ACTIVE SPACE DEBRIS REMOVAL USING EUROPEAN MODIFIED LAUNCH VEHICLE UPPER STAGES EQUIPPED WITH ELECTRODYNAMIC TETHERS

S. Ali Nasseri(1), Matteo Emanuelli(2), Siddharth Raval(3), Andrea Turconi(4), Cristoph Becker (5)
Space Generation Advisory Council, c/o ESPI, Schwarzenbergplatz 6, A-1030 Vienna, AUSTRIA
(1) ali.nasseri@utoronto.ca,
(2) matteo.emanuelli@spacegeneration.org,
(3) sid123_jit@yahoo.co.in,
(4) andrea.turconi@gmail.com
(5) chr_becker@yahoo.co.uk

Abstract

During the past few years, several research programs have assessed the current state and future evolution of the Low Earth Orbit region. These studies indicate that space debris density could reach a critical level such that there will be a continuous increase in the number of debris objects, primarily driven by debris-debris collision activity known as the Kessler effect. This cascade effect can be even more significant when intact objects as dismissed rocket bodies are involved in the collision. The majority of the studies until now have highlighted the urgency for active debris removal in the next years. An Active Debris Removal System (ADRS) is a system capable of approaching the debris object through a close-range rendezvous, establishing physical connection, stabilizing its attitude and finally de-orbiting the debris object using a type of propulsion system in a controlled manoeuvre. In its previous work, this group showed that a modified Fregat (Soyuz FG's 4th stage) or Breeze-M upper stage (Proton-M) launched from Plesetsk (Russian Federation) and equipped with an electro-dynamic tether (EDT) system can be used, after an opportune inclination's change, to de-orbit a Kosmos-3M second stage rocket body while also delivering an acceptable payload to orbit. In this paper, we continue our work on the aforementioned concept, presented at the 2012 Beijing Space Sustainability Conference, by comparing its performance to ADR missions using only chemical propulsion from the upper stage for the far approach and the de-orbiting phase. We will also update the EDT model used in our previous work and highlight some of the methods for creating physical contact with the object. Moreover, we will assess this concept also with European launch vehicles (Vega and Soyuz 2-1A) to remove space debris from space. In addition, the paper will cover some economic aspects, like the cost for the launches' operator in term of payload mass' loss at the launch. The entire debris removal mission from launch to de-orbiting of the target debris object will be analysed using Analytical Graphic Inc.'s Systems Tool Kit (STK).

1. INTRODUCTION

Several studies have already assessed the current state and future evolution of orbital regions showing the increase in space debris threats coming from existing debris and future launches. In 2002, the Inter-agency Space Debris Committee developed a series of mitigation guidelines which were adopted in the 2007 United Nations (UN) resolution [1]. However, these guidelines, although important, address only active satellites currently in orbit and future launches. Despite their huge threats, continuously endangering active operational satellites, the existing debris were not contemplated. The orbital region where the danger coming from existing debris is higher is the low-Earth orbit (LEO) region due to a combination of high debris concentration, large number of crossings and high relative velocities [2]. The combination of these factors may lead to an exponential growth of debris objects by future cascade of collision [3], as outlined in Fig. 1.

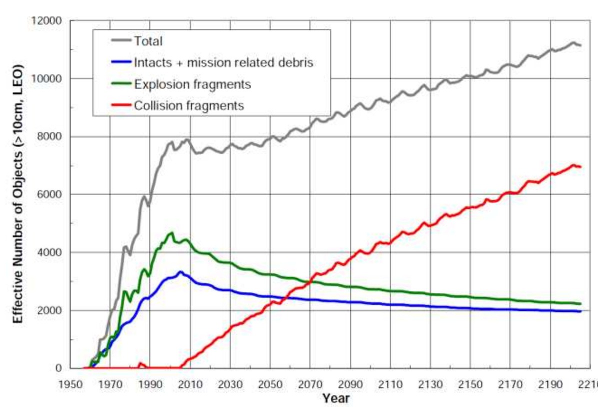

Figure 1. Future model of amount of large debris objects in the LEO region, based on a "no-launches after 2006" scenario [4].

