DESIGN AND EVALUATION OF AN ACTIVE SPACE DEBRIS REMOVAL MISSION WITH CHEMICAL AND ELECTRODYNAMIC TETHER PROPULSION SYSTEMS

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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. These studies also highlight the urgency for active debris removal. An Active Debris Removal System (ADRS) is capable of approaching the debris object through a close-range rendezvous, stabilizing its attitude, establishing physical connection, and finally de-orbiting the debris object. The de-orbiting phase could be powered by a chemical engine or an electrodynamic tether (EDT) system. The aim of this project is to model and evaluate a debris removal mission in which an adapted rocket upper stage, equipped with an electrodynamic tether (EDT) system, is employed for de-orbiting a debris object. This hybrid ADRS is assumed to be initially part of a launch vehicle on a normal satellite deployment mission, and a far-approach manoeuvre will be required to align the ADRS' orbit with that of the target debris. We begin by selecting a suitable target debris and launch vehicle, and then proceed to modelling the entire debris removal mission from launch to de-orbiting of the target debris object using Analytical Graphic Inc.'s Systems Tool Kit (STK).

I. TARGET DEBRIS IDENTIFICATION

The identification of the orbital region where the space debris situation is more critical and it is the starting point of this research.

I.I. Low Earth Orbit (LEO) or Geostationary Earth Orbit (GEO)?

89% of the ~950 operational satellites are either in a low earth orbit (LEO, 300-2000 km altitude) or a Geostationary orbit (GEO, ~36000 km altitude). Hence, these two regions form the first focus of our selection.

LEO and GEO both have specific characteristics regarding the presence and evolution of space activities; however, in the LEO region, satellites and debris elements are quite widely scattered in terms of altitude, inclination and ascending node. This, in combination with the fact that orbital speeds are considerably higher than in GEO, makes number of crossings and the relative velocities of the bodies during these crossings very high. The wide and random distribution of objects also implies that a system of graveyard orbits (as in the GEO case) is not practical.

The combination of a higher debris concentration, a large number of crossings and higher relative velocities in the LEO region may lead to an exponential growth of debris objects by a future cascade of collisions [7]. As most manned space-missions are performed at (low) LEO altitudes, it is essential that the risk of collision is minimized to the greatest possible extent.

I.II. Orbital parameters

Once the LEO region is defined as a primary target of our investigation, the most critical orbital parameters must be identified to choose a proper target for the mission. Studies were performed for predicting the probability of collision in the next centuries using NASA's LEGEND model, based on the past and current debris environment [1, 2]. These studies form the basis of further orbital selection. The collision probability in the next 50 years is higher at the altitude bands containing the highest fragments concentration caused by the catastrophic events of Fengyun 1c at ~850km and Iridium-Cosmos at ~800km. The critical altitude band is extended between 800km and 1000 km.

Using data from [8, 9], it is revealed that higher inclinations (60°-110°) are much more crowded as a direct result of the high number of past and present satellites which use these zones to fulfil their mission goals. The peak between 90° and 100° is due once again to the high amount of fragments of Fengyun 1c. Thus, efforts for actively remove debris should focus on objects in these orbits [10].

Unlike the semi-major axis and inclination, no particular trend can be seen in the right ascension of the ascending node (RAAN) of the current debris environment and future collisions. This is due to the oblateness of the Earth, which makes space debris RAAN a permanently evolving parameter [7].

I.III. Identification of target debris

Using the USSTRATCOM TLE database, which contains the Keplerian elements of all detectable debris objects, a list of all candidate disposable debris objects was created. The data was filtered based on object size and type, as well as the most populated orbital regions. When the rocket bodies are counted per type, the distribution in figure 1 is reached.

As it can be seen in the figure, the Russian Kosmos 3M rocket bodies are the perfect candidate for active de-orbiting due to the large number of bodies in orbit. Figure 2 illustrates the spatial distribution of Kosmos 3M 2^{nd} stage rocket bodies around the earth.

