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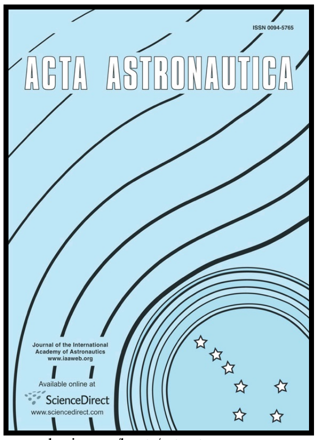

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Ranking upper stages in low Earth orbit for active removal

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Abstract

This paper addresses the problem of ranking the upper stages in orbit in order to evaluate their potential detrimental effects on the debris environment over the long-term, and the relative advantage of having them actively de-orbited. To do so, a new ranking scheme is introduced, applicable to any object in low Earth orbit (LEO) and able to prioritize the target objects potentially most critical for the future preservation of the LEO protected region. Applying the proposed approach, it was found, for instance, that the 22 most massive upper stages abandoned in LEO, at the beginning of 2015, are on the whole equivalent to several hundred average intact objects in sun-synchronous orbit, regarding their latent detrimental effects on the debris environment over the next 200 years. Most of them could therefore be the top priority targets of any worldwide coordinated effort for active removal and the prevention of new collisional debris. The ranking scheme was also applied to other main models of rocket bodies currently in orbit, trying to identify the combinations of orbital elements and upper stage types requiring particular attention.

1. Introduction

Currently, spent upper stages represent more than 42% of the intact objects abandoned in orbit, accounting for 57% of the abandoned mass (and 48% of the total mass, including operational spacecraft). Due to the fact that they belong to a relatively small number of models, compared to spacecraft, and are typically much more symmetric and simple shaped, rocket bodies are ideal candidates for active debris removal missions. Moreover, they are easier and safer to grab, lacking the fragile complement of appendages which characterizes most spacecraft.

In recent years, a popular way to evaluate the latent long-term environmental impact of an orbiting object was to conceive a ranking scheme based on reasonable hypotheses [1] [2] [3] [4] [5] [6] [7] [8]. In this paper, the problem of ranking the upper stages in LEO, in order to evaluate their potential detrimental effects on the debris environment over the long-term, and the relative advantage of having them actively de-orbited, was addressed by applying a new ranking scheme, further developing and extending an approach introduced in [4] and [5]. It is applicable to any object in LEO (payloads included) and able to prioritize the targets potentially most critical for the future preservation of the LEO protected region [9], but its application to rocket bodies, i.e. to homogeneous classes of objects, is much more straightforward, reliable and meaningful.

2. Ranking scheme for abandoned space objects in LEO

Concerning the potential long-term adverse effects on the debris environment, and the relative advantage of performing active de-orbiting, the ranking R of an object in LEO, where a higher ranking value is associated with a higher potential threat, should depend on the probability of catastrophic breakup P_c due to orbital debris collision, on the number of new "effective projectiles" N_p resulting from the breakup, and on the long-term impact on the environment of the resulting debris cloud [3] [5].

Being $F(t)$ the flux of orbital debris able to significantly breakup the target intact object, A the average collisional cross-section of the latter and t the time, the probability of target fragmentation can be expressed by the following relationship [10], taking into account that the cross-section of typical impactors is 2–4 orders of magnitude smaller than A:

$$P_c = 1 - e^{-\int F(t) \cdot A \cdot dt} \quad \textbf{(1)}$$

However, being $F(t) << 1$, Eq. (1) can be approximated by [10]:

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

Unfortunately, the time evolution of $F(t)$ is affected by significant uncertainties [11], basically because, among many other things, the traffic evolution, the impact of new technologies and the rate of compliance with mitigation guidelines cannot be reliably predicted beyond 20 years from now, as well known to all researchers involved in long-term orbital debris modeling. These are the main reasons why the "best guess" long-term extrapolations elaborated in the 1980's and 1990's are remarkably different from the current ones and nothing will prevent the repetition of similar circumstances a few decades from now.
However, the attention here was focused on a ranking scheme easy to manage and compute, "relative" and not "absolute" in essence, and intended to be used "now" as an additional simple tool for the preliminary evaluation of satellite orbit choice, mission mitigation requirements and, possibly, active debris removal strategies in the coming 20–30 years. A reasonably good compromise to meet such goals was, therefore, considered the choice to include in the ranking scheme just the current flux F_{cat} of cataloged debris, giving:

$$P_c \sim F_{cat} \cdot A \cdot L_T \tag{3}$$

where L_T is the target object residual lifetime, which can be expressed, in terms of the body mass-to-area ratio M/A, as:

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

being $l(h)$ a "normalized" average lifetime function [5], which in our case was estimated for the average intact object in LEO in 2013 [4] [12], with M_0 = 934 kg and A_0 = 11 m^2, i.e. A_0/M_0 = 0.012 m^2/kg. For nearly circular orbits, the large majority in LEO, h represents the mean altitude. Eq. (3) then becomes:

$$P_c \sim F_{cat} \cdot l(h) \cdot M \tag{5}$$

Concerning the fragments generated by a catastrophic breakup, their cumulative number N_p larger than a given characteristic size can be roughly evaluated using the NASA standard breakup model [13] [14]. It is proportional to the cumulative mass of the target object and impacting debris, raised to the 0.75th power. However, 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 expression [3] [4] [5]:

$$P_c \cdot M^{0.75} \sim F_{cat} \cdot l(h) \cdot M^{1.75} \tag{6}$$

In order to characterize the long-term impact on the environment of the resulting debris cloud, further factors to be included in Eq. (6) were investigated [5], but the added complexity, coupled with the inherent uncertainties and the generally limited numerical impact of such improvements, led to the choice of concentrating on Eq. (6). In fact, also because most of the intact objects and debris in LEO are characterized by medium or high orbital inclinations, Eq. (6) already incorporates most of the story regarding the potential criticality of the target objects analyzed in the present study.