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A study performed by NASA, using their LEGEND debris evolutionary model, investigated the future of the LEO environment considering compliance with UN guidelines and a repetition of the 1999-2006 launch cycle, which is an underestimation of the future situation according to more recent forecasts [5]. The scenario was completed with the assumption of an ongoing space debris removal program, starting 2020. According to the cases analysed, illustrated in Fig. 2, to stabilize the LEO debris environment 5 large objects have to be removed per year.

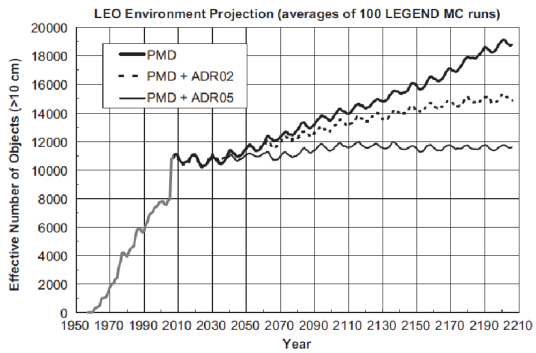


Figure 2. Comparison of three different scenarios. From top to bottom: post mission disposal (PMD) according [1] (removal within 25 years), PMD and Autonomous Debris Removal (ADR) of 2 objects per year, and PMD and ADR of 5 objects per year.

The necessity of an efficient space debris removal program is highlighted by these results. Moreover, due to the high frequency of disposal missions, the system chosen should be highly cost-effective. The combination of these factors led to the consideration of a solution that can be implemented on several launches as a piggyback payload, using the residual propellant and power from the upper stage to make a far approach manoeuvre towards the selected debris object. This choice limits the amount of propellant and consequently ΔV that can be used for the far-guidance phase. In previous publications [7], the critical region of interest for a future Active Debris Removal (ADR) mission was identified, corresponding to an altitude between 800km and 1000km, with an inclination ranging from 60° to 110°. Considering the total mass of the orbiting objects and the risk of cascade collisions, the larger space debris were identified as suitable ADR target. Moreover, since larger debris are easy to track and well defined in size, mass and shape, it reduces the assumptions to be made while designing a disposal system. Among the large number of orbiting objects, rocket bodies are the objects that match these characteristics and among the total number of intact rocket bodies, Kosmos-3M upper stages represent the biggest number with 157 stages orbiting. In the selected region of interest, 141 rocket bodies are being tracked, as illustrated in Fig. 3, the majority of which are at an inclination of around 80°. In the following analysis, we will focus on an existing Kosmos-3 M debris as a case study. This object is classified as SL-8 R/B 32053 according to the US Space Track catalogue. The selected debris has an orbital altitude of 959 km, an inclination of about 83° and a mass of 1435 kg. This debris and debris similar to it do not decay automatically within the 25 years guideline, making an ADR mission necessary for timely disposal. Moreover, due to its larger size, this debris is prone to create debris through the Kessler effect. In fact, many studies on active space debris removal conducted by various entities currently focus on the Kosmos 3M family of rocket bodies for mission simulation purposes.

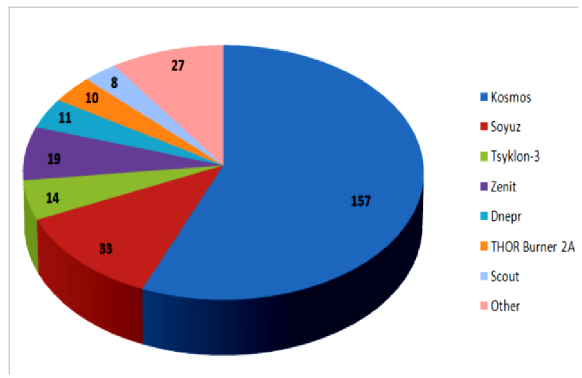


Figure 3. Types of rocket bodies in the critical region.

2. MISSION CONCEPT

The concept analyzed in this work focuses on modifying a launch vehicle upper stage by the addition of an electrodynamic tether system and a grabbing mechanism. All de-orbiting subsystems have to be integrated onto the upper stage which is used for propulsion and attitude control purposes. This enables the upper stage to act as a hunter system after delivering its primary payload. This approach to space debris removal has several merits:

- No new debris is added during each space launch.
- One large space debris can be de-orbited per launch. This helps stabilize the debris environment.
- Since many of the subsystems such as the Attitude Control System (ACS) are available on board the upper stage, the cost and complexity of developing the debris removal system are reduced.

