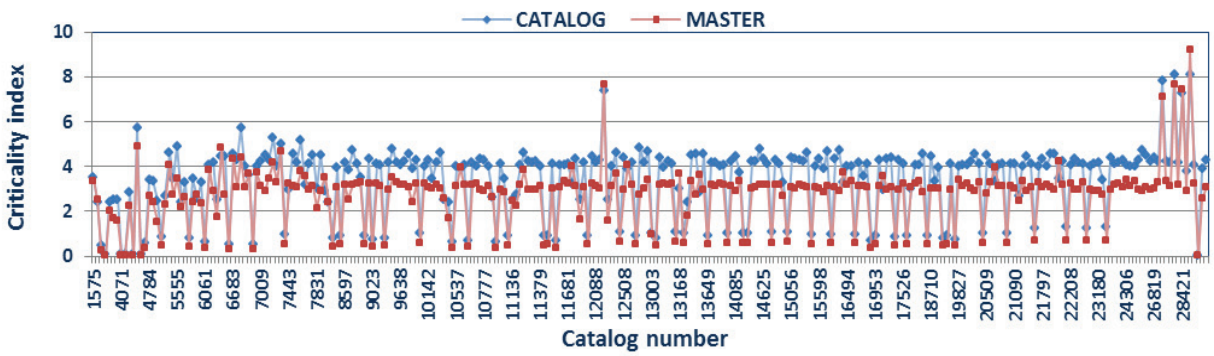

Fig. 21. Criticality index of the Russian SL-8 Kosmos upper stages (M = 1435 kg)

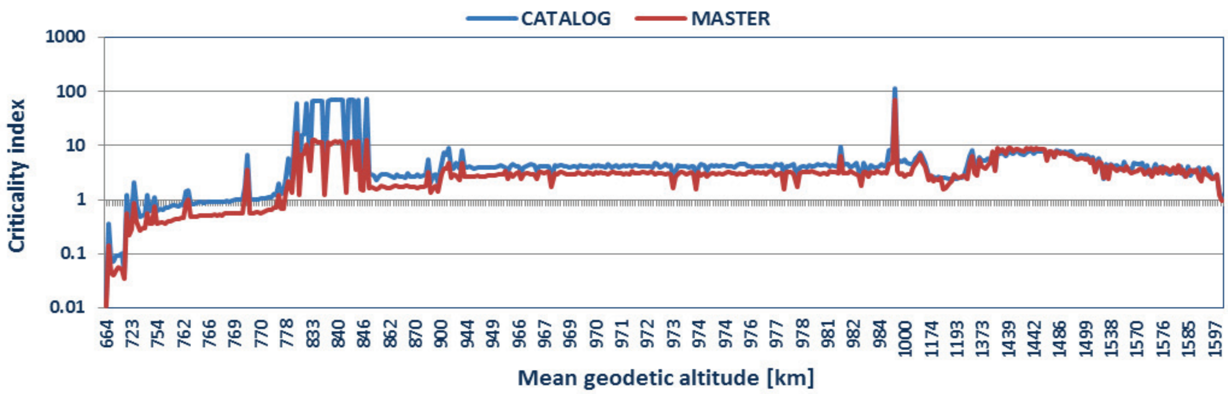

Fig. 22. Criticality index of the orbital stages in LEO with a perigee height ≥ 650 km and with a mass ≥ 1000 kg, as a function of the mean geodetic altitude

remediation measure will become feasible. A higher criticality index will correspond to a higher removal priority, in terms of the expected long-term benefits for the debris environment.

As shown in the previous analysis and made clearer in Figs. 23-25, there would be plenty of targets for ADR: among the intact objects analyzed, 148 spacecraft with $M \geq 1000$ kg, 146 spacecraft with $M < 1000$ kg and 367 orbital stages with $M \geq 1000$ kg resulted to have $R_N > 1$, i.e. a potential debris environment criticality greater than that associated with a 1-ton object abandoned in sun-synchronous orbit at 800 km. And even though a few tens of the spacecraft were still operational when the analysis was carried out, the abandoned objects with $R_N > 1$ were more than 600.