2.1 Normalized and dimensionless ranking index

Starting from Eq. (6) and considering as yardstick the above mentioned average intact object in LEO in 2013 [4] [12], placed into a sun-synchronous orbit with a mean altitude h_0 of 800 km and with an associated inclination i_0 of 98.5°, the sought normalized and dimensionless ranking index R_N can be defined as follows:

$$R_N \equiv \frac{F_{cat}}{F_{0cat}} \cdot \frac{l(h)}{l(h_0)} \cdot \left(\frac{M}{M_0}\right)^{1.75} \tag{7}$$

where F_{0cat} is the flux of cataloged debris on the reference object and $l(h) / l(h_0) \equiv 1$ when $h > h_0$. The latter cut off, set at a lifetime around 200 years, was introduced to avoid weighting too much objects with very long residual

lifetimes, much longer than any reasonable temporal horizon for the current modeling and technology projections. A smaller lifetime cut off, around 100 years, could have been just as appropriate, but the former choice was dictated by the fact that many of the current debris modeling projections are ran over two centuries.
The meaning of a ranking index so defined is quite immediate, being R_N referred to an average intact object in LEO placed in the most popular orbital regime, the sun-synchronous one. The value found for a specific object should weight proportionally its latent detrimental effects on the long-term debris environment with those of the reference body.

2.2 Logarithmic ranking index

Even though R_N has a quite straightforward meaning, 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:

$$R_{NL} \equiv \log_{10}(R_N) + 1 \quad \textbf{(8)}$$

This means that $R_{NL} = R_N = 1$ for the reference body, and $R_{NL} \geq 0$ when $R_N \geq 0.1$, i.e. 1/10 of the ranking index for the reference body.

3. Rocket bodies in orbit

Starting from the unclassified catalog maintained by the US Strategic Command, as of 7 January 2015, a detailed census of the intact upper stages present in circumterrestrial space and in LEO, with semi-major axis ≤ 8378 km, was carried out. The results obtained are summarized in Table 1.

Table 1: Intact rocket bodies in orbit, as of 7 January 2015

Rocket Body	Dry Mass [kg]	Length/ Diameter [m]	Stage	Total number in orbit	Total number in LEO	Refer-ence
RUSSIAN FEDERATION & UKRAINE						
SL-3 VOSTOK	1100	2.84/2.56	Stage 2 Vostok 8A92M-2	53	53	EA
SL-4 SOYUZ	2355	6.74/2.66	Stage 2 Soyuz 11A511U-2 (Block I)	4	3	EA
SL-6 MOLNIYA	1160	3.20/2.40	Stage 3 Molniya 8K78M	105	3	EA
SL-8 KOSMOS	1435	6.0/2.40	Stage 2 2 Kosmos-1 (1575, 1589); 288 Kosmos-3M 11K65M	290	290	EA
SL-11/TSYKLON	400	2.5/2.0	Stage 3 Tsiklon-2 11K69	1	1	JANE
SL-12/PROTON	2440	6.3/3.7	Stage 4: Block-DM	210	3	IRG
SL-14/TSIKLON-3	1407	2.58/2.25	Stage 3: Tsiklon-3	110	110	JANE
SL-16/ZENIT-2	9000	11.5/3.9	Stage 2: Zenit-2	22	22	EA
SL-18/START-1	300	2.50/1.40	Stage 4: Start-1	3	3	EA
SL-19/ROKOT	1600	1.30/2.50	Stage 3: Rokot-3 Briz	9	8	EA
SL-23/ZENIT-3SL	2720	5.60/3.70	Stage 3: Zenit-3	6	0	EA
SL-24/DNEPR-1	2360	1.00/3.00	Stage 3: Dnepr	16	16	SF
SL-26/SOYUZ-FREGAT	930	1.55/3.35	Fregat upper stage	2	0	SF

SL-27/STRELA	725	0.50/2.50	APB upper stage	2	2	SF
SOZ (aux motor)	56			62	4	
BLOCK-DM	2440	6.3/3.7	Block-DM upper stage	32	0	IRG
BRIZ	2390	2.65/4.00	Briz-M upper stage	86	7	RSW
FREGAT	930	1.5/3.35	Fregat upper stage	19	0	SF
EUROPE						
DIAMANT-A /-B P4	68	2.0/0.7	Stage 3	6	6	AC
BLACK ARROW	87	1.2/0.7	Stage 3	1	1	AC
ARIANE 1	34	1.2/0.8	Stage 4: Mage 1	2	1	AC
ARIANE 2	1600	11.5/2.7	Stage 3	4	0	AC
ARIANE 3	1600	11.5/2.7	Stage 3	4	0	AC
ARIANE 44LP	1800	11.05/2.6	Stage 3: H10	10	0	
ARIANE 44L	1800	11.05/2.6	Stage 3: H10	19	0	
ARIANE 40	1800	11.05/2.6	Stage 3: H10	7	7	
ARIANE 42P	1800	11.05/2.6	Stage 3: H10	5	1	
ARIANE 44P	1800	11.05/2.6	Stage 3: H10	6	0	
ARIANE 42L	1800	11.05/2.6	Stage 3: H10	7	0	
ARIANE 5	2575	5.0/5.4	EPS stage in LEO	61	2	
AVUM	147	1.7/2.31	Vega upper stage	1	1	WIKI
IRIS	256	2.30/1.30	Solid rocket engine	1	1	
UNITED STATES						
SCOUT X-1	181	2.5/0.5	Stage 4: Altair 1A	1	1	AC
SCOUT X-4	37	2.5/0.6	Stage 4: Altair 2	8	8	AC
SCOUT B	25	2.5/0.6	Stage 4: Altair 3	3	2	AC
SCOUT B-1	25	2.5/0.6	Stage 4: Altair 3	3	3	AC
SCOUT A	37	2.53/0.64	Stage 4: Altair	10	10	AC
SCOUT A-1	37	2.53/0.64	Stage 4: Altair	1	1	AC
SCOUT D-1	25	2.5/0.6	Stage 4: Altair 3	2	2	AC
SCOUT G-1	25	2.5/0.6	Stage 4: Altair 3	9	9	AC
TITAN TRANSTAGE	1950	4.57/3.05	Titan Transtage	19	0	EA
TITAN 4B	4500	9.9/3.1	Stage 2: Titan 403B	1	1	AC
DELTA 1	30	1.83/0.46	Stage 3: X-248A-7	5	1	
DELTA 1	37	2.53/0.64	Stage 3: X-258	10	8	
DELTA 1	25	1.48/0.50	Stage 3: FW-4D	8	4	
DELTA 1	65	1.50/0.94	Stage 3: STAR-37D	9	0	
DELTA 1	83	1.70/0.94	Stage 3: STAR-37E	6	0	
DELTA 1	785	6.28/1.40	Stage 2: DELTA-E	3	3	
DELTA 1	784	6.28/1.40	Stage 2: DELTA-F	5	5	
DELTA 1	820	5.97/1.38	Stage 2: DELTA-P	21	20	
DELTA 1	950	5.89/1.70	Stage 2: DELTA-K	2	1	
DELTA 2	950	5.89/1.70	Stage 2: DELTA-K	32	25	
DELTA 2	232	2.04/1.24	Stage 3: PAM-D	20	1	
DELTA 2	82	1.70/0.94	Stage 3: STAR-37FM	1	0	
DELTA 4	2850	12.0/4.0	Stage 2: DCSS-4	9	0	