The mission stages are summarized in Fig. 4. In this work, we will take a holistic approach at analyzing the mission by analyzing the capability of the system to carry out the mission and the type of components required for a successful mission.

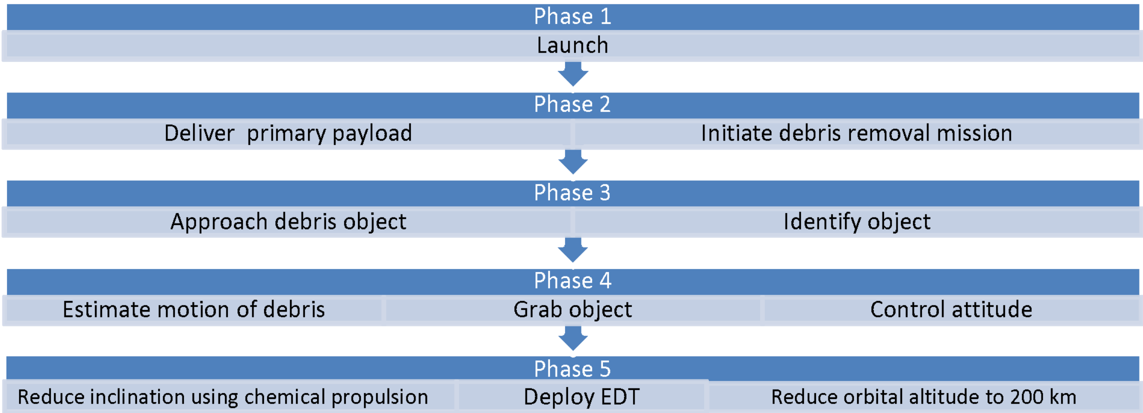


Figure 4. Different stages of the active space debris removal mission.

2.1 Launch

The choice of a proper launch vehicle would fundamentally affect the mission, as the mission relies on the launch vehicle upper stage for success. The first characteristic of the launch system, is capability to reach the target orbit. This capability not only relies on the launcher, but also the launch site. In this case, the target orbit is at an altitude of 900 km and an inclination of 83°. As several manoeuvres will be required to reach the target orbit and change inclination after grabbing the object, the upper stage should be restartable. Along with the final stage restart capability, another parameter affecting the choice of a proper launcher is the propellant capacity of the launcher's upper stage. The upper stage is required to inject a primary payload into an orbit. Then, it needs to move close to the target object, grab it and then reduce inclination in order to operating the electrodynamic tether or proceed to standard chemical de-orbiting. Since at least 5 objects need to be removed per year to stabilize the debris environment, it seems reasonable to assess the suitability of different classes of launchers for debris removal. The suitability of the following launchers will be analyzed in this work:

- The Soyuz 2 with the Fregat upper stage launched from the Plesetsk and Kourou spaceports.
- The Proton M launch vehicle with the Breeze-M upper stage launched from the Plesetsk spaceport.
- The Vega launch vehicle launched from Kourou spaceport.

As it is evident from this list, small and medium and heavy launch systems are represented. Hence, the results will shed some light on the suitability of each class of launch vehicles for such a mission. Calculation from other heavy launchers (Altas 5 and Delta IV) have been conducted already and the results will be shown in a future publication.

2.2. System Components

Other than the upper stage itself, the ADR system requires several subsystems to be able to de-orbit the target debris.

2.2.1. The Electrodynamic Tether System

Electrodynamic tethers (EDTs) are long conducting aluminium tapes, such as one deployed from a tether satellite, which can operate on electromagnetic principles as generators, by converting their kinetic energy to electrical energy, or as motors, converting electrical energy to kinetic energy. EDT's fall into the low thrust propulsion category (10mN < F < 500mN). EDT propulsion is propellant-less and fully reusable. For longer thrust time they are lighter than electric propulsion, but collision avoidance is critical due to their large length. The main advantage of the EDT for space debris removal is that it does not require propellant. This reduces cost and improves reliability of in-space propulsion and operations. Additionally, the electrodynamic tether drag may actually provide a cost-effective method to rapidly and safely remove spent upper stages and unused spacecraft from low earth orbit. EDT systems have long been studies for space debris removal missions. Fig. 5 illustrates the results of one such analysis. By digitizing Fig 6., mathematical relationships were statistically developed between the tether systems thrust and the inclination with R^2 = 0.9997. These equations were used as a preliminary thrust model for the EDT system. Recent studies have theorized that a bare EDT carrying a plasma contactor as cathode at one end would not required a power source, because the current would be generated by the interaction between the contactor and the surrounding plasma, generating a drag force. Not requiring propellant or power, EDT is more efficient than electric propulsion at low inclination orbits in term of impulse per required mass[8].

