MULTIPLE REMOVAL OF SPENT ROCKET UPPER STAGES WITH AN ION BEAM SHEPHERD

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ABSTRACT

Among the many advantages of the recently proposed ion beam shepherd (IBS) debris removal technique is the capability to deal with multiple targets in a single mission. A preliminary analysis is here conducted in order to estimate the cost in terms of spacecraft mass and total mission time to remove multiple large-size upper stages of the Zenit family. Zenit-2 upper stages are clustered at 71 degrees inclination around 850 km altitude in low Earth orbit. It is found that a removal of two targets per year is feasible with a modest size spacecraft. The most favorable combinations of targets are outlined.

1. INTRODUCTION

About 2,500 tons of debris material, divided into retired spacecraft, rocket bodies, break-up fragments and non-fragmentation sources (e.g. solid rocket motor effluents), surrounds the Low Earth Orbit (LEO) region. Collisions of debris objects with active spacecraft as well as with other debris have occurred and are expected to increase posing a serious threat for space activities in the near future.

The size distribution of the LEO debris objects follows roughly a power law where the number of fragments rises steeply with decreasing size. As a consequence, the direct threat to active spacecraft is nearly entirely dominated by small untracked fragments ('shrapnels') producing non-catastrophic collisions. These objects are too small to be routinely and accurately tracked with today's infrastructure but still heavy enough to be lethal for a spacecraft [3].

On the other hand, the potential long-term orbital environment degradation is due to collision involving large objects. These catastrophic collisions will in the end feed the small fragments population that threatens space assets. Ultimately, as it is widely recognised, the root of the space debris problem is due to potential large (i.e. ton-class) objects collisions. Hence, any proposal to tackle the space debris problem will face the challenge of removing a certain amount of properly selected ton-class objects by deorbiting them or by repositioning them in uncrowded orbital regions. The extent of such an amount will depend on the desired impact in terms of reducing future collisions in LEO . Some analyses have advocated the removal of "five large objects per year" as the minimum necessary effort for the stabilisation of the LEO environment. However, the mass of the objects to be removed was not specified making it a somewhat "ambiguous recipe". The removal of an average "7-tons of large objects material per year" was once proposed at a conference attended by one of these authors.

By looking at the taxonomy of resident debris objects[1] one immediately realizes that the quasi totality of the LEO debris mass is concentrated into objects with mass larger than 200 kg and that objects greater than 1 ton make up more than about 75% of the total LEO mass. That means that whatever removal concept is adopted, it must demonstrate the capability to deal with a typical ton-class object or larger. These objects concentrate at LEO altitude peaks of 950-1000 km and 800-850 km and around specific inclinations (82, 98, 71, 75 deg). The necessary deorbiting impulse will need to be provided with some means (electric vs. chemical propulsion, propellantless methods), at a given cost in terms of required mass, and transmitted to the body (with contactless, docking or capturing methods) without the risk of creating extra debris and by proper control of the system throughout the descending manoeuvre. Finally, the necessary measures to deal with removal permission, international coordination and transparency, liabilities issues, will need to be discussed. The three key challenges of active debris removal can then be summarised as:

1. Need for an economically viable removal solution of properly selected targets
2. Minimization of operation risks to avoid failures
3. Need for an appropriate legal and policy framework.

The present article addresses the first two challenges and the ability of the recently proposed ion beam shepherd concept (IBS) to deal with them.

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[1] All the debris data employed here were kindly provided by ESA Space Debris Office through DISCOS.

Proc. '6th European Conference on Space Debris'
Darmstadt, Germany, 22–25 April 2013 (ESA SP-723, August 2013)

Table 1. Major upper stage families currently in orbit

upper stage	*mass [ton]*	n° *in orbit*	*tot mass [ton]*
Cyclone-3	*1.39*	*110*	*153*
Zenit-2	*8.23*	*22*	*181*
Kosmos-3M	*1.42*	*296*	*421*
TOTAL		*428*	*755*

2. UPPER STAGES AS IDEAL REMOVAL TARGETS

About half of the total (˜2,500 tons) LEO debris mass is composed by rocket upper stages clustered in high inclination orbital regions.

By looking more closely at the LEO objects population heavier than 1-ton we find about 63% of their total mass concentrated into launchers upper stages. Overall, upper stages make up about 47% of the *total* LEO debris mass. Furthermore, about 64% of the total LEO upper stage mass, or equivalently about 30% of the total debris mass in LEO is grouped into only three families: Cyclone-3, Zenit-2 and Kosmos-3M (Table 1) designed by the great soviet engineer Mikhail Yangel at the Yuzhnoye Space Design Office (SDO) in present Ukraine.