ATLAS AGENA D	673	7.09/1.52	Stage 2: Agena D	1	1	AC
ATLAS D	37	2.53/0.64	Stage 2: X-258	10	6	AC
ATLAS F BURNER	116	0.84/0.66	Stage 2: Burner 2	1	1	EA
ATLAS F	83	1.70/0.94	Stage 2: Star 37 E	2	0	EA
ATLAS 35 F	83	1.70/0.94	Stage 2: Star 37 E	1	0	EA
ATLAS 75 E	126	2.03/1.25	Stage 2: Star 48B	1	0	EA
ATLAS 14 E	126	2.03/1.25	Stage 2: Star 48B	1	0	EA
ATLAS 41 E	27	1.2/0.69	Stage 2: Star 27	1	1	EA
ATLAS 55 E	126	2.03/1.25	Stage 2: Star 48B	1	0	EA
ATLAS CENTAUR	2358	10.10/3.05	Stage 2: Centaur-B	1	1	EA
ATLAS CENTAUR	2631	9.60/3.05	Stage 2: Centaur-D, D1A, D1AR	23	1	EA
ATLAS 1 CENTAUR	1700	9.15/3.05	Stage 2: Centaur I	3	1	EA
ATLAS 2 CENTAUR	2053	10.10/3.05	Stage 2: Centaur II	5	0	EA
ATLAS 2A CENTAUR	2293	10.10/3.05	Stage 2: Centaur IIA	7	0	EA
ATLAS 2AS CENTAUR	2293	10.10/3.05	Stage 2: Centaur IIA	4	0	EA
ATLAS 3B CENTAUR	2130	11.68/3.05	Stage 2: Centaur IIIB	1	1	EA
ATLAS 5 CENTAUR	2026	12.68/3.05	Stage 2: Centaur V	12	0	EA
THOR ABLESTAR	590	5.9/1.4	Stage 2: Able-Star	12	12	AC
THOR AGENA B	867	7.1/1.5	Stage 2: Agena-B	4	4	AC
THOR AGENA D	673	7.09/1.52	Stage 2: Agena-D	6	5	EA
THOR ALTAIR	25	2.53/0.64	Stage 2: Altair 3	1	1	EA
THOR BURNER 2	116	0.8/0.7	Stage 3: Burner 2	15	14	AC
THOR BURNER 2A	115	0.4/0.7	Stage 3: Burner 2A	2	2	AC
THORAD AGENA D	673	7.09/1.52	Stage 2: Agena-D	3	3	EA
THORAD DELTA	83	1.70/0.94	Stage 3: Star 37E	1	0	EA
THORAD DELTA	113	2.27/1.38	Stage 2: TR-201	2	2	
FALCON 1	510	2.70/1.678	Stage 2	1	1	SLR
FALCON 9	4900	15.0/3.66	Stage 2	2	0	SF
IUS	700	3.15/2.34	Stage 1	9	0	WIKI
IUS	300	1.98/1.60	Stage 2	7	0	WIKI
TOS	1130	3.29/2.34	Solid rocket stage	1	0	AC
PEGASUS	203	2.08/0.97	Stage 3	21	20	EA
TAURUS	203	2.08/0.97	Stage 4	5	5	EA
MINOTAUR	203	2.08/0.97	Stage 4	3	3	SLR
VANGUARD	31	2.0/0.5	Stage 3	2	1	EA
IABS	275	0.68/2.90	Rocket stage	1	0	EA
ANIK (PAM-D)	232	2.04/1.24	PAM-D rocket stage	4	0	EA
ARABSAT (PAM-D)	232	2.04/1.24	PAM-D rocket stage	1	0	EA
ASC (PAM-D)	232	2.04/1.24	PAM-D rocket stage	1	0	EA
AURORA (PAM-D)	232	2.04/1.24	PAM-D rocket stage	1	0	EA
INMARSAT (PAM-D)	232	2.04/1.24	PAM-D rocket stage	1	0	EA
INSAT (PAM-D)	232	2.04/1.24	PAM-D rocket stage	1	0	EA