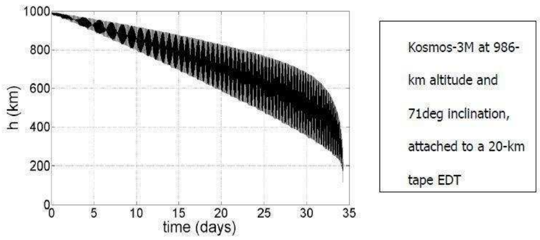


Figure 5. Sample de-orbiting analysis for a Kosmos-3M second stage [9].

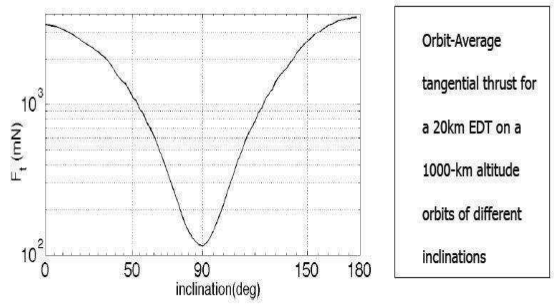


Figure 6. Simulation of EDT performance vs. inclination at which EDT is used [9].

2.2.2. Grabbing Mechanism

Obviously, the ADR system will require to somehow connect with the debris object. A grabbing mechanism needs to be installed onboard the upper stage for this purpose. The design of such a system is mainly governed by the characteristics of the target debris object: size, mass, shape, attitude and angular motion. Since the contributors to space debris threat in the orbital region considered are mainly rocket bodies, the grabbing mechanism can target characteristics shared between such objects, such as nozzles and combustion chambers.

Tab. 1 summarizes some of the methods used for grabbing space debris. Due to the fact that our system is expendable, it seems reasonable to choose the simplest grabbing system in order to reduce cost and complexity. However, such a simple system such as a net might not be suitable or reliable for missions involving large objects. More detailed analysis is required to choose the exact grabbing device for such a concept. At this point, it seems reasonable to keep the net and robotic arm concepts as possible grabbing methods. The grabbing mechanism has to be supported by a vision based system for target identification and motion estimation.

Table 1. Comparison of different grabbing mechanisms.

Method	Pros	Cons
Docking through propulsive nozzle	Application for a wide range of rocket bodies. Usable also if the target is spinning.	Very precise close approach required. Not applicable to tumbling targets.
Harpoon	Projectile designed to anchor safely into a wide range of materials.	Possible creation of new debris during the impact, risk of explosion, attitude modification.
Net	Indifferent to target attitude.	Net’s material to be flexible and resistant. Net deployment required specialized manoeuvres.
Robotic arm	Applicable to different type of space debris. Provides the most control on the space debris.	De-tumbling procedure required. Accurate pre-inspection of the debris to chose the grabbing point. Most complex.

2.3. Summary of System Mass Properties

In order to analyze the feasibility of the concept, the mass of system components need to be estimated. The estimated mass properties for the system are summarized in Tab. 2. A total mass of 200 kg was used for all simulations in this work. It was assumed that we will have access to batteries on board the upper stage for power and the upper stage attitude control system (ACS) for attitude control. Since the grabbing mechanism has not been finalized yet, a conservative mass estimation was made based on typical masses for robotic arms.

Table 2. Summary of mass properties of the system.