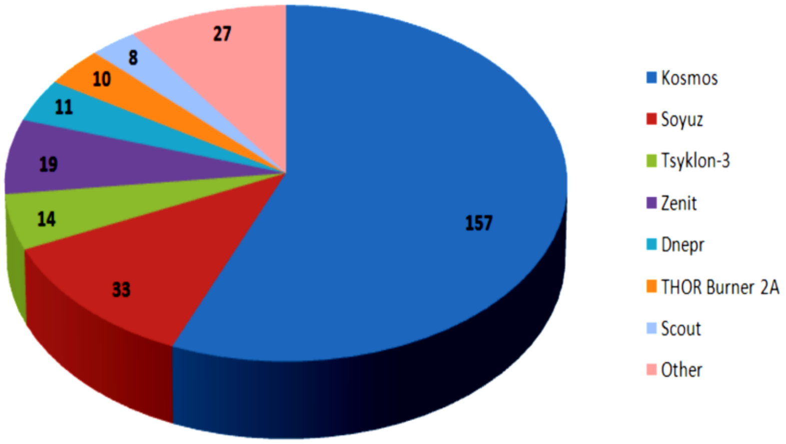


Figure 1: Types of rocket bodies in the critical region

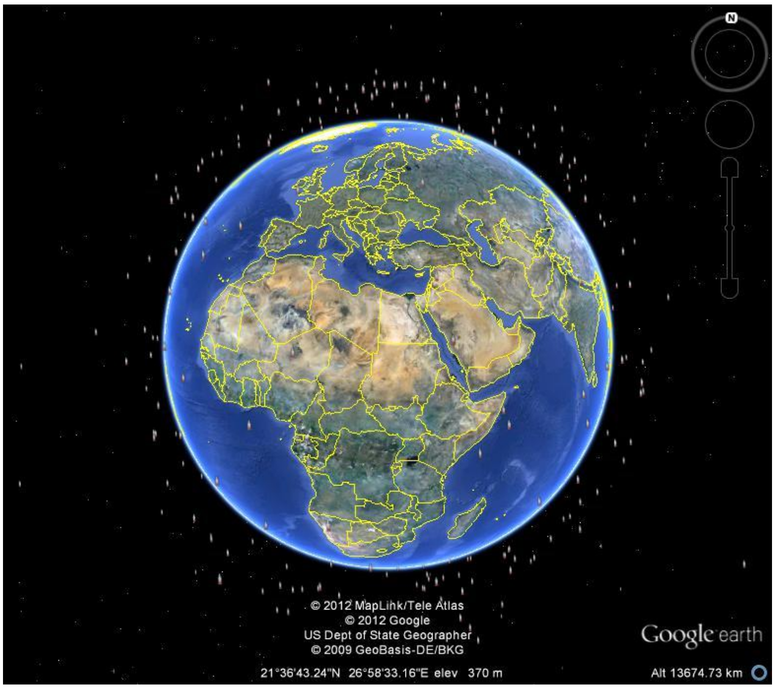


Figure 2: Spatial distribution of Kosmos 3M rocket body in LEO (created in Google Earth based on data from US space track catalogue and UCS satellite database)

The STK software and Space Track database were used to model the low Earth orbit environment according to spatial distribution of Kosmos 3M rocket bodies, as depicted in figure 3. The Orbits of 156 rocket bodies are illustrated in figure 3 with boundaries set at a perigee of 800 km and 1000 km. The high density of Kosmos 3M bodies is clear from the crowded image. Only 15 rocket bodies are at an inclination between 0° and 80° (illustrated with light blue colour on figure 3). For the band of interest (80°-100°), 141 rocket bodies were listed (illustrated with blue colour on the figure). The majority of these objects are at an inclination of around 80°.

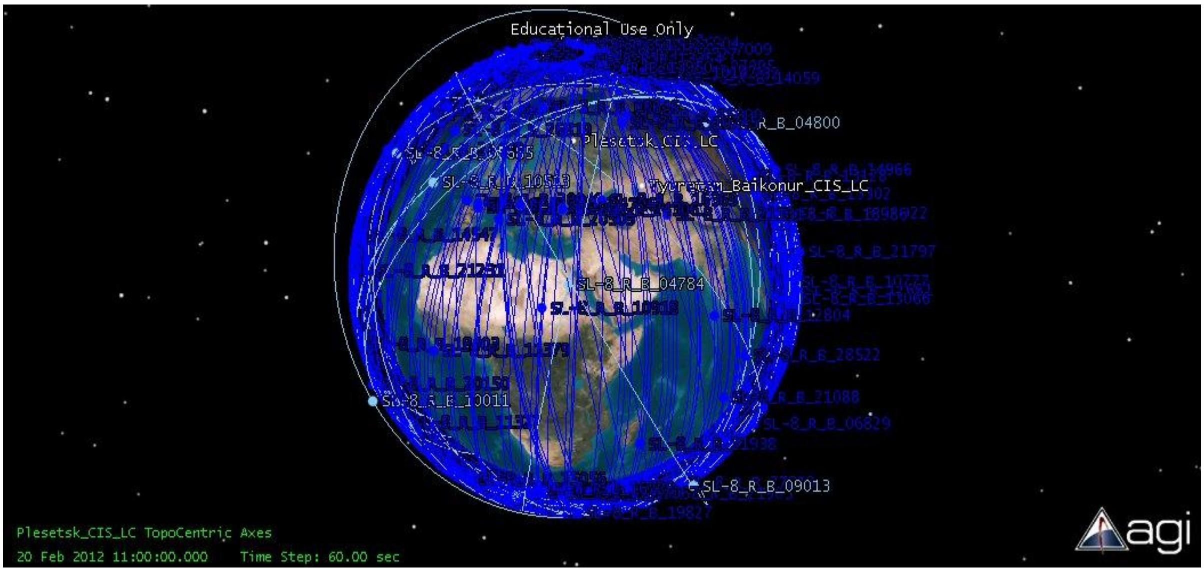


Figure 3: Spatial distribution and orbits of Kosmos 3M rocket body in LEO

Of all the bodies available, one was arbitrarily chosen as the target of the mission. This body is only chosen to analyze a representative mission and may change based on future studies. According to the US Space Track catalogue, the rocket body is classified as **SL-8 R/B 32053**. The orbital parameters of this object are summarized in table 1 and figure 4.