MARCOPOLO (PAM-D)	232	2.04/1.24	PAM-D rocket stage	1	0	EA
MORELOS (PAM-D)	232	2.04/1.24	PAM-D rocket stage	2	0	EA
NATO (PAM-D)	232	2.04/1.24	PAM-D rocket stage	1	0	EA
OPTUS (STAR 63F)	326	1.78/1.60	Star 63F rocket stage	3	0	EA
PALAPA (PAM-D)	232	2.04/1.24	PAM-D rocket stage	1	0	EA
SATCOM (PAM-D2)	431	1.8/1.6	PAM-D2 rocket stage	2	0	EA
SBS (PAM-D)	232	2.04/1.24	PAM-D rocket stage	2	0	EA
SKYNET (PAM-D2)	431	1.8/1.6	PAM-D2 rocket stage	1	0	EA
SPACENET (PAM-D)	232	2.04/1.24	PAM-D rocket stage	1	0	EA
TELSTAR (PAM-D)	232	2.04/1.24	PAM-D rocket stage	2	0	EA
CHINA						
CZ-2C	4000	7.50/3.35	Stage 2	13	13	EA
CZ-2C	?	?	SD/CTS dispenser stage	1	0	EA
CZ-2D	4000	10.41/3.35	Stage 2	5	5	EA
CZ-3	2000	7.48/2.25	Stage 3	5	0	EA
CZ-3B	2800	12.38/3.00	Stage 3	8	0	EA
CZ-3A	2800	12.38/3.00	Stage 3	7	0	EA
CZ-3C	2800	12.38/3.00	Stage 3	4	0	EA
CZ-4	2000	6.24/2.90	Stage 3	7	7	SLR
CZ-4B	2000	6.24/2.90	Stage 3	12	12	SLR
CZ-4C	2000	6.24/2.90	Stage 3	14	14	SLR
JAPAN						
H-1	1800	10.32/2.49	Stage 2	2	2	EA
H-1	360	2.34/1.34	Stage 3	1	0	EA
H-2	2700	10.60/4.00	Stage 2	3	1	EA
H-2A	3000	9.20/4.0	Stage 2	13	5	EA
N-1	63.5	1.70/0.94	Stage 3: Star 37N	4	4	EA
N-2	83.1	0.84/0.66	Stage 3: Star 37E	2	1	EA
M-3H	130	2.30/1.14	Stage 3: M-3A	1	0	EA
M-4S	73	1.80/0.79	Stage 4: M-40	2	2	EA
M-5	1000	3.60/2.20	Stage 3: M-34	1	0	EA
EPSILON	800	2.3/1.4	Stage 3: KM-V2b	1	1	SF
INDIA						
PSLV	920	2.60/1.34	Stage 4	21	15	EA
IRS (PSLV)	920	2.60/1.34	Stage 4	1	1	
SOUTH KOREA						
KSLV-1	200	2.4/1.0	Stage 2: KARI	1	1	SLR
NORTH KOREA						

UNHA 3	300	3.70/1.20	Stage 3	1	1	SLR

References

EA – Mark Wade's Encyclopedia Astronautica: http://www.astronautix.com/
Gunter's Space Page: http://space.skyrocket.de/
SLR – Space Launch Report: http://www.spacelaunchreport.com/
SF – Spaceflight101- Launch Vehicle Library: http://www.spaceflight101.com/launch-vehicle-library.html
RSW – Russian Space Web: http://www.russianspaceweb.com/rockets_launchers.html
AC – Encyclopedia Astronautica: http://www.friends-partners.org/partners/mwade/spaceflt.htm
WIKI – Encyclopedia Wikipedia: https://it.wikipedia.org/
Rocket and Space Technology: http://www.braeunig.us/space/
IRG – International Reference Guide to Space Launch Systems, 4th edition, 2004
JANE – IHS Jane's Space Systems & Industry, 2012-2013

Among 1682 unclassified upper stages, 821, i.e. approximately 49%, were in LEO (Table 2). The associated total mass was 2706 metric tons, of which 1199 metric tons, i.e. about 44%, in LEO (Table 2). The average rocket body mass was 1609 kg, and 1460 kg for those upper stages with a mean altitude ≤ 2000 km.

Table 2: Geopolitical distribution of rocket bodies and associated masses

	Total Number	**Number in LEO**	**Total Mass [kg]**	**Mass in LEO [kg]**
Russian Federation & Ukraine	1032	525	1,848,692	915,349
United States	386	191	313,522	87,263
Europe	134	20	268,041	20,482
China	76	51	201,200	138,000
Japan	30	16	53,556	22,583
India	22	16	20,240	14,720
North Korea	1	1	300	300
South Korea	1	1	200	200
Total	**1682**	**821**	**2,705,751**	**1,198,897**

Concentrating the attention on the rocket bodies contributing with at least 20 metric tons to the mass in LEO (as of 7 January 2015), it was found that they belong to just nine types, listed in Table 3, accounting for nearly 73% of the stages and nearly 88% of the mass. Concerning the development of active removal technologies, this fact is extremely relevant, because having to face the retrieval and de-orbiting of objects belonging to a few basic models, often placed in similar orbits, would present a lot of obvious advantages [15] [16] [17].

4. Ranking of selected upper stages

The ranking scheme introduced in Section 2 was therefore applied to the models of rocket bodies present with more than 50 objects in LEO. In addition, due to their very large mass (see Tables 1 and 3), the second stages of the Zenit-2 (SL-16) launcher were included as well in this preliminary analysis (Table 4). The subset of rocket bodies analyzed

so far accounted for approximately 64% of the stages and 73% of the mass in LEO, then representing a quite significant sample.
The orbital distribution of the stages listed in Table 4 is shown in Figures 1, 2, 3, 4 and 5. As can be seen, more than 90% of them had inclinations higher than 70°. The flux of cataloged debris on each of the rocket bodies was estimated with the Space Debris Impact Risk Analysis Tool (SDIRAT) [18] [19] [20] and the associated ranking was computed using Eq. (6) and Eq. (7).
As summarized in Table 4, the 22 Zenit-2 second stages resulted equivalent to nearly 811 average intact objects into an 800 km sun-synchronous orbit, with a mean $R_N \cong 37$ per object. The latter figure was equivalent to the overall ranking of either 110 Tsiklon-3 third stages or 53 Vostok second stages. The two top values of R_N, 64.49 and 57.04, were associated with the cataloged objects 20625 and 17590, respectively, at an altitude of approximately 840 km and with an inclination of 71°, while the ranking decreased to just 2.24 for the Zenit-2 stage 25861, at 630 km and with an inclination of 98° (Figure 6).

