Active Debris Removal System: Current and Future Developments

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***Abstract*—Since the first launch of a satellite in 1957 (Sputnik 1) the number of objects orbiting around Earth has increased. Today this number is estimated around five thousand, many of them being not operative, and so not controllable in any way. For the last fifteen years, the space communities have proposed different ways to reduce these numbers. One of these is the Active Debris Removal (ADR). Starting from this problem, this paper aims at proposing a new methodology to reduce the number of debris, using ADR technology. This will be done by studying a mission with the aim of removing five debris in one year to a dead orbit with lifetime of 25 years. This paper will consider all the aspects of the mission from the launch to the end of life of the satellite. The debris will be removed using expendable foam to increase the area of the debris and decrease their burn time. Finally, the study of costs and risks associated with the mission will be presented. This new approach is feasible and potentially offers new ways to reduce the number of debris in orbit. This will increase the safety of today's operating satellites for telecommunication, navigation and military purpose. This will also make future missions possible. At the end, there is a feasibility study of a magnetic ADR technology. This strategy is not possible nowadays, but with the improvements in the next 10 years, it could become one of the best ways to remove space debris.**

I. INTRODUCTION

An orbital debris is any man-made object in orbit around the Earth that is not controlled. This includes dismissed satellites, rocket stages and the results of two objects colliding. Today it is estimated that around 20,000 pieces of debris larger than a soft ball and 50,000 of them not larger than 1 cm are orbiting the Earth [1]. All of them have velocity around 7.5 km/s. This velocity is enough to even allow a small debris to disable a satellite. An impact with a bigger object can provoke a reaction chain that can make impossible new missions to space. The numbers above do not include thousands of smaller objects because it is impossible to trace them with the current technology. This paper will then propose some new approaches to reduce the number of debris, and to make future space missions possible, with a high safety standard.

A. Problem Description

Some researchers and scientists have pointed out the risk associated with the increasing number of objects orbiting around the Earth. In 1978 Donald J. Kessler with the so-called Kessler syndrome theorized that the risk of a catastrophic clash chain could not be reduced to zero, due to the high density of orbiting objects.

This would happen even if no new satellite were launched [2]. The increasing number of debris orbiting around the Earth reported in Figure 1 poses a hazard to every new mission.

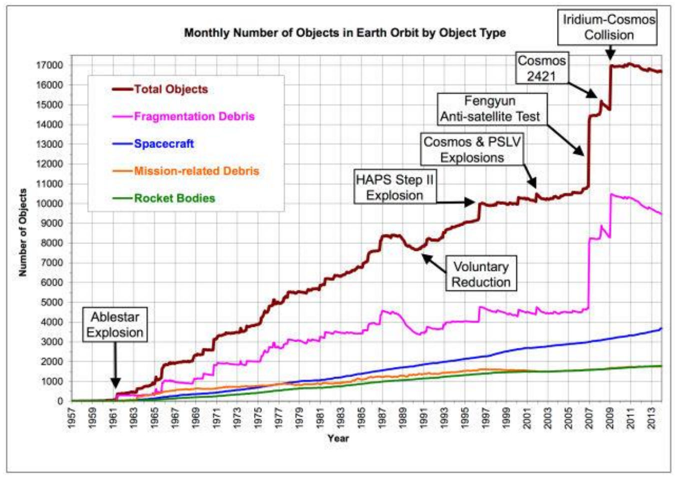

Fig.1 ***Debris growth in the last 55 years***

B. Motive of the Project

The aim of this report is to perform a preliminary analysis of a space mission able to reduce the debris' population in the Low Earth Orbit (LEO). Some calculation will be performed to prove that is possible to remove 5 debris, and place them to a dead orbit with a lifespan of 25 years. All this has to be accomplished in one year.

C. Approximation Used for Calculations

Since this paper is only a preliminary study, some assumptions were made, to make the calculations easier. They are reported hereunder:

- The mass of the satellite is assumed to be constant during the whole mission. The mass of fuel consumed is then calculated from the increment in velocity ΔV necessary for the maneuver.
- The orbits are considered circular, since the value of the eccentricity is low ($e < 0.003$). Their radius is the average value between the values at apogee and perigee.
- Optimal expansion of the foam is assumed.

