AN INDEX FOR RANKING ACTIVE DEBRIS REMOVAL TARGETS IN LEO

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ABSTRACT

In order to evaluate the potential environmental criticality, regarding the evolution of orbital debris, of the objects lost or abandoned in low Earth orbit, a new normalized and dimensionless ranking index was presented, using as benchmark a nearly 1-ton object placed into an 800 km sun-synchronous orbit. It was applied to 58 objects with a mean altitude in between 600 and 1000 km and with a dry mass greater than 3000 kg. They accounted for about 11% of the mass present in low Earth orbit, operational spacecraft included.

The maximum value found corresponded to the massive second stage of a Zenit launcher, abandoned close to 1000 km. Envisat ranked first among the spacecraft no longer operational, but only 22nd in the group considered, after 20 Zenit second stages and a CZ-2C rocket body. Most of the mass with a criticality index greater than 1, i.e. 90%, was concentrated at 830 ± 40 km.

1 INTRODUCTION

The main reason behind the adoption of the so-called "25-year rule" [1], endorsed by the Inter-Agency Space Debris Coordination Committee (IADC), was preventing the undue build-up of intact spacecraft and rocket bodies, in which approximately 95% of the mass in Earth orbit is currently concentrated [2], in order to avoid the long-term instability triggered by mutual collisions and catastrophic breakups [3-5].

A popular way to gauge the latent long-term environmental impact of an orbiting object, refraining from running thousands of complex simulations based on quite uncertain scenario assumptions and forecasts, is to conceive a ranking scheme based on plausible inferences [6-16]. The main advantage of the latter heuristic approach is the adoption of easy to understand and apply rules, while the main drawback is the likely oversimplification of a problem, the long-term evolution of orbital debris around the Earth, which, in addition to unavoidable uncertainties, presents an inherent stochastic, and possibly chaotic, character. In spite of this limitation, simplified ranking schemes may represent a good starting point for a preliminary analysis of environmental criticality and prioritization of intact targets for Active Debris Removal (ADR).

This paper introduces a ranking index developed for estimating the potential adverse effects on the debris environment in Low Earth Orbit (LEO), having particularly in mind a mid-term (a few decades) temporal horizon, i.e. a time interval in which the current technological capabilities and developments, economical and regulatory conditions, international negotiation and political situation can be reasonably extrapolated [10,13]. Starting from the basic assumption that a higher criticality index should be associated with a higher potential threat and could be expressed as the product of two functions, the first depending on the probability of catastrophic breakup due to orbital debris collision and on the number of new "projectiles" resulting from the breakup, the second characterizing the long-term impact on the environment as a function of the fragments cloud lifetime, volume of space involved and interaction with the pre-existing debris distribution, an index is developed and discussed, showing what complications can be avoided without compromising the effectiveness of the definitions adopted.

The underlining goal was always a blend of intuitive simplicity and environmental relevance, computing the ranking in relative terms as a function of an average intact object in LEO placed in the most popular orbital regime, the sun-synchronous one. Finally, the ranking index is applied to a selection of relevant upper stages and spacecraft abandoned in orbit.

2 SPACE OBJECT RANKING SCHEME

Considering its potential mid and long-term adverse effects on the debris environment, the ranking R of an abandoned object in LEO, where a higher ranking value is associated with a higher potential threat, can be expressed as the product of two functions:

$$R = f \cdot g \qquad (1)$$

The function f depends on the probability of catastrophic breakup P_c, due to a collision with a piece of orbital debris, and on the number of new "projectiles" N_p resulting from the breakup. The function g characterizes, instead, the long-term impact on the environment as a function of the lifetime of the cloud of fragments generated, of the volume of space involved

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and of the interaction with the pre-existing debris distribution.