Table 3: Upper stage models accounting for ≥ 20 metric tons in LEO

	Number in LEO	**Mass in LEO [kg]**
Kosmos (SL-8) Second Stage	290	416,150
Zenit-2 (SL-16) Second Stage	22	198,000
Tsiklon-3 (SL-14) Third Stage	110	154,770
CZ-4 Third Stage	33	66,000
Vostok (SL-3) Second Stage	53	58,300
CZ-2C Second Stage	13	52,000
Delta 1 & 2 Second Stage	54	47,375
Dnepr-1 (SL-24) Third Stage	16	37,760
CZ-2D Second Stage	5	20,000
Total	**596 (72.6%)**	**1,050,355 (87.6%)**

The 290 Kosmos second stages resulted equivalent to approximately 239 average intact objects into an 800 km sun-synchronous orbit, with a mean $R_N = 0.82$ per object. 108, i.e. more than 37%, had both R_N and $R_{NL} > 1$, 44 with inclination of 74° and 64 with inclination of 83°. They were concentrated between 750 and 1000 km (Figure 7). The top value of R_N, 1.83, was associated with the cataloged object 13992, at an altitude of approximately 770 km and with an inclination of 74° (Figure 7).
The 110 Tsiklon-3 third stages, on the other hand, resulted equivalent to just 38 average intact objects into an 800 km sun-synchronous orbit, with a mean $R_N = 0.34$ per object. Only 5 rocket bodies, between 944 and 948 km and with an inclination close to 82.5°, had both R_N and $R_{NL} > 1$ (Figure 7). The top value of R_N, 1.56, was associated with the cataloged object 17291, at an altitude of approximately 945 km (Figure 7).
Also the 53 Vostok second stages resulted equivalent to a nearly identical number of reference objects, i.e. 37, with a mean $R_N = 0.70$ per object. 23 rocket bodies, between 800 and 900 km and with an inclination of 81°, had both R_N and $R_{NL} > 1$ (Figure 7). The two top values of R_N, 1.76 and 1.75, were associated with the cataloged objects 7210 and 8027, at 847 and 866 km, respectively (Figure 7).

Table 4: Upper stages in LEO ranked in this paper

	Number in LEO	Mass in LEO [kg]	Total R_N	Mean R_N
Kosmos (SL-8) Second Stage	290	416,150	239.12	0.82
Zenit-2 (SL-16) Second Stage	22	198,000	810.75	36.85
Tsiklon-3 (SL-14) Third Stage	110	154,770	37.59	0.34
Vostok (SL-3) Second Stage	53	58,300	37.12	0.70
Delta 1 & 2 Second Stage	54	47,375	11.47	0.21
Total	**529 (64.4%)**	**874,595 (72.9%)**	**1136.05**	**2.15**