The spacecraft with $M \geq 1000$ kg and $R_N > 1$ spanned the altitude range from 700 to 1700 km, but were mostly concentrated between 800 and 1000 km, near 1200 km and close to 1500 km (Fig. 23). The spacecraft with $M < 1000$ kg and $R_N > 1$ were instead largely found between 900 and 1000 km and around 1400 km (Fig. 24). Finally, the rocket bodies with $R_N > 1$ extended across the altitude range from 750 to 1700 km, with two main concentrations, between 750 and 1200 km, and between 1350 and 1600 km (Fig. 25).

In addition to the priority ranking of potential targets for active removal and debris remediation, the criticality index may also be used for mitigation, in particular to evaluate in advance, for instance during mission design, planning, or operation, the relative appropriateness of end-of-life disposal orbits, or the possible impact of failed disposal maneuvers. Let consider, as an example, six satellites in sun-synchronous orbit, operational when the analysis was carried out: Aqua, Landsat 8 and Terra, at 700 km, Metop A and B, at 817 km, and NOAA 19, at 849 km. According to the IADC mitigation guidelines, all these spacecraft would have to be disposed into a significantly lower orbit, at the end-of-life, in order to comply with the “25-year rule”. However, for Aqua ($R_N = 0.21$), Landsat 8 ($R_N = 0.20$) and Terra ($R_N = 0.38$), a failure to do so, remaining in the operational orbit, would have been much less critical, from the debris environment point of view, than for NOAA 19 ($R_N = 2.10$) and, even more, for Metop A ($R_N = 8.11$) and Metop B ($R_N = 8.01$).

8. Conclusions

Among the 386 intact objects in LEO with $R_N > 2$, 83% were orbital stages and 17% spacecraft. Even considering the 116 objects with $R_N > 5$, the rocket