Being $F(t)$ the flux of debris able to induce the catastrophic breakup of the target object, A the average collisional cross-section of the latter and t the time, the probability of catastrophic fragmentation in a given time interval can be written as follows, taking into account that in general the condition $P_c < 0.1$ applies:

$$P_c \approx \int F(t) \cdot A \cdot dt \quad (2)$$

Unfortunately, the time evolution of $F(t)$ is affected by significant uncertainties [17] and, in any case, the computation of the integral in Eq. 2 for each specific target object would be cumbersome, even assuming very simple laws, also because the debris flux leading to a catastrophic fragmentation is a function of the target mass M, orbit inclination and decaying altitude as well.

Therefore, as a first strong simplifying assumption, it was chosen to include in the ranking scheme just the current flux $F = F(h,i,M)$, provided either by a state-of-the-art debris model or by a sufficiently complete debris catalog, at the (mean) altitude h and inclination i of the target, supposed to be in a reasonably low eccentricity orbit, e.g. < 0.02, as often is the case in LEO. This led to:

$$P_c \sim F(h,i,M) \cdot A \cdot L_T \quad (3)$$

where L_T is the object residual lifetime. In Eq. 3, a relatively small altitude decrease was assumed during the residual orbital lifetime of the objects. This represented, of course, a further simplification, but due to the exponential decreasing density of the atmosphere with the height, and the corresponding increase of the scale height, in practice the objects subjected to air drag spend most of their residual lifetime very near to their end-of-life disposal altitude, so the use of L_T in Eq. 3 was considered a reasonable simplifying assumption.

Considering a distribution of drag coefficients not too far from a standard average value, which is reasonably true for intact objects in LEO, L_T can be approximated as the product between the object mass-to-area ratio M/A and a "normalized" lifetime function $l(h)$:

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

Fig. 1 shows the lifetime function $L_{T0}(h)$ computed, in terms of the initial altitude in nearly circular orbit and assuming average solar activity conditions with a flux at 10.7 cm (*F10.7*) of 125 standard flux units and a geomagnetic index $Kp = 2$, for an average intact object in LEO, as of mid 2013 [9,17,18], with $M_0 = 934$ kg and $A_0 = 11$ m^2 [9,10,13]. The "normalized" lifetime function $l(h)$ can be therefore computed as follows:

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

where $L_{T0}(h)$ can be well approximated, for computational purposes, by the polynomial interpolation shown in Fig. 1, very good above 600 km.

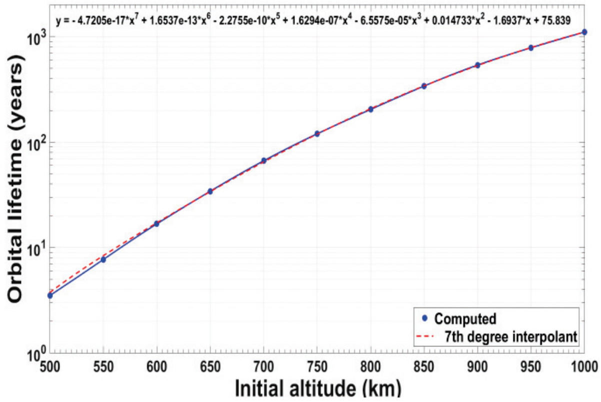

Figure 1. Mean orbital lifetime, as a function of the initial altitude in nearly circular orbit, of an average intact object in LEO, as of mid 2013. The computed values can be well reproduced by the polynomial interpolation shown in the figure, in particular above 600 km.