Mean Motion (deg/s)	0.0573292
Eccentricity	0.002639
Inclination (deg)	82.976
Argument of Perigee (deg)	151.655
RAAN (deg)	233.421
Mean Anomaly (deg)	208.605

Table 1 Orbital parameters of the SL-8 R/B 32053 object [9]

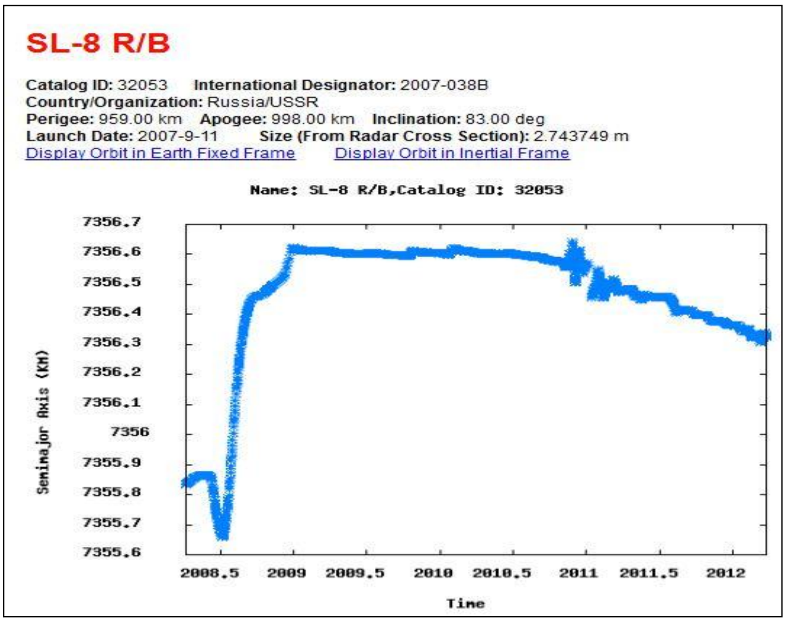


Figure 4 Evolution of semi-major axis of the SL-8 R/B 32053 object [9]

I.IV. Kosmos 3M's de-orbiting justification

Considering the size and mass of a Kosmos 3M 2nd stage and the mean value of the orbital parameters seen previously, the orbit of a typical Kosmos 3M 2nd stage was modelled in STK, as illustrated in Figure 5.

A lifetime analysis with the J2M propagator was carried out using a nominal altitude of 900km and inclination of 80°. The result was that Kosmos 3M will not decay automatically (limit at 64km) before 25 years, which is a requirement for space debris stated by the United Nations Committee on the Peaceful Uses of Outer Space [11]. In fact, it decays only 70km after a 100 years based on a simulation in STK.