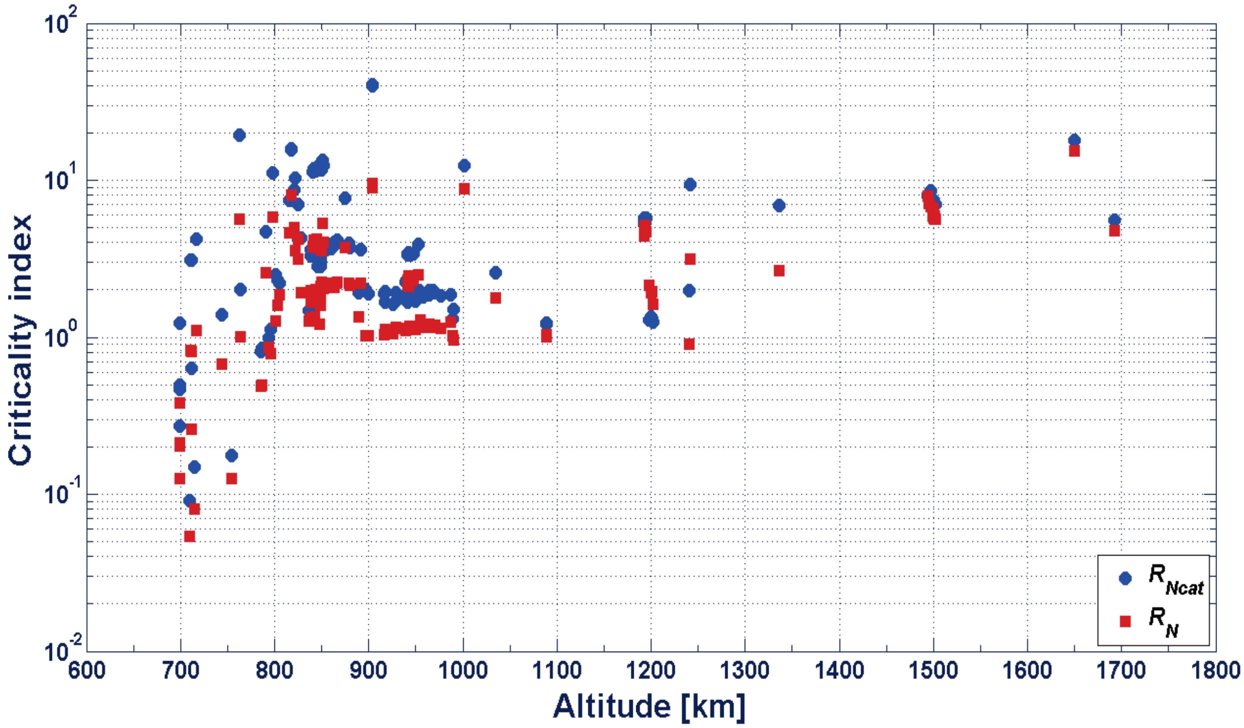

Fig. 23. Criticality index of the spacecraft in LEO with a perigee height ≥ 650 km and with a mass ≥ 1000 kg, as a function of the mean geodetic altitude

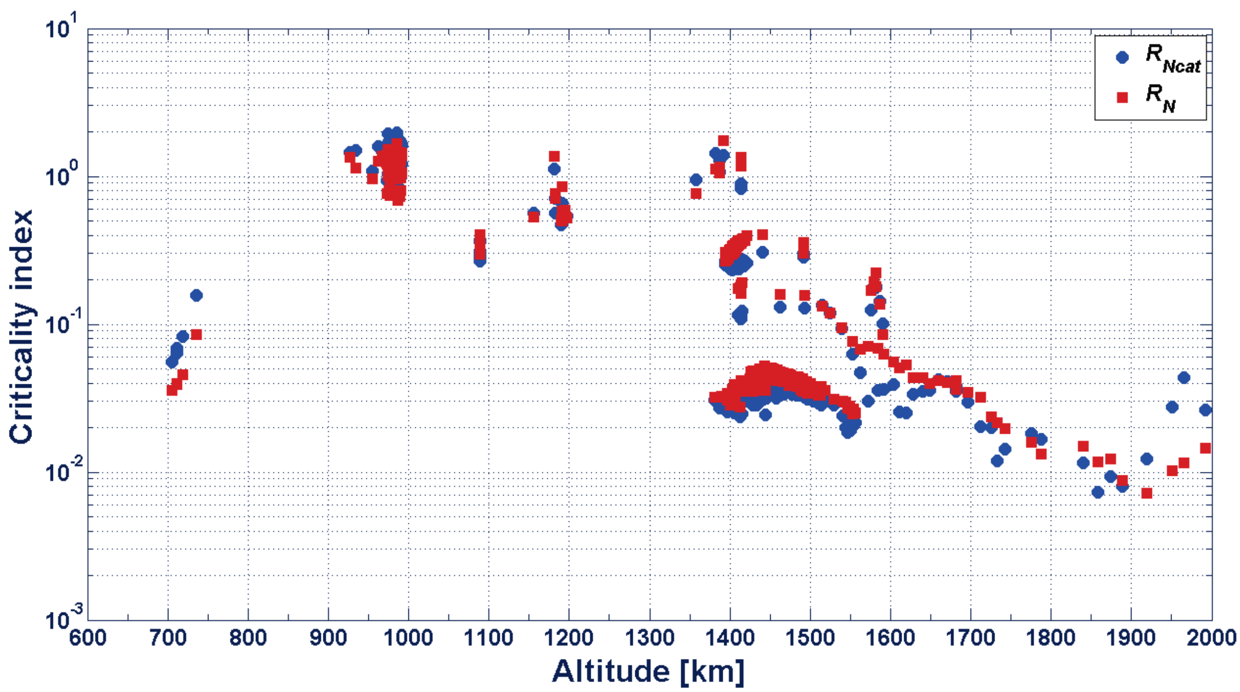

Fig. 24. Criticality index of the constellation satellites in LEO with an individual mass < 1000 kg and a mean height > 900 km, as a function of the mean geodetic altitude