Subsystems	Mass (kg)
EDT mass [8]	80
Grabbing Mechanism	100
Motion Estimation	5
Power System	5
Misc.	10
Total	200

2.4. Chemical Propulsion Manoeuvres and Corresponding ΔVs

Having defined the launch site and the launcher, it is possible to start simulating a general far approach for the Kosmos 3M second stage identified with the code SL-8 R/B 32053. To perform the simulation, STK's Astrogator was used as propagator. For each launcher, first the launch was modelled based on altitude, inclination and relative velocity values in the corresponding user manual. Using several manoeuvres, during which the primary payload is released, the upper stage reaches the target orbit at an altitude of 920 km and an inclination of 83°. At this point, the upper stage should approach the debris and connect with it. The grabbing manoeuvre has been postponed for future work, as the holistic feasibility of the missions needs to be assesses first. After grabbing the target debris, a series of manoeuvres are needed to reduce the inclination. These manoeuvres are needed since, according to the model used in this work, the EDT works efficiently at lower inclinations. Note that, using attitude changes, it is possible to use the tether at higher inclinations, but that will use more propellant and be hard to control due to the high debris density at these altitudes. One of the goals of this simulation was to calculate the ΔV required for the manoeuvres to evaluate if the launch vehicle upper stage possesses enough propellant to carry out the mission. The required velocity increment for each manoeuvre is summarized in Tab. 3, as calculated using STK. Note that in the case of VEGA, the number of restarts by the upper stage engine limits the number of manoeuvres.

Table 3. Velocity increments required for each manoeuvre using the upper stage (calculated from STK simulations).

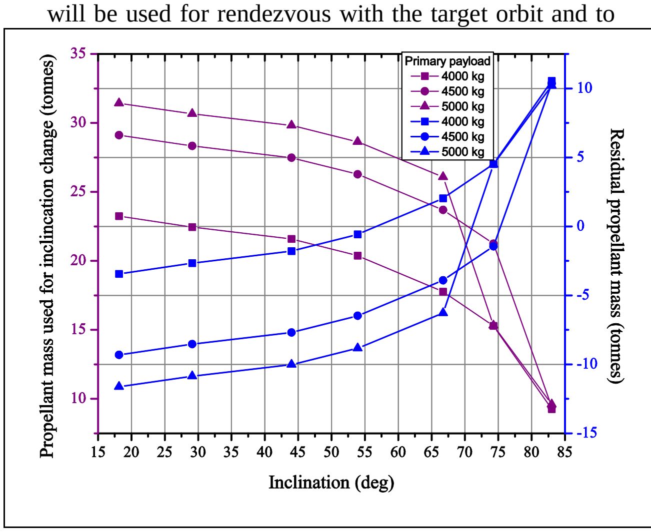
Manoeuvre	Δ V (km/s)			
Launch Vehicle	Soyuz 2 Plesetsk	Soyuz 2 Kourou	Proton M	Vega
Altitude increase	0.105	0.164	0.105	0.181
Hohmann transfer	0.056	0.143	0.056	0.196
Combined change	0.849	2.200	0.849	2.139
Inclination change 1 (83 to 74 deg)	1.710	1.101	1.71	1.101
Inclination change 2 (74 to 66 deg)	1.101	0.600	1.101	0.501
Inclination change 3 (66 to 53 deg)	1.809	1.908	1.809	-
Inclination change 4 (53 to 43 deg)	1.402	1.300	1.402	-
Inclination change 5 (43 to 29 deg)	1.576	1.900	1.576	-
Inclination change 6 (29 to 18 deg)	2.808	1.700	2.808	-

2.6. Propellant Use Analysis for Different Launch Vehicles

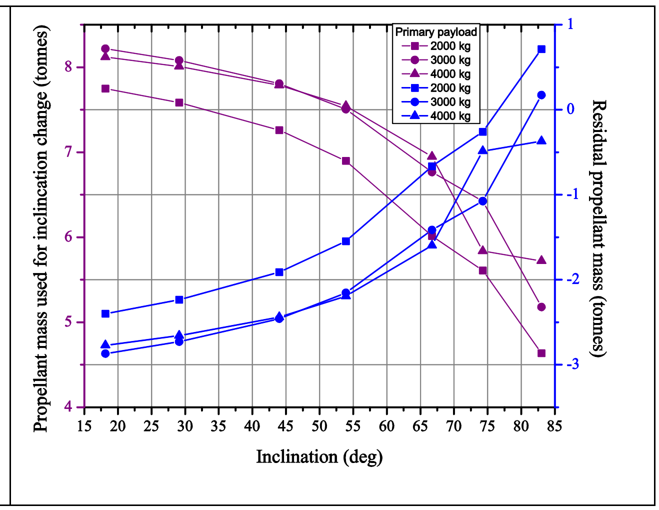
A crude analysis of different possible manoeuvres was performed to assess whether the upper stages possess enough propellant to:

1. Release a primary payload into the target orbit (an orbit near the target debris).
2. Perform manoeuvres to decrease inclination to an inclination were the tether system can provide enough thrust for de-orbiting.
3. Reduce the altitude of the debris object to 200 km, where it will decay rapidly and re-enter the earth atmosphere.