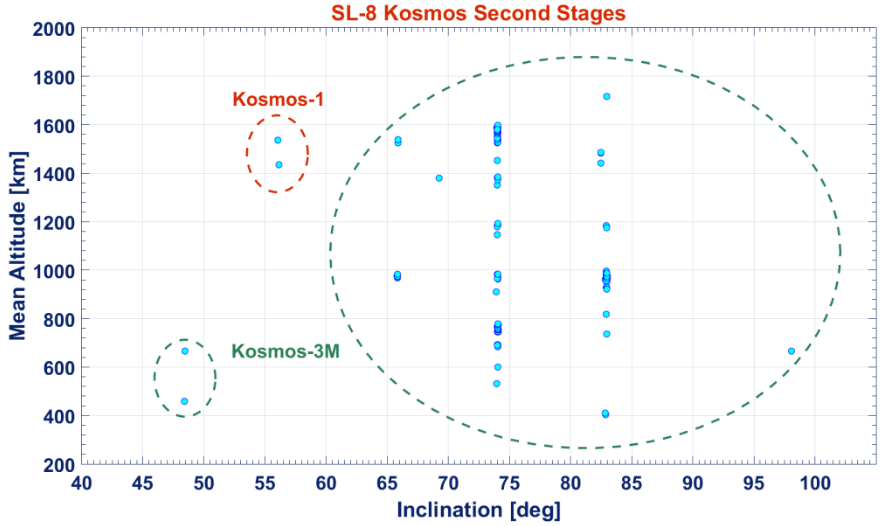

Figure 1: Orbital distribution of Kosmos (SL-8) second stages

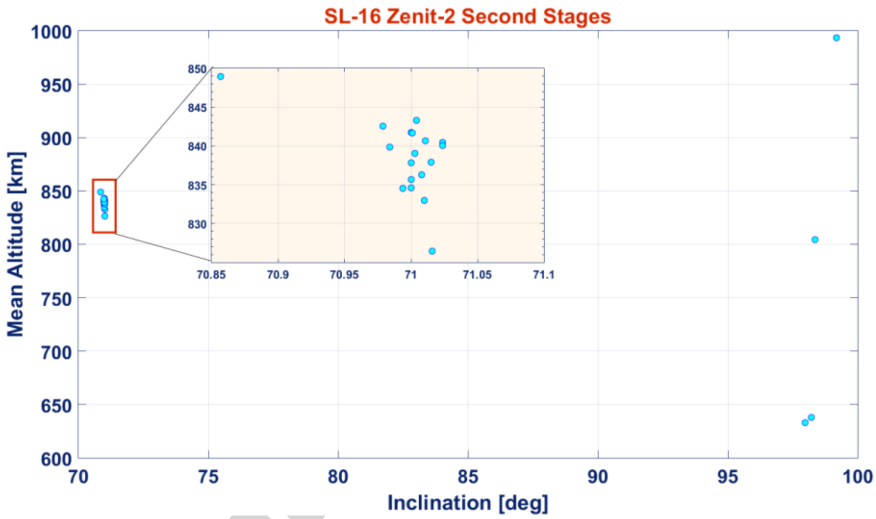

Figure 2: Orbital distribution of Zenit-2 (SL-16) second stages

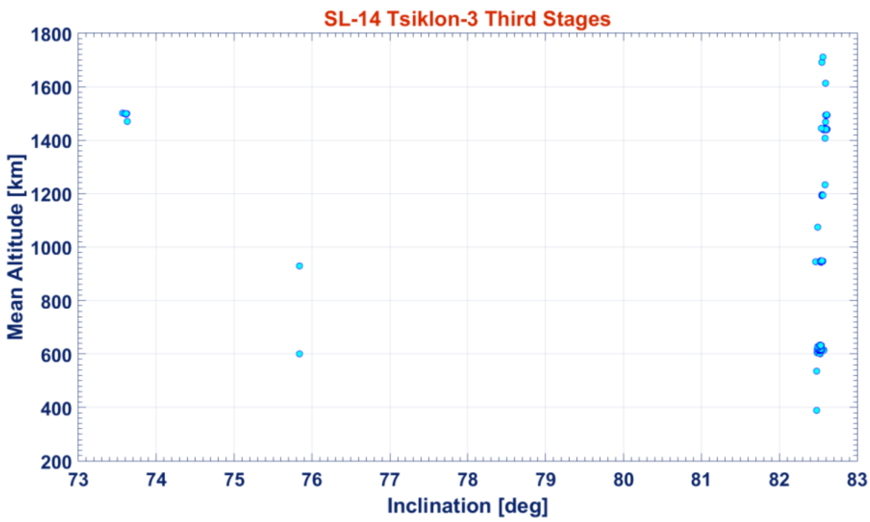

Figure 3: Orbital distribution of Tsiklon-3 (SL-14) third stages

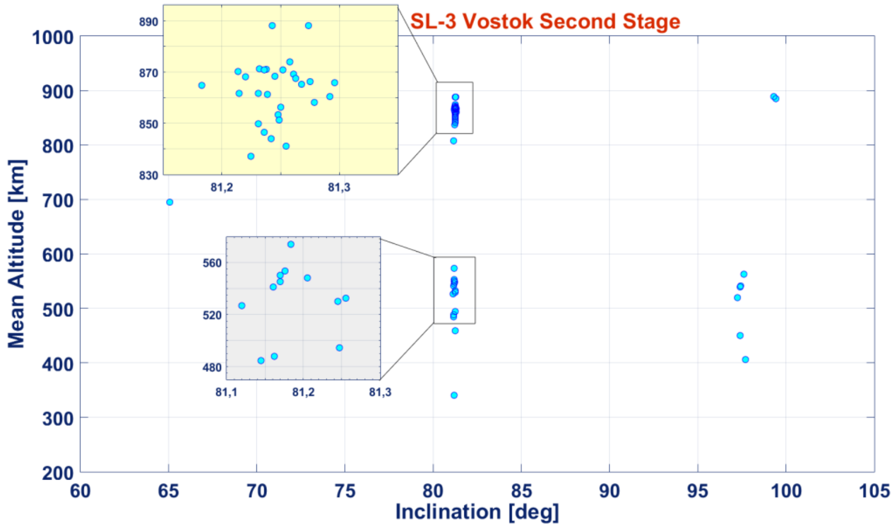

Figure 4: Orbital distribution of Vostok (SL-3) second stages

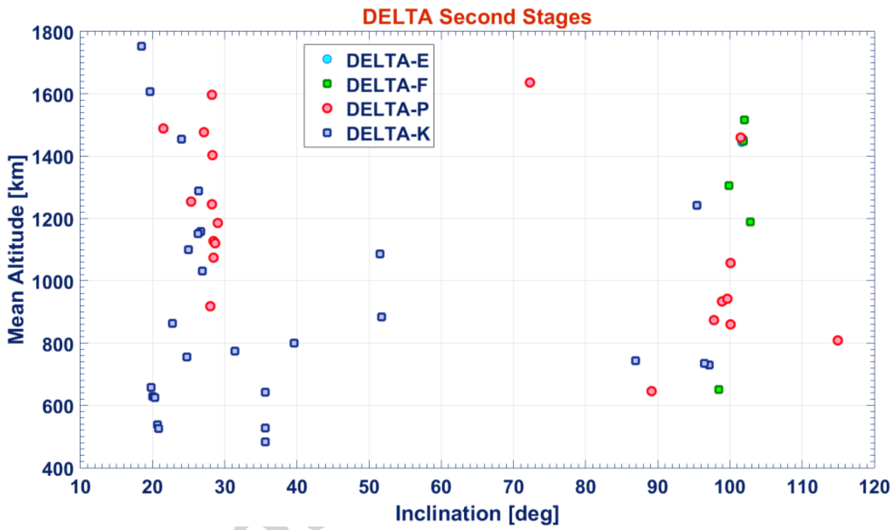

Figure 5: Orbital distribution of Delta 1 and 2 second stages

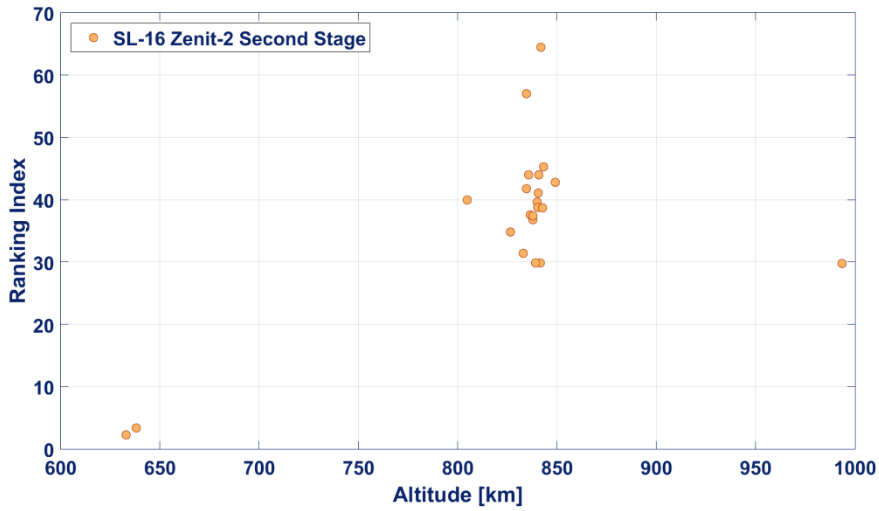

Figure 6: Ranking index R_N evaluation for the Zenit-2 (SL-16) second stages

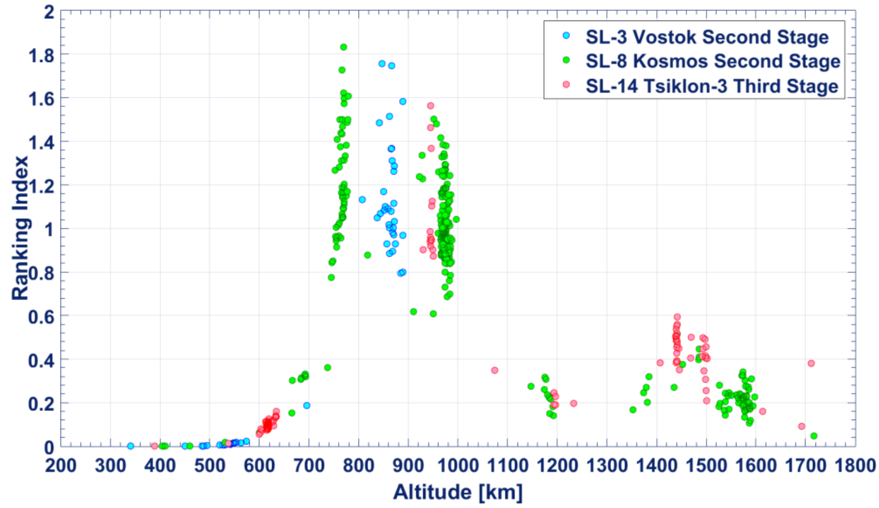

Figure 7: Ranking index R_N evaluation for the Vostok (SL-3), Kosmos (SL-8) and Tsiklon-3 (SL-14) upper stages

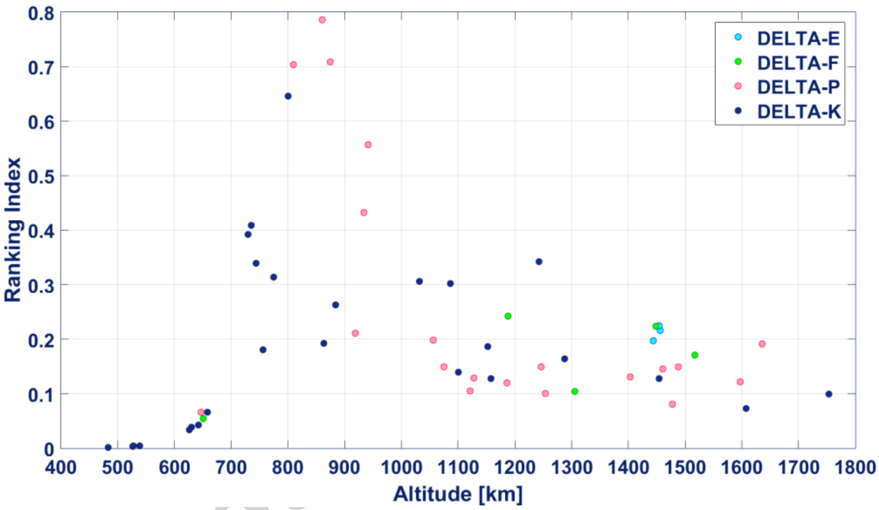

Figure 8: Ranking index R_N evaluation for the Delta 1 and 2 second stages

Finally, the 54 Delta 1 and 2 second stages resulted equivalent to approximately 11 average intact objects into an 800 km sun-synchronous orbit, with a mean R_N = 0.21 per object. None of them had R_N > 1, with a top value of 0.79 associated with the Delta P rocket body 13778, at an altitude of approximately 861 km and with an inclination of 100° (Figure 8). The 5 stages with R_N > 0.50 were found between 800 and 950 km (Figure 8).

5. Conclusions