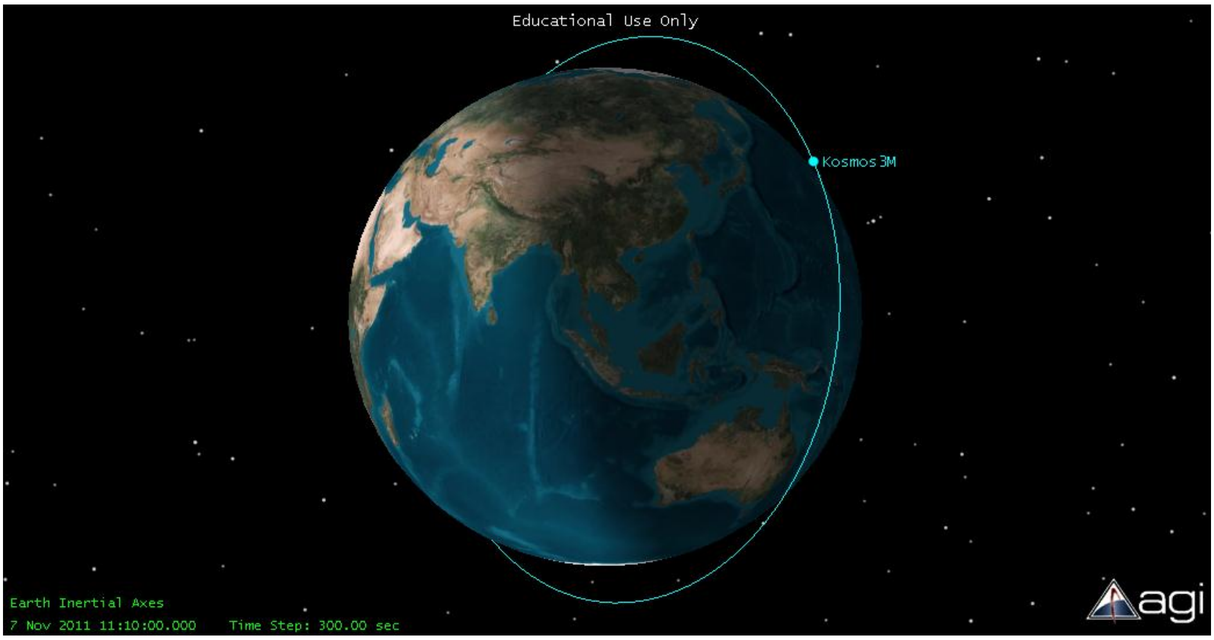


Figure 5: STK model of a typical Kosmos 3M second stage orbit

II. DEFINITION OF LAUNCH VEHICLE AND LAUNCH SITE

After identifying the target, the next step is defining the launch site and launch system. The choice depends on the target orbit and the availability of a suitable launch vehicle. According to these criteria, the following potential launch sites were shortlisted:

- Vandenberg (USA - 34°43′57″N 120°34′05″W),
- Kourou (French Guyana - 5.305°N 52.834°W)
- Plesetsk (Russian Federation - 62°57′35″N, 40°41′2″E).

The reason why the Baikonur Cosmodrome was not considered as a possible choice was the possibility that based on news reports Russia might abandon all facilities at Baikonur and launch all missions from Plesetsk in the next 5 years [12].

Another important feature of the desired launch vehicle is the final stage restarting capability. Our approach is integrating all de-orbiting subsystems onto the upper stage and using the upper stage for propulsion purposes. As several manoeuvres will be required to reach the target orbit and change inclination after grabbing the object, restartability is required.

Another parameter that affects the choice of launcher is the propellant capacity of the launcher's upper stage. The upper stage is required to inject a primary payload into orbit, move our system to the target orbit and then reduce inclination for deploying the tether system. Based on all these parameters, a list of active launch vehicles was created, as outlined in table 2. This list summarizes launch vehicles with polar/SSO launch capability, their upper stage properties and the availability of a model in STK. Considering all the required characteristics, the Soyuz vehicle with the Fregat upper stage was chosen as the primary launch vehicle. The Proton-M launch vehicle with the Breeze-M upper stage will be considered as an alternative system. The Plesetsk Cosmodrome was chosen as the launch site as both launch vehicles can be launched from this site. The Plesetsk Cosmodrome is a military site in the North-West Russia, 800 km from Moscow.