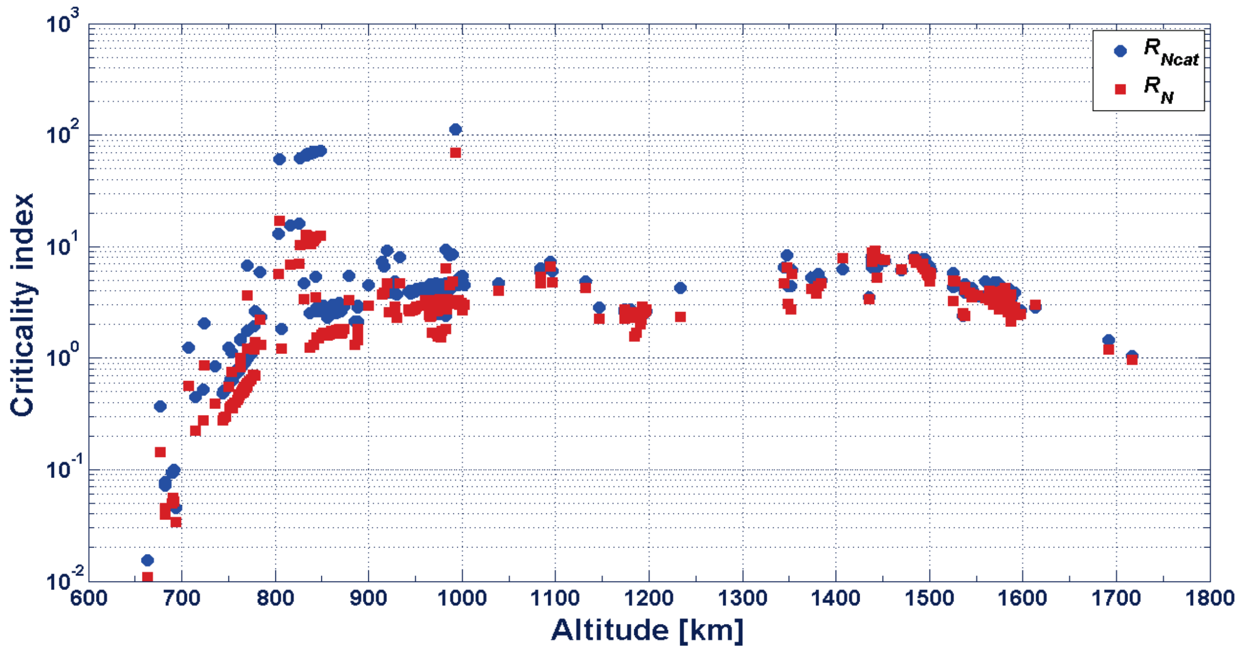

Fig. 25. Criticality index of the orbital stages in LEO with a perigee height ≥ 650 km and with a mass ≥ 1000 kg, as a function of the mean geodetic altitude

bodies accounted for 80% of the total. This was certainly a good news from the debris remediation point of view, because the upper stages are probably an easier target for active removal, characterized as they are by a simpler shape, a high degree of geometric and mass distribution symmetry, a less fragile structure and, probably, a less complicated rotational motion. In addition, they belong to a few families of similar objects, making the business of grappling and de-orbiting them repeatable many times with the same technologies and procedures.