The proposed ranking scheme was preliminarily applied to 529 rocket bodies in LEO, belonging to just 5 types, but accounting for more than 64% of the total number and nearly 73% of the total mass of upper stages with a mean altitude below 2000 km. In terms of debris environment criticality, the sample analyzed was cumulatively equivalent to 1136 average intact objects into an 800 km sun-synchronous orbit, with a mean R_N = 2.15 per object. The environmental criticality was largely dominated by the 20 massive Zenit-2 second stages between 800 and 1000 km, followed by the Kosmos second stages, mainly between 750 and 1000 km, by the Tsiklon-3 third stages, around 950 km, by the Vostok second stages, between 800 and 900 km, and by the Delta 1 and 2 second stages, broadly scattered between 700 and 1800 km (Figures 6, 7 and 8). A further significant presence of Kosmos and Tsiklon-3 upper stages, even though quite lesser in terms of criticality ranking, was found between 1350 and 1600 km.
Of course, any ranking scheme, as that described in this paper, represents a coarse simplification of a problem, namely the definition of the environmental criticality of an orbiting object immersed in an evolving debris

population, which is affected by considerable uncertainties. It should be therefore handled with care, in particular when using the ranking results in absolute terms. However, for the relative comparison of the environmental criticality of homogeneous classes of objects, as the rocket body types analyzed in this paper, the results obtained can be considered quite reliable, significant and easy to understand, in spite of the simplifying assumptions adopted and the many underlying uncertainties.