Launch Vehicle	Country	PEO characteristic	Payload (kg)	Launch Site	Upper Stage						
					Dimensions (m × m)	Dry Mass (t)	Propulsion	Propellant Mass (t)	Lift-off mass (t)	Restart?	STK model ?
Dnepr-1	Ukraine	800 km, I = 87.3	400	Baikonur	1 * 3	2,35	RD-869 (UDMH-N2O4)	1,91	4,26	N	Y
Zenit	Russia	200 km, I = 99	11380	Baikonur	10.4 * 3.9	8,3	(Kerosene-LO2)	-	89,9	N	Y
CZ-2D	China	200/400 km, I = 90	2750/1175	JSLC	10.4 * 3.35	4	YF-22 B (UDMH-N2O4)	36	40	N	N
CZ-2C	China	600 km, I = 90	800	JLSC	7.5 * 3.35	4	YF-22 (UDMH-N2O4)	35	39	N	N
Taurus-XL	US	400 km, I = 98	880/1050	VAFB	2.1 * 0.97		Solid	-	0,98	N	Y
Minotaur	US	740 km, I = 98.6	335	VAFB	1.34 * 0.97	0,126	Solid	0,771	0,897	N	Y
Taurus	US	800 km, I = 98.2	580-600/740	VAFB	1.34 * 0.98		Solid	0,77	0,893	N	Y
CZ-2E/ETS	China	1000km, I = 86	4930	XLSC	2.936 * 1.7	0,541	SPTM-17 (solid)	5,444	5,98	N	Y
Ariane 5	EU	800 km, i = 98.6	9500	ELA3	3.356 * 3.936	1,25	AESTUS (MMH-N2O4)	9,7	11	Y	Y
GSLV	India	407 km, I = 51.6	5000	SHAR	8.7 * 2.9	2,2	KVD - 1 (LH2-LO2)	12,5	14,7	Y	N
PSLV	India	800 km, I = 99.1	1200	SHAR	2.65 * 1.34	0,92	PS-4/L2 (MMH-Mon-3)	2	2,92	Y	Y
Delta-4H	US	500 km, I = 90	21700	VAFB	13.7 * 5.13	3,49	RL 10B-2 (LH2-LO2)	27,2	30,69	Y	Y
Delta-4M	US	500 km, I = 90	7350-11700	VAFB	12.2 * 4.07 or 13.7 * 5.13	2.850/3.490	RL10B-2 (LH2-LO2)	20.410/27.200	23.260/30.690	Y	Y
Delta-2	US	833 km, I = 98.7	1591-3186	VAFB	5.88 * 2.44	0,95	AJ 10-118 K (Aerozine-N2O4)	6	6,95	Y	Y
ATLAS 2, 2A	US	185 km, I = 90	5510-6170	VAFB	10.06 * 3.05	1,84	RL-10A-3-3A or RL-10A-4 (LH2-LO2)	16,74	18,8	Y	Y
ATLAS 5	US	189 km, I = 90	9050-10750	VAFB	12.68 * 3.05	1.914/2.106	RL-10A-4-2 (LH2-LO2)	20.672/20.830	22.586/22.936	Y	Y
CZ-3	China	200 km, I = 90	3000	XLSC	7.48 * 2.25	2	YF-73 (LH2-LO2)	8,5	10,5	Y	Y
CZ-4	China	900 km, I = 99	1650-2800	TSLC	1.92 * 2.9	1	YF-40 (UDMH-N2O4)	14,15	15,15	Y	N
Soyuz-ST	Russia	900 km, I = 90	3850	Baikonur	1.5 * 3.35	1	S5-92 (UDMH-N2O4)	5,35	6,535	20	Y
Vega	EU	700 km, I = 80	1580	ELA1	2.04 * 1.952	0,418	(UDMH-N2O4)	0,55	0,968	5	Y
Soyuz-Ikar-Fregat	Russia	700 km, I = 90	3000	Plesetsk	2.61 * 2.72 or 1.5 * 3.35	2.352/1	UDMH-N2O4	0.3-0.9/5.35	3.29/6.535	20	Y
Proton-M	Russia	170 km, I = 72.7	19975	Baikonur	2.61 * 4.1	2,37	UDMH-N2O4	19,8	-	8	Y
Falcon 1	US	700 km, I = 85	450	VAFB	-		Kestrel (RP-1-LO2)			Y	Y
H-2A	Japan	800 km, I = 98.6	4400	Tanegashim	10.7 * 4	3	LE-5B (LH2-LO2)	17	20	Y	N
Falcon 9	US	900 km, I = 80	7246	VAFB	-		Merlin (RP-1-LO2)			2	N
CZ-3B/3C	China	800 km, I = 90	6000	XLSC	12.375 * 3	0,3	YF-75 (LH2-LO2)	18,193	20,6	2	Y
Soyuz-2	Russia	820 km, I = 98.7	4350/4900	Plesetsk	1.5 * 3.35	1	S5-92 (UDMH-N2O4)	5,35	6,535	20	Y
Proton-K	Russia	SSO	4600	Baikonur	5.5/6.3 * 3.7	2.500/3.370	Kerosene or Sintin-LO2	14,8	17.3/18.2	7	Y
ROCKOT	Russia	800 km, I = 90	1340	Plesetsk	2.61 * 2.5	1,6	11DM58 (UDMH-N2O4)	4,9	6,5	8	Y

Table 2. Potential launch vehicles and their details [13, 14, 15]

III. ELECTRODYNAMIC TETHER

Electrodynamic tethers (EDTs) are long conducting wires, 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.

In this work, both EDT and chemical propulsion systems will be used on basis of suitability for the mission. The main advantage of the EDT is that, we don't 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.

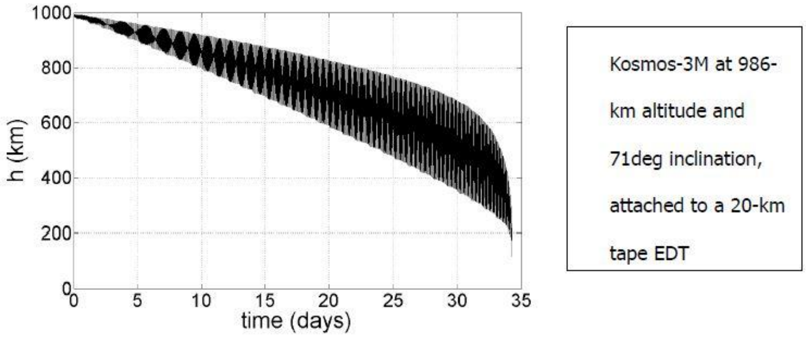


Figure 6: Sample de-orbiting analysis for a Kosmos-3M second stage [16]

IV. MISSION SIMULATION IN STK

Having defined the launch site and the launcher, it is possible to start simulating a general far approach, considering a launch from Plesetsk targeting the Kosmos 3M 2nd stage identified with the code SL-8 R/B 32053 according to the US Space Track catalog.

To perform the simulation, STK's Astrogator was used as propagator. The first part consisted of reproducing the Soyuz launch, using the Soyuz users' manual as reference for altitude, inclination and relative velocity.

After the Soyuz transfer is completed and the payload is released at 820 km, the Fregat module starts performing a Hohmann transfer to raise the apogee to 920 km with a combined manoeuvre changing eccentricity and inclination (0 and 83°) reaching the same orbit of the target space debris.