Eq. 3, representing the probability of collision with orbital debris for the object of interest, can be then written in the following way:

$$P_c \sim F(h,i,M) \cdot l(h) \cdot M \quad (6)$$

In order to evaluate the number of new "projectiles" N_p resulting from a possible catastrophic collisional breakup, the NASA standard breakup model was used [19,20]. 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 impacting debris, raised to the 0.75th power. However, in the overwhelming majority of cases, the cumulative mass is in practice very close to the target mass, being the latter typically 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 function f [8,9]:

$$f \equiv P_c \cdot M^{0.75} \sim F(h,i,M) \cdot l(h) \cdot M^{1.75} \quad (7)$$

In order to define the function g, the first step was the characterization of the long-term impact on the environment of the debris cloud resulting from a potential catastrophic breakup due to orbital debris hypervelocity collision. To do so, and in analogy to what is currently done in several biological sciences, the concept of Collisional Debris Cloud Decay of 50% (*CDCD*50) of the catalogable fragments, i.e. those with typical size $d \geq 10$ cm in LEO, was introduced [10,13]. Given a collisional cloud of debris larger than 10 cm, released around a certain mean altitude, its *CDCD*50 represents the time needed for the orbital decay of 50% of the fragments 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, assuming average solar activity conditions with *F10.7* = 125 standard flux units and geomagnetic index *Ap* = 15, and debris clouds with area-to-mass ratio and velocity distributions similar to those observed following the Fengyun 1C, Cosmos 2251 and Iridium 33 catastrophic collisional fragmentations [21,22]. For computational purposes, the estimated cloud half-life can be approximated using the polynomial interpolation shown in Fig. 2.

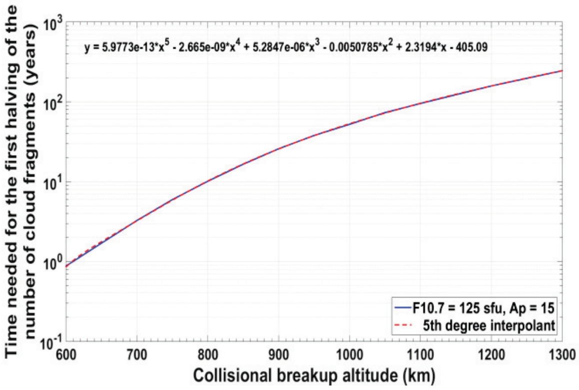

Figure 2. First halving time of the number of catalogable debris generated by a catastrophic collision (CDCD50), as a function of the breakup altitude in nearly circular orbit. The estimated cloud half-life can be well reproduced using the polynomial interpolation shown in the figure.

Regarding the characterization of the volume of space affected by the potential breakup and the interaction of the resulting cloud of fragments with the pre-existing debris distribution, the choice fell on the ratio between the flux of debris $\geq d$ at mean altitude h and orbital inclination i, and the flux of the identical debris population at the same altitude, but at inclination $i = 0°$. This function z was therefore defined in the following way:

$$z(h,i,d) \cong \frac{F(h,i,d)}{F(h,i=0°,d)} \tag{8}$$

In LEO, it has a strong dependence on the orbit inclination i, but varies relatively slightly with the height h. A representative plot of z, based on the flux of debris with $d \geq 10$ cm computed with the MASTER-2009 model [23], is shown in Fig. 3 for some LEO altitudes of interest.

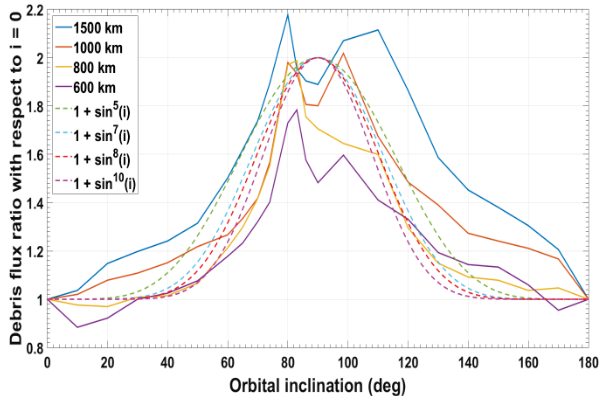

Figure 3. Plot of z(h,i), for debris with d ≥ 10 cm, as a function of orbit inclination and altitude (in nearly circular orbit). The orbital debris fluxes were obtained for mid-2014 with the MASTER-2009 model, but the general trend can be reproduced reasonably well by simple functions of the form $z = 1 + \sin^n(i)$.