Upper stages are ideal candidates for the implementation of large-scale debris removal operations for at least three main reasons:

1. A successful technology demonstration mission aimed at a few targets could open the way towards the removal of hundreds of tons of debris material in the future.
2. Upper stages families are clustered at specific inclinations, which makes it possible to implement multiple removal operations (if the removal technology allows multiple uses).
3. Upper stages are less affected by confidentiality issues complicating removal operations at international level.

Among the different upper stage families listed in table 1 we here focus on the Zenit-2 family as its members are the most likely to undergo a collision (due to their large cross section) with the worst consequences for the LEO environment (due to the large fragmented debris mass that would be left in orbit).

The characteristics of the 22 Zenit upper stages left in orbit are reported in Table 2 with reference to the epoch 01-Jan-2017 at midnight.

Table 2. Zenit-2 upper stages currently in orbit

n	*ID*	*h (km)*	*i (deg)*	*e*	Ω *(deg)*
1	16182	835	71.0	0.0009	0.6
2	17590	837	71.0	0.0003	144.7
3	17974	834	71.0	0.0015	264.2
4	19120	826	71.0	0.0022	319.9
5	19650	839	71.0	0.0015	8.9
6	20625	841	71.0	0.0017	140.5
7	22220	836	71.0	0.0011	53.3
8	22285	841	71.0	0.0007	204.8
9	22566	839	71.0	0.0012	58.0
10	22803	835	71.0	0.0018	243.0
11	23088	841	71.0	0.0005	274.0
12	23343	635	98.2	0.0006	35.4
13	23405	839	71.0	0.0001	207.7
14	23705	842	71.0	0.0010	22.3
15	24298	848	70.9	0.0018	57.0
16	25400	805	98.3	0.0011	302.1
17	25407	839	71.0	0.0008	35.3
18	25861	629	97.9	0.0015	315.9
19	26070	841	71.0	0.0016	311.0
20	27006	994	99.1	0.0014	138.8
21	28353	841	71.0	0.0005	69.1
22	31793	843	71.0	0.0003	22.6

3. A KEY TECHNOLOGY FOR ACTIVE DEBRIS REMOVAL

The ion beam shepherd (IBS)[1] is a contactless debris removal concept that exploits the momentum of the accelerated ions to produce a force on a nearby target body by pointing the thruster exit towards it . The ions reaching the target surface penetrate in the material substrate until they stop as a result of nuclear collisions, transfer their momentum, and generate an action force, which does not require mechanical contact with the target. In order to produce a continuous "contactless" actuation on the target the shepherd satellite must employ at least two propulsion systems: a primary Impulse Transfer Thruster (ITT) pointed at the target and a secondary Impulse Compensation Thruster (ICT) generating a counteractive force on the shepherd in order to avoid the latter from accelerating away.

As an active debris removal device, the IBS concept offers a number of key advantages outlined below:

1. Deorbit efficiency. The mass needed to produce the deorbit impulse is minimised thanks to the use of high specific impulse electric propulsion. For instance, roughly 260 m/s delta-V are needed to have a debris spiraling down from a 1000 km to a 500 km altitude circular orbit (to then reenter naturally within a 25-year time frame). For a 8,250 kg

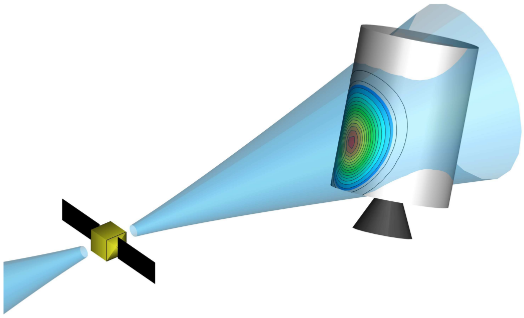

Figure 1. IBS concept for active space debris removal.

Zenit-2 upper stage, and employing two oppositely thrusting ion engines with a 3500 s specific impulse, that would correspond to about 150 kg of Xenon, just ˜1.8% of the total debris mass. A comparable mass would need to be allocated for the power system considering a reasonably large thrust (75 mN for each thruster, requiring an estimated total 4 kW power) leading to a 12 months total deorbit time. After adding margins, structural weight and subsystems (thermal control, reaction control and mechanisms, communications, data handling etc.) the final spacecraft mass would very likely not exceed the 500 kg envelope, that is less than 6% of the debris mass. For a comparison, a targeted reentry to a 50 km perigee orbit of the same debris performed with a chemical propulsion system would need about 850 kg mass just for propellant.

2. Low risk. Because no mechanical contact is required to transfer the deorbiting impulse and the IBS can work at a safe distance from the (non-cooperative possibly tumbling/rotating) debris the risk of collisions, with consequent generation of extra debris or even spacecraft failure, is greatly reduced.