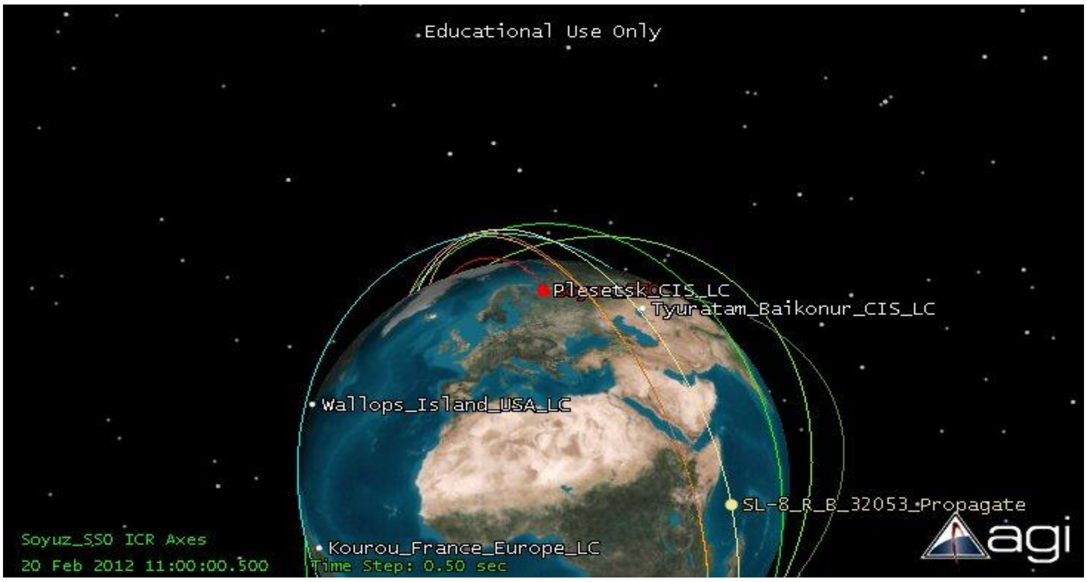


Figure 6: Far approach manoeuvre model in AGI STK

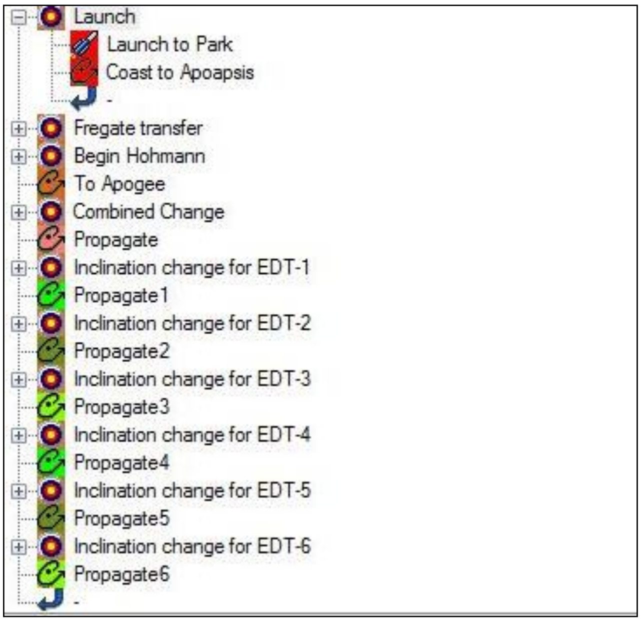


Figure 7: List of manoeuvres as implemented in STK's Astrogator

At this point, the Fregat module should approach, release the tether and the micro tug should perform the close approach manoeuvre. As this study is focused on the feasibility of the mission at this point, such details have been left for future work.

After grabbing the target debris, a series of manoeuvres are needed to reduce the inclination (the complete list of manoeuvres is shown in figure 8). The reason for this is that the EDT works efficiently at lower inclinations (See figure 8).

By digitizing figure 8, mathematical relationships were statistically developed between the tether systems thrust and the inclination as follows (R^2 = 0.9997):

$T(mN) = 0.0077 * i^3 - 0.8542 * i^2 - 21.315 * i + 3391.5 \ (i < 90°)$ [1]

$T(mN) = -0.0001 * i^4 + 0.0604 * i^3 - 9.5709 * i^2 + 646 * i - 15987 \ (i > 90°)$ [2]

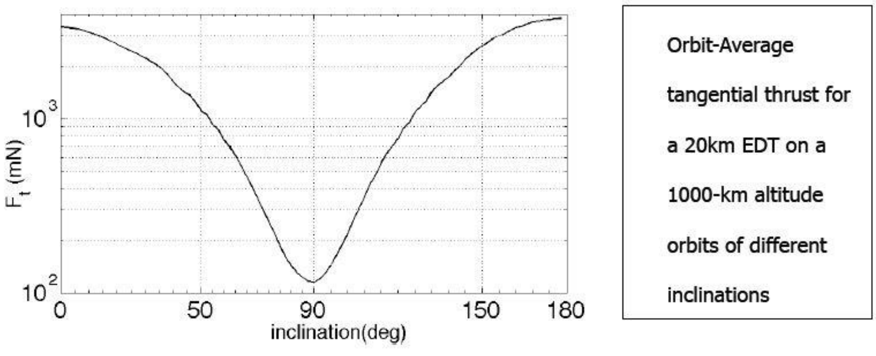


Figure 8: Simulation of EDT performance vs. inclination at which EDT is used [16]

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 table 3, as calculated using STK.