Of course the function z could be evaluated case by case using an appropriate environmental model like MASTER-2009, as was made in the past [10,13], but Fig. 3 clearly shows that the observed general trend can be reproduced reasonably well also by a very simple function of the form:

$$z(h,i,d) = 1 + \sin^n(i) \tag{9}$$

where an appropriate setting might be, for example:

$$n = 8 \tag{10}$$

i.e.

$$z = 1 + \sin^8(i) \tag{11}$$

The function g in Eq. 1 can be therefore defined as follows:

$$g \equiv CDCD50(h) \cdot \left[1 + \sin^8(i)\right] \tag{11}$$

completing the intended set up of the ranking function R, which becomes:

$$R \equiv F(h,i,M) \cdot l(h) \cdot M^{1.75} \cdot CDCD50(h) \times$$

$$\times \left[1 + \sin^8(i)\right] \tag{12}$$

3 NORMALIZED AND DIMENSIONLESS CRITICALITY RANKING INDEX

From a practical point of view, it was highly desirable deriving from R a criticality ranking index R_N both normalized and dimensionless. For this purpose, the average intact object in LEO, as of mid-2013 [9,18], was used for defining a reference object, with $M_0 = 934$ kg, placed into a circular sun-synchronous orbit with the following characteristics: $h_0 = 800$ km and $i_0 = 98.5°$.

The normalized and dimensionless criticality ranking index R_N was then defined in the following way:

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

$$\times \frac{CDCD50(h)}{CDCD50(h_0)} \cdot \frac{1+\sin^8(i)}{1+\sin^8(i_0)} \quad (13)$$

where it was set:

$$l(h)/l(h_0) \equiv 1 \text{ when } h > h_0 \quad (14)$$

and:

$$\frac{CDCD50(h > 1250\text{km})}{CDCD50(h = 1250\text{km})} \equiv 1 \quad (15)$$

These conditions, corresponding, in the case of Eq. 14, to a residual orbital lifetime of about 200 years for the target object (see Fig. 1), and, in the case of Eq. 15, to a half-life of about 200 years for the potential debris cloud (see Fig. 2), were introduced to avoid of weighting too much, in relative terms, 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 ratios instead of absolute values, R_N is nearly independent from the specific assumptions, e.g. solar activity, used to build the $l(h)$ and the $CDCD50$ functions.

With this definition, the intuitive meaning of the criticality ranking index defined above is easy to understand, because the normalized and dimensionless parameter R_N is referred to an average intact object in LEO placed in the most popular orbital regime, the sun-synchronous one. The number R_N obtained for a specific object basically compares, in a "proportional" way, its latent detrimental effects on the long-term debris environment with those of the reference body. In other words, a criticality index $R_N = 3$, for example, would imply, according to the ranking scheme devised, that the object under evaluation would be equivalent, concerning its long-term detrimental effects on the debris environment, to 3 reference objects in sun-synchronous orbit, and, in case of candidate search for active debris removal, it should be ranked accordingly.

4 LOGARITHMIC CRITICALITY INDEX

Notwithstanding the intuitive meaning of R_N, its values may span a range of many orders of magnitude, so a logarithmic index R_{NL} might be more functional in certain cases. It was defined in the following way:

$$R_{NL} \equiv \log_{10}(R_N) + 1 \quad (16)$$

in order to obtain $R_{NL} = R_N = 1$ for the reference body, and $R_{NL} \geq 0$ when $R_N \geq 0.1$, i.e. 1/10 of the criticality ranking index for the reference body.

5 RANKING THE HIGHEST MASS OBJECTS IN LEO

The ranking scheme presented in the previous sections was applied to the abandoned objects in LEO having the following characteristics, at the end of February 2017:

- A dry mass greater than 3000 kg;
- A mean altitude in between 600 and 2000 km;
- An apogee height lower than 2000 km.