Table 1. Abandoned satellites with $R_N > 7$ (3 May 2017)

Name	Mass (kg)	Height (km)	Incli-nation	R_N
Cosmos 2392†	6000	1649	63°	15.34
Meteor 3M	2500	1001	99°	8.80
Cosmos 1312††	1500	1494	83°	7.99
Cosmos 1410††	1500	1494	83°	7.95
Cosmos 1589††	1500	1495	83°	7.12

† Arkon-1 satellite
†† Geo-IK satellites

There were 51 top ranking abandoned objects with $R_N > 7$, 46 (90%) orbital stages and 5 (10%) spacecraft. The latter are listed in Table 1. The European satellite Envisat, with $R_N = 5.69$, ranked 73rd, preceded by 59 orbital stages and 13 abandoned spacecraft. Regarding instead the top 46 rocket bodies, the situation is summarized in Table 2. The 20 SL-16 Zenit upper stages dominated the scene, between 800 and 1000 km, with the highest rankings associated with the two rocket bodies left in sun-synchronous orbit. Then followed 5 SL-8 Kosmos and 20 SL-14 Tsyklon-3 upper stages, between 1400 and 1500 km, and a single CZ-2C rocket body, abandoned in sun-synchronous orbit at 825 km.

Table 2. Orbital stages with $R_N > 7$ (3 May 2017)

Type	Mass (kg)	Height (km)	Incli-nation	R_N
SL-16 stage Catalog #27006	9000	993	99°	69.07
SL-16 stage Catalog #25400	9000	804	98°	16.99
SL-16 stages [18]	9000	≥ 826 ≤ 849	71°	10.29 12.66
SL-8 stages [4]	1435	≥ 1441 ≤ 1486	82°	7.12 9.22
SL-14 stages [20]	1407	~ 1440	83°	7.72 8.93
SL-8 stage Catalog #12115	1435	1453	74°	7.64
CZ-2C stage Catalog #31114	4000	825	98°	7.06

Concerning the R_{Ncat} index, much easier to be computed and updated, overall the ranking order was roughly the same obtained with R_N, but presented significant changes in the top list. There were 76 top ranking abandoned objects with $R_N \geq 7.6$, 46 (61%) orbital stages and 30 (39%) spacecraft. Among the abandoned spacecraft, Envisat became the leader, with

$R_{Ncat} = 19.33$, followed by Cosmos 2392 (Arkon-1, $R_{Ncat} = 17.88$), Cosmos 1066 (Astrofizika, $R_{Ncat} = 13.41$), Meteor 3M ($R_{Ncat} = 12.36$), 19 Tselina-2 spacecraft ($10.33 \leq R_{Ncat} \leq 12.52$), Midori-2 ($R_{Ncat} = 11.21$), Meteor 3-3 ($R_{Ncat} = 9.42$), four Geo-IK geodesy satellites, Cosmos 1803 ($R_{Ncat} = 8.51$), 1410 ($R_{Ncat} = 8.08$), 1312 ($R_{Ncat} = 7.95$) and 1589 ($R_{Ncat} = 7.72$), and COBE ($R_{Ncat} = 7.68$).

Regarding the orbital stages, the ranking list was much more stable. Looking again at the top 46 rocket bodies, the leader was again the SL-16 Zenit upper stage with catalog number 27006 ($R_{Ncat} = 112.50$), followed by the other 19 twin stages ($60.71 \leq R_{Ncat} \leq 79.09$). The list continued with one CZ-2D and two CZ-2C rocket bodies ($13.14 \leq R_{Ncat} \leq 15.98$), five SL-24 Dnepr-1 upper stages ($8.05 \leq R_{Ncat} \leq 9.41$), one SL-19 Rokot upper stage ($R_{Ncat} = 8.30$), 14 SL-14 Tsyklon-3 upper stages ($7.60 \leq R_{Ncat} \leq 8.20$), and three SL-8 Kosmos stages ($7.84 \leq R_{Ncat} \leq 8.12$).

In conclusion, the environmental criticality of the main intact objects abandoned in LEO, both spacecraft and orbital stages, was coherently estimated with a couple of new criticality indexes. The results obtained identified and ranked several hundreds of suitable targets for active debris removal, if such remediation measure will become economically feasible on a large scale in the future. However, the criticality indexes detailed in the paper might also be used for mitigation purposes, in particular during mission design and planning, for instance to assess the relative merits and drawbacks of operational and disposal orbits, both for spacecraft and upper stages, from the debris environment point of view.

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