Maneuver	Velocity Increment (km/s)	Provided by
Launch to Park Orbit	-	Launch Vehicle
Altitude increase	-	Upperstage
Hohman transfer	-	Upperstage
Combined change	-	Upperstage
Inclination change 1 (83 to 74 deg)	1.71	Upperstage/EDT
Inclination change 2 (74 to 66 deg)	1.101	Upperstage/EDT
Inclination change 3 (66 to 53 deg)	1.809	Upperstage/EDT
Inclination change 4 (53 to 43 deg)	1.402	Upperstage/EDT
Inclination change 5 (43 to 29 deg)	1.576	Upperstage/EDT
Inclination change 6 (29 to 18 deg)	2.808	Upperstage/EDT

Table 3 Velocity increments required for each manoeuvre (calculated from STK simulation)

V. PROPELLANT USE ANALYSIS FOR DIFFERENT POSSIBLE MANOEUVRES

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 manoeuvre to decrease inclination to an inclination were the tether system can provide enough propulsion for deorbiting.
3. De-orbit the debris in acceptable time.

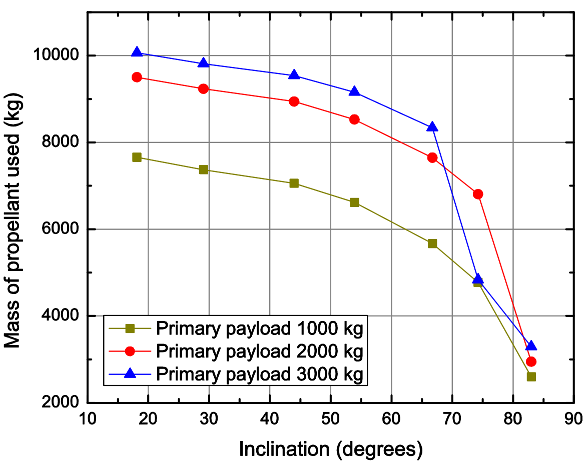
The simulation was performed based on the manoeuvres and EDT thrust curves outlines in the previous sections. It should be noted that part of the upper stage propellant will be used for rendezvous with the target orbit, which has not been considered in this analysis. Moreover, the affect of increased 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. Two upper stages were used in the analysis. The properties of these upper stages are outlined in table 4. It should be noted that the range of primary payload masses were identified using the launch vehicle's catalogue and space launches data in [17] and [18].

	Soyuz upper stage (Fregat)	Proton upper stage (Breeze-M)
Primary payload mass (ton)	1-3	4-5
Vacuum specific impulse (s) [13]	327	325.5
Propellant mass (ton) [13]	5.35	19.8
Structural mass (ton) [13]	1	2.37
EDT mass (kg) [16]	80	
Debris altitude (km)	900	
Debris inclination (deg)	83	
Kosmos 3M mass (kg) [13]	1435	
Target orbit (km)	500	

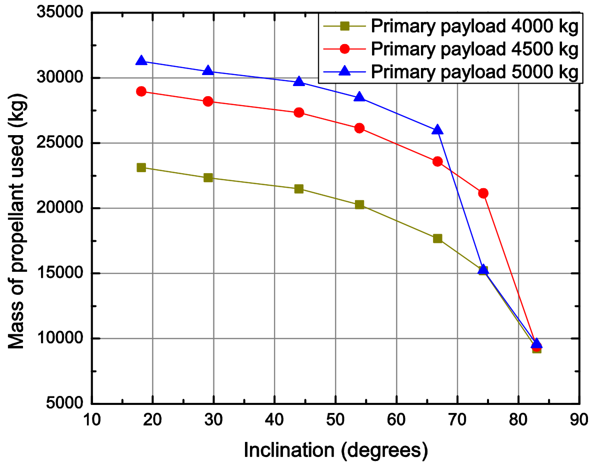
Table 4 Properties of the upper stages and target debris used in the simulation

The results of this analysis are summarized in figure 9. This figure shows that the Soyuz upper stage (Fregat) possess enough propellant to reduce the inclination to about 70 degrees, where the debris will reach the reduced altitude in about 150 days. The same analysis shows that, for the Proton upper stage (Breeze M), the inclination can be reduced to even 55 degrees and the time to de-orbit to less than 100 days.