3. Adaptability. An impinging ion beam transfers its linear momentum independently of the particular debris shape or material as long as there is a proper beam overlap with the debris envelope. For a debris of generic shape and size, this can be achieved by simply placing the shepherd at the correct distance (based on the ion beam divergence) and correctly pointing the beam towards the debris. This makes the IBS adaptable to any type of large-size debris (upper stages and payloads) without specific design modification. That represents a crucial advantage with respect to docking/capturing methods, which tend to be target-dependent.

4. Reusability. Neglecting spacecraft parts degradation, the IBS has only one expendable element: propellant. But thanks to the high specific impulse characterising ion thrusters fuel expenditures are drastically reduced and multiple removal operations are possible. As a matter of fact, it is the multiple removal operation capability that increases the IBS efficiency compared to other solutions. Chemical propulsion system can be hardly reused due to the exponential dependence of Tsiolkovsky's rocket equation exacerbated by the low specific impulse. A solar sail cannot reboost itself in LEO (due to the large drag pressure compared to solar pressure). An electrodynamic tether could reboost itself but would need to carry a dedicated power plant.

5. Manoeuvrability. The ability to manoeuvre the shepherd spacecraft during the transfer to the target and the shepherd+target system during the deorbiting phase is crucial in order to reduce both mission costs and collision risks. In order to make a debris removal mission economically viable it is very attractive to have the removal spacecraft flying as a secondary payload. However, that places important constraints on the destination orbit: eventually the spacecraft will need to have the capability to orbital manoeuvring to transfer itself to the selected target and to do so in an efficient way. In addition, impacts between the debris and other objects during the deorbiting phase have to be avoided at all costs and that requires sufficient collision avoidance capability throughout the descent. Unlike other deorbiting concepts the IBS has full and efficient manoeuvrability in all directions, as it hosts high efficiency ion thrusters that facilitate all types of orbital changes (altitude change, inclination adjustment, rendezvous operations, collision avoidance).

6. Technology readiness. A high technology readiness level (TRL) for all spacecraft components is important as it drastically reduces development risk (budget and schedule). Altogether the IBS spacecraft is of conventional design except for the propulsion system (which is employed in a different way than usual) and the guidance control and navigation (GNC) system (which requires high performance). The core of the IBS technology is represented by ion thrusters already flown in Earth orbits and interplanetary space. As far as GNC, high performance sensors have been flown on past missions (e.g. GSFC Relative Navigation Sensor System tested on board STS Atlantis in 2009, Neptec´s Tridar tested on board ISS in 2009).

4. FULL DEORBITING VS. REPOSITIONING

Whatever removal campaign is employed, be it a "5 large object per year" or a "7-ton per year" strategy, the impact in terms of removal cost rapidly escalates in time and becomes overwhelming after just a few years. While high deorbit efficiency, reusability for multiple removal operations and secondary payload opportunities greatly reduce such cost a tradeoff between complete removal and repositioning to uncrowded orbital regions could provide an additional cost saving opportunity to be seriously considered.

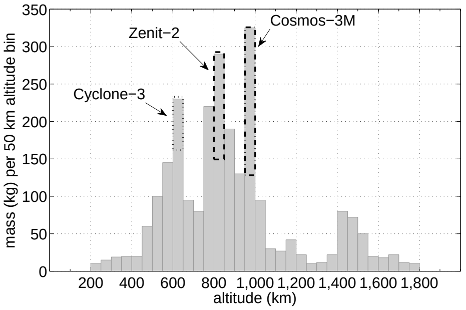

Figure 2. Current object mass distribution (adapted from [4]).

If one looks at the current object mass distribution in LEO (figure 2) there appear to be three major high mass density regions at altitudes of 600-650 km, 800-850 km and 950-1000 km. Ukrainian and Russian-made upper stages launched during the Soviet era dominate or greatly contribute to the size of these peaks. In addition, one can immediately notice the existence of relatively uncrowded orbit altitudes between these peaks at 650-750 km and around 900-950 km.

Now, because the ultimate goal of an active debris removal campaign is to stabilise the LEO environment reducing as much as possible the likelihood of future collisions one can argue that a much cheaper repositioning of large quantities of debris objects in nearby uncrowded regions should be traded off with a comparably much more expensive full removal. Apart from the dramatic cost reduction of repositioning one can add that the second option does not rule out the possibility to accomplish the first at a later stage of technology development and with a reduced delta-V cost (if the debris are repositioned to a lower altitude). Finally, a massive repositioning campaign can leave open the option of in-orbit debris recycling [2].

Figure 3 shows a possible redistribution of the LEO object mass that could be achieved by moving a total 70 ton mass of Zenit-2 upper stages from ˜825 to ˜725 km altitude (at a price of ˜64 m/s of ΔV) and 95 tons of Cosmos-3M upper stages from ˜975 to ˜925 km altitude (˜25 m/s of ΔV).