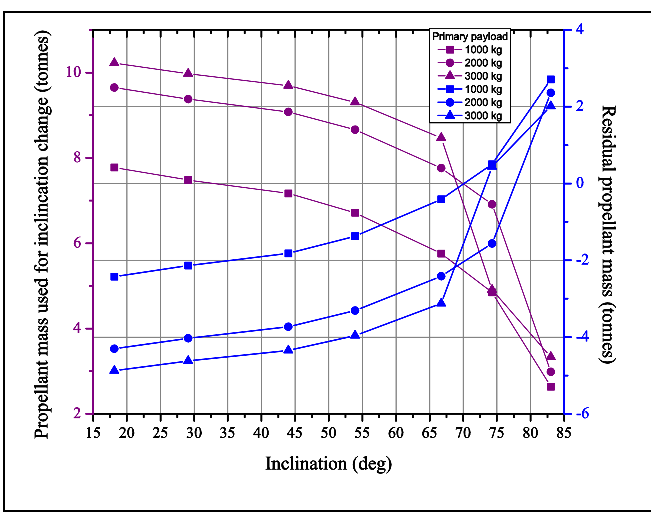
The simulation was performed based on the manoeuvres and EDT thrust curves outlined in previous sections. It should be noted that part of the upper stage propellant will be used for rendezvous with the target orbit and to control its attitude, which has not been considered in this analysis. Moreover, the effect of increased drag (from having the Kosmos 3M body and the tether system connected to the upper stage) has not been taken into account. Overall, this analysis is conservative enough for our study. The properties of these upper stages were taken from the corresponding user manuals. The results of the analysis, summarized in Fig. 7, show that the proposed method is suitable for medium to heavy launchers and cannot be used with small launchers such as VEGA. Fig. 8 shows the time it takes to reduce orbital altitude to the targeted altitude (200 km) for the different launchers. This figure shows that all upper stages are capable of reducing the orbital altitude in less than 100 days. With launchers such as Soyuz, this time can be as short as 50 days.



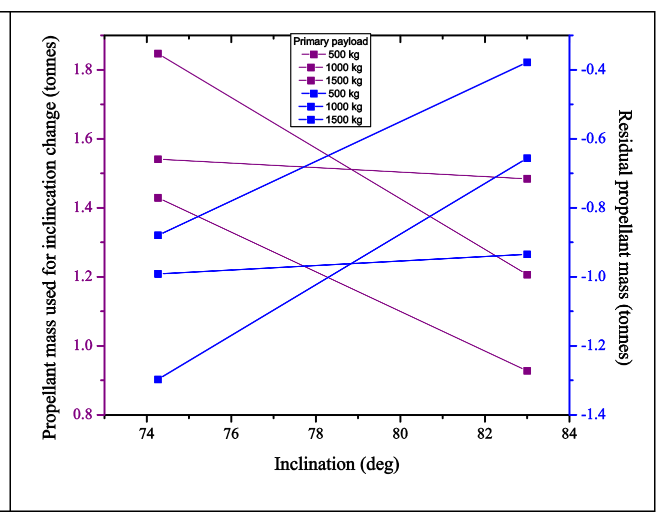
(c) Proton M



(d) Soyuz from Kourou



(e) Soyuz from Plesetsk



(f) VEGA

Figure 7. Propellant mass used for inclination changes and residual propellant mass after the maneuvers.