References

[1] Liou, J.-C., and N.L. Johnson. 2009. A sensitivity study of the effectiveness of active debris removal in LEO. *Acta Astronautica* 64:236–243.

[2] Liou, J.-C. 2011. An active debris removal parametric study for LEO environment remediation. *Advances in Space Research* 47:1865–1876.

[3] Utzmann, J., M. Oswald, S. Stabroth, P. Voigt, A. Wagner, and I. Retat. 2012. Ranking and characterization of heavy debris for active removal. In: *Proceedings of 63rd International Astronautical Congress*. Paper IAC-12-A6.2.8.

[4] DeLuca, L.T., M. Lavagna, F. Maggi, P. Tadini, C. Pardini, L. Anselmo, M. Grassi, U. Tancredi, A. Francesconi, S. Chiesa, N. Viola, and C. Bonnal. 2013. Active removal of large massive objects by hybrid propulsion module. In: *5th European Conference for Aero-Space Sciences*, Paper p469.

[5] Anselmo, L., and C. Pardini. 2014. Compliance of the Italian satellites in low earth orbit with the end-of-life disposal guidelines for space debris mitigation. In: *Proceedings of 65th International Astronautical Congress*. Paper IAC-14-A6.4.5.

[6] Radtke, J., S.K. Flegel, S. Roth, and H. Krag. 2014. Deriving the spacecraft environment criticality from Monte-Carlo simulations of the space debris environment. In: *Proceedings of 65th International Astronautical Congress*. Paper IAC-14-A6.2.6.

[7] Rossi, A., G.B. Valsecchi, and E.M. Alessi. 2014. An evaluation index for the ranking of LEO objects. In: *Proceedings of 65th International Astronautical Congress*. Paper IAC-14-A6.2.7.

[8] Rossi, A., G.B. Valsecchi, and E.M. Alessi. 2015. The criticality of spacecraft index. *Advances in Space Research* 56:449–460.

[9] IADC Steering Group & Working Group 4 (Mitigation). 2007. IADC space debris mitigation guidelines. Document IADC-02-01, Revision 1. Inter-Agency Space Debris Coordination Committee (IADC).

[10] Chobotov, V.A. (Ed.) 2002. *Orbital Mechanics*. Third Edition. American Institute of Aeronautics and Astronautics, Inc., Reston, Virginia, pp. 315–316.

[11] Dolado-Perez, J.C., C. Pardini, and L. Anselmo. 2015. Review of uncertainty sources affecting the long-term predictions of space debris evolutionary models. *Acta Astronautica* 113:51–65.

[12] Pardini, C., and L. Anselmo. 2014. Review of past on-orbit collisions among cataloged objects and examination of the catastrophic fragmentation concept. *Acta Astronautica* 100:30–39.

[13] Johnson, N.L., P.H. Krisko, J.-C. Liou, and P.D. Anz-Meador. 2001. NASA's new breakup model of EVOLVE 4.0. *Advances in Space Research* 28:1377–1384.

[14] Krisko, P.H. 2011. Proper implementation of the 1998 NASA breakup model. *Orbital Debris Quarterly News* 15.4:4–5.

[15] De Luca, L.T., F. Bernelli, F. Maggi, P. Tadini, C. Pardini, L. Anselmo, M. Grassi, D. Pavarin, A. Francesconi, F. Branz, S. Chiesa, N. Viola, C. Bonnal, V. Trushlyakov, and I. Belokonov. 2013. Active space debris removal by hybrid engine module. *Acta Astronautica* 91:20–33.

[16] Tadini, P., U. Tancredi, M. Grassi, L. Anselmo, C. Pardini, A. Francesconi, F. Branz, F. Maggi, M. Lavagna, L.T. DeLuca, N. Viola, S. Chiesa, V. Trushlyakov, and T. Shimada. 2014. Active debris multi-removal mission concept based on hybrid propulsion. *Acta Astronautica* 103:26–35.

[17] De Luca, L.T., M. Lavagna, F. Maggi, P. Tadini, C. Pardini, L. Anselmo, M. Grassi, U. Tancredi, A. Francesconi, D. Pavarin, F. Branz, S. Chiesa, and N. Viola. 2014. Large debris removal mission in LEO based on hybrid propulsion. *Aerotecnica Missili & Spazio, The Journal of Aerospace Science, Technology and Systems* 93:51–58.

[18] Pardini, C., and L. Anselmo. 1998. Space debris impact risk analysis tool (SDIRAT). Report CNUCE-B4-1998-015. CNUCE Institute, CNR, Pisa, Italy.

[19] Pardini, C., and L. Anselmo. 1999. Assessing the risk of orbital debris impact. *Space Debris* 1:59–80.

[20] Pardini, C., and L. Anselmo. 2000. SDIRAT: Introducing a new method for orbital debris collision risk assessment. In: *Proc. of the International Symposium on Space Dynamics*. Paper MS00/23.

Highlights

- The upper stages abandoned in orbit were categorized in detail in terms of number, mass and orbital distribution.
- The types contributing to a significant amount of the mass and number in LEO were identified.
- A new ranking index was applied to estimate their long-term criticality for the orbital debris environment.
- The ranking obtained could also be used for active removal priority listing.