5. MULTIPLE REMOVAL OF ZENIT-2 UPPER STAGES

An optimisation analysis for the removal of multiple Zenit-2 upper stages is now conducted. At this preliminary level of study only the removal of 2 subsequent targets is treated, which keeps the analysis more simple and compact. The generalisation to the removal of N targets will be dealt with in the future.

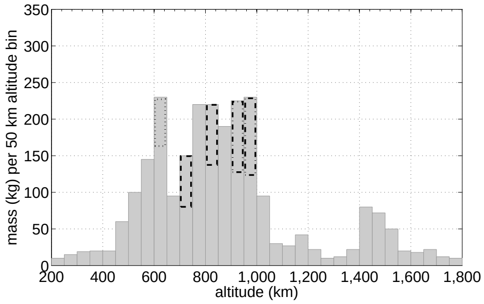

Figure 3. Object mass distribution after repositioning.

5.1. Removal scheme

The proposed removal scheme assumes that the IBS spacecraft is coorbiting with a first selected target and start deorbiting at the reference epoch of January 1st 2017 at midnight GMT. For simplicity all debris orbits are considered circular and external perturbations neglected except the J2 acceleration and the deorbit force of the beam, which, again for simplicity, is assumed constant along the orbit and is applied continuously until the object is transferred to a selected destination orbit with no change of inclination performed. The achievable thrust will depend of the selected thruster and is scaled down by introducing a beam momentum transfer efficiency factor of 90% and a solar illumination efficiency factor of 66% typical of a 71 deg inclination 850 km altitude orbit.

Once the destination orbit is reached the IBS stays in this orbit for a waiting time period Δt_w until the precession induced by the J2 perturbation is such that by the time it takes to the IBS to reach the orbit of the subsequent target the line of nodes of the IBS orbit and the target orbit will overlap. After the waiting time Δt_w the IBS is maneuvered to reach the altitude of the second target with the required inclination change following a quasi-optimal Edelbaum thrust steering strategy. The second target is finally transferred to the same target altitude of the first.

5.2. Optimisation performance index

The selected optimisation performance index proposed here (to be maximised) is defined as:

$$J = \frac{m_{deb}/m_{fuel}}{\Delta t_{tot}/\Delta t_{ref}},$$

where $m_{deb} = m_1 + m_2$ is the total debris mass removed, m_{fuel} is the total fuel mass spent, Δt_{tot} is the total ma-

Table 3. Highest ranking Zenit-2 pairs for removal to a 725 km altitude orbit

n_1	n_2	J	Δt_{tot}(days)	Δt_w(days)	m_{fuel} (kg)
4	19	532	271.6	6.7	29.9
5	1	399	266.8	7.1	33.2
11	3	365	281.2	20.3	33.9
17	22	360	321.0	39.1	33.4
17	14	346	304.9	37.7	33.4
7	17	325	342.0	80.6	32.5
14	5	323	315.8	48.9	34.0
21	9	319	297.4	19.5	36.9
3	10	307	377.5	124.5	31.8
21	15	289	325.2	36.4	37.1

neuver time and $\Delta t_{ref} = 1day$ is a reference time chosen to make the index non-dimensional.

Other than the selected target debris pair and the altitude of the destination orbit the performance index will depend on the initial wet mass of the IBS spacecraft (m_{IBS}) the maximum thrust force provided by the thrusters (F_{max}) and their specific impulse (I_{sp}) here assumed equal for the two thrusters.

We should point out that other more elaborated performance indexes can be considered in the future (see [5]).

5.3. Results

An optimisation analysis has been conducted based on the repositioning destination altitude of 725 km. A pair of 75 mN RIT-22 ion thrusters with 3400 s specific impulse and 4 kW total power consumption is assumed. The total wet IBS mass is assumed to be 400 kg.

The results are reported in Table 3 which highlights that 2 objects can typically be repositioned in less than a year with less than 40 kg total propellant. The waiting time is almost always a small fraction of the total mission time, which means that natural precession due to the descent and ascent phases of the IBS is sufficient to provide most of the required orbital plane differential rotation needed. Finally, one can notice that several targets belong to more than one combination, which suggests that favorable removal conditions of 3 or more targets may be achievable.

6. CONCLUSIONS

A preliminary optimisation analysis has been conducted to investigate the capability of the ion beam shepherd concept to be used for multiple removal purposes. It is seen that the repositioning of two Zenit-2 upper stages per year to a low-density orbit of 725 km altitude is feasible with a modest spacecraft size and very limited fuel consumption. Future work will analyse the IBS performance with more than two targets and the influence of different spacecraft system design conditions.

ACKNOWLEDGMENTS

This work was partly supported by the STARDUST ITN Network funded by the European Commission through the Marie Curie Action FP7-PEOPLE-2012-ITN and partly by the (former) Spanish Ministry of Science and Innovation under the research grant 'Dynamical Simulations of Complex Space Systems' contract number AYA2010-18796.

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