Being the exact value of the mass affected by a certain uncertainty, in particular for Russian and Chinese objects, the list might be not completely accurate, but would offer, in any case, a good picture of the situation concerning the most massive abandoned objects in LEO.

According to the filtering criteria adopted, the list included a European spacecraft, Envisat (7611 kg), 21 Russian spacecraft, i.e. Okean-O (6150 kg) and 20 Tselina-2 satellites (3250 kg), 3 second stages of the Japanese H-2A launcher (3100 kg), 3 second stages of the Chinese CZ-2D launcher (4000 kg), 8 second stages of the Chinese CZ-2C launcher (4000 kg), and 22 second stages of the Russian/Ukrainian Zenit launcher (8900 kg): in total, 58 objects, with an aggregate mass of nearly 328 metric tons, representing 4.4% of the mass present in orbit [2] and 10.9% of the mass present in LEO [24].

The flux of debris $F(h,i,M)$ able to cause a catastrophic breakup was computed with the MASTER-2009 model, revised in 2012 and updated to 2017 by assuming a business-as-usual scenario. The results obtained are detailed in Tabs. 1-6. In terms of environment potential criticality, the situation was clearly dominated by the second stages of the Russian/Ukrainian Zenit launcher. For one of them, 2001-056F, $R_N = 125.20$ was found, followed by 1996-051B, with $R_N = 45.30$. Another 16 stages were characterized by a criticality index around 40, 2 by an index around 30, and only 2, the lowest ones, by an index below 1 (Tab. 1).

The Tselina-2 satellites were mostly characterized by criticality indices in between around 10 and 12 (Tab. 2). The maximum value found was R_N = 12.12 for Cosmos 2406, while the minimum was R_N = 6.96 for Cosmos 1656. Regarding the second stages of the Chinese CZ-2C launcher, only two objects displayed a relatively big criticality index, 2007-010B with R_N = 14.40 and 2004-046B with R_N = 9.62, with another rocket body around 1 and the remaining 5 below 1 (Tab. 3). Also among the second stages of the CZ-2D launcher there were two objects with sizeable indices, 2011-068C with R_N = 11.39 and 2016-068B with R_N = 9.19, while the remaining rocket body presented a very small value (Tab. 4).

Object	Altitude (km)	Inclination (°)	Criticality Ranking R_N
1985-097B	845 × 831	71.00	39.28
1987-027B	839 × 834	71.00	39.28
1987-041B	846 × 824	71.01	39.28
1988-039B	844 × 812	71.01	32.13
1988-102B	850 × 829	71.00	39.81
1990-046B	856 × 831	71.00	41.41
1992-076B	845 × 830	71.00	39.28
1992-093B	847 × 838	71.02	41.41
1993-016B	851 × 834	71.01	41.07
1993-059B	849 × 823	70.99	39.24
1994-023B	848 × 839	71.00	41.41
1994-074B	646 × 634	98.17	0.40
1994-077B	843 × 840	70.98	40.30
1995-058B	850 × 834	71.02	41.07
1996-051B	862 × 840	70.85	45.30
1998-043G	813 × 801	98.48	28.80
1998-045B	845 × 834	71.01	39.81
1999-039B	646 × 622	98.09	0.36
2000-006B	853 × 829	71.00	40.35
2001-056F	1006 × 986	99.29	125.20
2004-021B	849 × 841	71.00	41.94
2007-029B	846 × 843	70.97	41.89

Table 1. Criticality ranking index for the second stages of the Russian/Ukrainian Zenit launcher (M = 8900 kg).

Concerning the second stages of the Japanese H-2A launcher, only for 2002-056E a significant index, R_N = 5.51, was obtained, being the remaining two well below 1 (Tab. 5). The same was found for the Russian spacecraft Okean-O, while, as expected, the European Envisat satellite presented a noteworthy R_N = 14.32 (Tab. 6). However, even though, in the last few years, Envisat received a lot of attention in the media and among the space debris community, it ranked only 22nd in terms of environment criticality among the massive objects considered in this study. Certainly, it was the first among the abandoned spacecraft, but many upper stages would need more consideration.