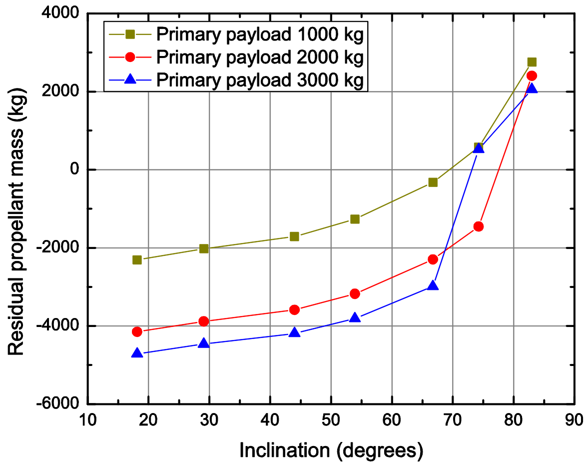
Of course, weight reductions (for example reducing the weight of the primary debris) would permit the use of more fuel for inclination change manoeuvres which will practically reduce the time to de-orbit even further.



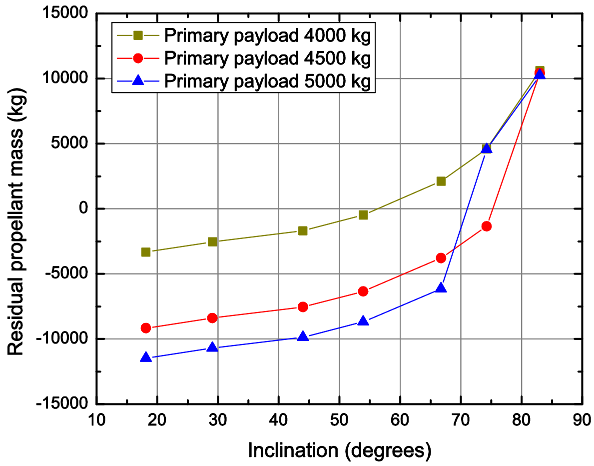
(a) Propellant used versus inclination at which EDT is turned on for the Soyuz upper stage



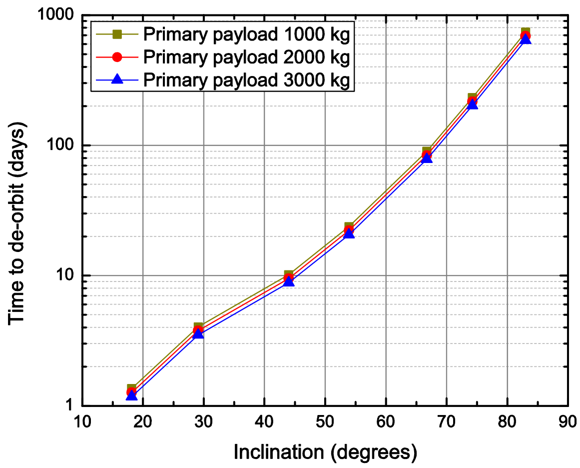
(b) Propellant used versus inclination at which EDT is turned on for the Proton upper stage



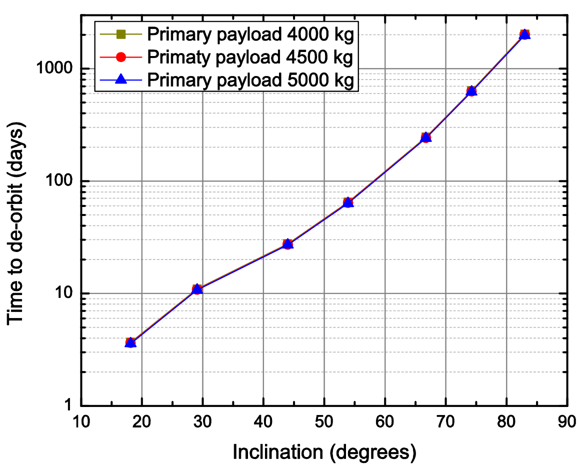
(c) Residual propellant versus inclination at which EDT is turned on for the Soyuz upper stage



(d) Residual propellant versus inclination at which EDT is turned on for the Proton upper stage



(e) Time to de-orbit versus inclination at which EDT is turned on for the Soyuz upper stage



(f) Time to de-orbit versus inclination at which EDT is turned on for the Proton upper stage

Figure 9: Results of simulation of manoeuvres with the Proton and Soyuz upper stages

CONCLUSIONS AND FUTURE WORK

Our preliminary simulation shows that a modified Soyuz or Proton upper stage equipped with a tether system, can deliver a primary payload to a 900 km polar orbit and connect to a Kosmos 3M 2nd stage to de-orbit it. The Soyuz has enough propellant to reduce the inclination of the orbit to 70-80 degrees, while the Proton upper stage can reduce it to 55 degrees at most. The electrodynamic tether system can be deployed at these inclinations to provide propulsion to de-orbit the debris. Overall, the modified Fregat can de-orbit the space debris in 150 days while the modified Breeze M can perform the de-orbiting in about 70 days.

It is clear that a hybrid solution using a chemical-EDT system is the best choice for this particular mission because of the short quantity of propellant left from previous stages of the mission.

Future work might include further simulation 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. A future goal is to simulate the EDT system using AGI's STK.

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