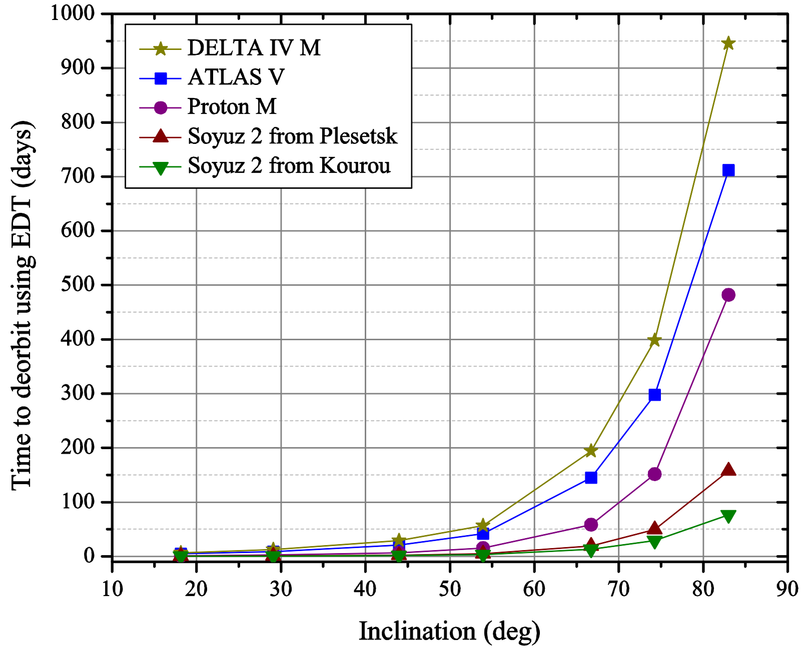


Figure 8. Time it takes for the EDT to reduce altitude to the targeted value of 200 km.

Weight reductions (for example reducing the weight of the primary payload) would permit the use of more fuel for inclination change manoeuvres which will practically reduce the time to de-orbit even further. Obviously, one might argue that de-orbiting directly using the upper stages chemical propulsion might be an option. Tab. 4 summarizes our analysis of direct de-orbiting using chemical propulsion. This can only be achieved at high inclinations; as such a manoeuvre will require at least a velocity increment of 0.5 km/s. As this means that the debris will enter at a high inclination, there can be safety concerns. Moreover, the availability of a secondary propulsion system increases the reliability of the debris removal in case more fuel is used for close rendezvous than anticipated.

Table 4. Velocity increment left for altitude reduction after inclination changes at nominal payload.

Inclination	**ΔV (km/s)**		
	Proton	**Soyuz from Kourou**	**Soyuz from Plesetsk**
83	4.043	0	1.820
74	2.333	0	0.110
66	1.232	0	0
53	0	0	0
43	0	0	0
29	0	0	0
18	0	0	0

3. MISSION COST ANALYSIS

Using back of the envelope calculations based on launch cost per kg of payload, the launch cost for the system ranges from $390 k to $1689 k, averaging at $848k. This estimate does not include the cost of insurance and operations. The total cost of the first prototype of the system, including development and manufacturing are estimated at 37 million dollars. As the upper stage removes itself and a rocket body, it seems reasonable that the removal cost per kg of debris will be lower than launch costs per kg using this concept, which is important in choosing ADR methods [10].

4. IMPLEMENTATION

There are several issues that exist regarding the implementation of this concept. Firstly, where should the system be installed? Due to length of the tether after deployment, it seems that the system should be broken down into two packages. One package, which includes the grabbing mechanism can be packaged in a way to fit into one of the piggyback payload sites on the upper-stage and be structurally incorporated to the upper stage. The second package, containing the EDT, can be installed on the other side of the upper-stage, to provide room for its deployment. The second question is how should it be used? Without any regulatory policies with regard to space debris, this question is hard to answer. Several options exist, including:

- The launch service providers could include this de-orbiting service as an additional service on their launcher. Hence, if regulations force satellite operators to de-orbit their satellite after use, they can buy this service from the launch provider.
- On the other hand, regulations might force the launch provider to de-orbit all objects it has launched, in which case the cost of de-orbiting will be part of the launch costs and this system will definitely benefit the launch provider.

Obviously, as rules and regulations with respect to debris removal are clarified, the procedure used for implementing this concept can be finalized.

5. CONCLUSIONS AND FUTURE WORKS

Our preliminary simulation shows that the proposed solution can remove a rocket body from high altitude high inclination LEO orbits in a timely manner using medium to heavy launchers. In addition, heavy launchers could hypothetically carry out the mission without using EDT. Future work will include further simulations to refine the preliminary result showed in this paper. Moreover, the close approach, grabbing and stabilization of the space debris have to be studied in detail, defining a suitable grabbing mechanism. Furthermore, consideration on re-entry safety has to be taken into account. These issues are currently being addressed and will be presented in future meetings.

6. ACKNOLOWDGEMENTS

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