Cosmos Satellite No.	Altitude (km)	Inclination (°)	Criticality Ranking R_N
1603	858 × 832	71.03	10.15
1656	851 × 797	71.11	6.96
1697	859 × 837	70.96	11.69
1833	868 × 831	70.91	11.68
1844	869 × 822	70.90	10.13
1943	852 × 832	71.00	9.89
1980	846 × 841	71.00	9.89
2082	856 × 833	71.04	10.15
2219	861 × 833	71.06	10.42
2227	863 × 834	70.98	11.34
2237	858 × 845	70.83	11.80
2263	864 × 833	70.93	11.33
2278	853 × 841	71.05	11.70
2297	860 × 835	71.02	11.35
2322	856 × 840	70.99	11.34
2333	866 × 831	70.91	11.47
2360	857 × 846	70.82	11.80
2369	855 × 841	70.99	10.40
2406	866 × 842	71.00	12.12
2428	855 × 848	70.91	11.82

Table 2. Criticality ranking index for the Russian Tselina-2 satellites (M = 3250 kg).

Object	Altitude (km)	Inclination (°)	Criticality Ranking R_N
2004-046B	908 × 704	98.19	9.62
2007-010B	871 × 785	98.41	14.40
2009-061B	786 × 668	98.05	1.39
2011-030B	689 × 606	97.79	0.15
2011-039B	705 × 641	98.39	0.29
2013-035B	747 × 673	98.33	0.79
2014-059B	691 × 626	98.15	0.20
2014-066B	685 × 674	98.00	0.40

Table 3. Criticality ranking index for the second stages of the Chinese CZ-2C launcher (M = 4000 kg).

6 CONCLUSIONS

A new ranking index to evaluate the environment criticality of the objects lost or abandoned in LEO was presented. It was applied to 58 objects resident in LEO above 600 km and with a dry mass greater than 3000 kg. They accounted for more than 10% of the mass present in low Earth orbit, operational spacecraft included.

Compared with a reference object with a mass around 1 ton and placed into an 800 km sun-synchronous orbit, all the 11 objects having a mean altitude below 700 km displayed a normalized and dimensionless criticality index lower than 1, while the maximum value found, 125, corresponded to the massive second stage of a Russian/Ukrainian Zenit launcher abandoned close to 1000 km.

Object	Altitude (km)	Inclination (°)	Criticality Ranking R_N
2011-068C	846 × 792	98.52	11.39
2013-018E	658 × 629	98.42	0.02
2016-068B	796 × 749	98.37	9.19

Table 4. Criticality ranking index for the second stages of the Chinese CZ-2D launcher (M = 4000 kg).

Object	Altitude (km)	Inclination (°)	Criticality Ranking R_N
2002-056E	837 × 735	98.39	5.51
2009-002J	644 × 572	98.22	0.04
2009-002J	658 × 579	98.45	0.06

Table 5. Criticality ranking index for the second stages of the Japanese H-2A launcher (M = 3100 kg).

Satellite	Altitude (km)	Inclination (°)	Criticality Ranking R_N
Envisat	766 × 765	98.25	14.32
Okean-O	642 × 639	98.18	0.23

Table 6. Criticality ranking index for Envisat (M = 7611 kg) and Okean-O (M = 6150 kg).

Among the spacecraft no longer operational, the highest index, 14, was found for the European satellite Envisat. However, it ranked only 22nd in the group of the 58 massive objects considered, preceded by 20 Zenit second stages and by a second stage of the Chinese CZ-2C launcher. Moreover, most of the mass with a criticality index greater than 1, i.e. 90%, was concentrated around 830 ± 40 km, at an altitude significantly higher than the Envisat's one.

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