- While studying the motion of satellite, all effects like air drag, Earth's magnetic field, solar wind or Earth's oblateness effect were not considered.

II. Mission Description

This mission consists in different phases detailed below:

1. ***Launch:*** For the launch phase, it is important to choose an orbit that the selected launcher can reach. This orbit must be around 90° of inclination and with radius around 700-800 km.
2. ***Catching Phase:*** The catching phase is performed with robotic arms that will grab the debris from their nozzles.
3. ***De-orbit:*** After the satellite catches the debris it will begin the de-orbiting phase. Using its thruster, the satellite will move the debris to a lower orbit. In the meantime, the debris will be charged to make more effective the expansion of the foam.
4. ***Targeting Next Debris:*** When the debris is at the right altitude, the satellite will detach from it and move to the next target.
5. ***Foaming Process:*** To avoid any unwanted interaction between the foam and the satellite, the foam will begin to expand only sometime after the separation of the satellite and the debris. Due to the different charge of the debris' surface and the foam the adhesion is assumed to be perfect. The expansion of the foam will increase the area of the debris, and allow shorter decay time.
6. ***Satellite End of Life:*** After the last debris has been de-orbited, the satellite will remain attached to it. With a combination of thruster and foam they will burn up together in the atmosphere.

A. Debris

From Figure 2, it is possible to see that the region with the highest density of debris is around 600-1200 km of altitude. Most them are in orbit with an inclination angle around 90°.

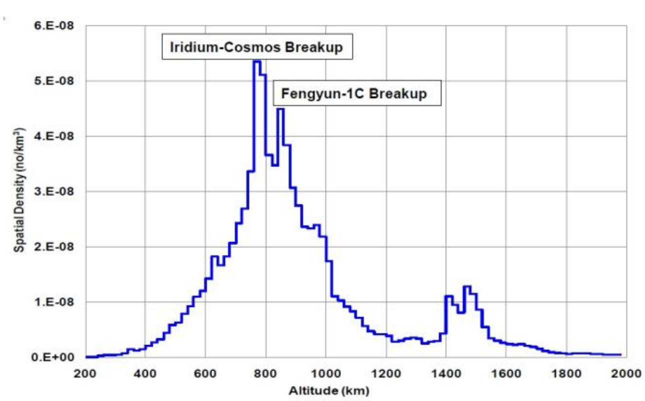

Fig. 2 ***Debris distribution according to 2011 NASA report [3]***

B. Selection of Debris

All the information about the debris are taken from Castronuovo 2011 [4]. The chosen debris are listed below. They are Thor Burner and have orbit radiuses between 700 and 900 km, and values of inclination around 98°. The orbits are assumed circular. Furthermore, the use of orbital parameters will simplify the calculations of orbital transfer maneuvers.

Table I: Selection of Debris and Their Characteristics

	Mass (kg)	i (deg)	Ω (deg)	ω (deg)
1	65	98.84	246.7	11.23
2	65	98.59	235.3	1.45
3	65	98.38	220.8	27.31
4	65	98.87	224.1	0.59
5	65	98.91	233.9	8.32

The selection of debris was made before discharging the electromagnetic concept. The small mass was selected to have small power requirement for the electromagnetic system.

Below is reported Fig. 3 that shows the debris' orbit around the Earth. The lines are bigger for clarity purpose.

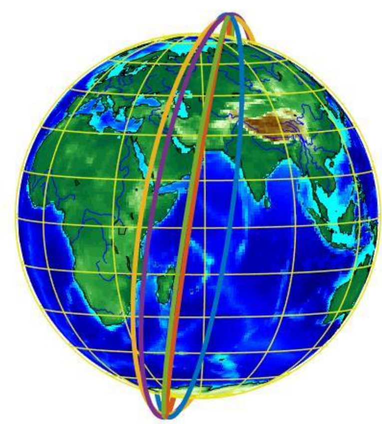

Fig. 3 Orbits Around Earth

C. Satellite

The satellite design is based on the existing Orbital Life Extension Vehicle (OLEV). The OLEV system is based on the SMART-1 platform developed by the Swedish Space Corporations, called SMART-OLEV. Some considerations on the satellite are made below:

1. *Satellite mass:* The first data to know is the mass of the satellite. This will also include the fuel needed to perform the mission.
2. *Propulsion System:* The satellite will use a low thrust system. Once the thrust T and specific impulse I_{sp} are known the value of the velocity change ΔV can be calculated. With this value, it is possible to calculate the mass of fuel needed to perform that maneuver. All the formulas necessary to obtain these values are reported below:

$$\Delta V_a = \left|\sqrt{\frac{\mu}{a_2}} - \sqrt{\frac{\mu}{a_1}}\right| \tag{1}$$

$$\Delta V_i = V\sqrt{2 - 2cos\left(\frac{\pi}{2}\Delta i\right)} \tag{2}$$

$$\Delta V_{\Omega} = \frac{\pi}{2}\sqrt{\frac{\mu}{a}}|\Delta\Omega| sin(i) \qquad (3)$$

To compute the ΔV for a low thrust maneuver that changes the radius (a), inclination (i) or the value of RAAN (Right Ascension of the Ascending Node, Ω) the formulas 1-3 are used, from [5].

Once the ΔV is calculated from parameters like the I_{sp} and the thrust T, that are typical for each engine, the time Δt required to perform a maneuver can be calculated with the formula below:

$$\Delta t = \frac{\Delta V}{f} \qquad \text{where} \qquad \left[f = \frac{T}{m_{sat}}\right] \ (4)$$

$$m_{sat} = m_{dry} + m_{fuel} + m_{debris} \ (5)$$

For de-orbiting maneuvers, as the satellite uses its thruster to move the debris, the mass of the latter must be included in the total mass of the system performing the maneuver.

When the ΔV is calculated and the values of T, I_{sp} and the final mass of the satellite m_f are known, the initial mass m_i can be calculated from eq. (6) below. Once these two values are known the value of the fuel required can be found from:

$$m_i = m_f\left(e^{\frac{\Delta V}{I_{sp}g_0}} - 1\right) \qquad (6)$$

$$m_{fuel} = m_i - m_0 \qquad (7)$$

Using the equations above, the total fuel and time required for the whole mission can be calculated: This provides a tool to verify if the satellite properties meet the mission requirements.

3. *Catching of the Debris:* Once the satellite is on the debris' orbit, some time is required to reach the debris. This time has been calculated in the worst-case scenario, i.e. the satellite gets to the debris' orbit at one point and the debris is situated at the opposite side of the orbit. The satellite will then move to a lower orbit than the debris, so it will travel faster than it and it would close the gap to the debris. When the distance is small enough, the approach phase begins. For the satellite's approach to the debris, a standard time to consider the maneuvers necessary to dock an orbiting object with unknown dynamics (e.g. possible rotations around different axes) is allotted. When the satellite has the same attitude as the debris, the catching phase begins. With the use of multiple robotic arms the satellite will grab the debris, and the de-orbit phase can start.
4. *De-Orbiting:* When the satellite and the debris are attached together this phase begins. In this part the satellite will use its engine to move the debris to a lower orbit. While moving towards the lower orbit, the satellite will charge the debris. This will increase the strength of the bonding between the foam and the debris' surface. When the lower orbit is reached the satellite will detach from the debris. Sometime after the satellite separation from the debris, the foam will deploy and cover the whole debris. When the foam is deployed the area of the debris will increase and this will allow a shorter decay time. The decay time can be calculated with the formula from ref. [6]

$$T_d = \frac{h}{\sqrt{\mu R}B\rho}\left(e^{\frac{H_0}{h}} - 1\right) \qquad (8)$$

Where $$B = \frac{C_d A}{m_{deb}} \qquad (9)$$

Here T_d is the decay time, H_0 is the altitude at which the debris is, ρ is the density at that altitude and h is the scale height. In the definition of B are included the front area A and the drag coefficient of the debris C_d. It also includes the mass of the debris m_{deb}.

The scale height (h) is taken from [7]. The density has been calculated assuming an exponential atmosphere. The value of the decay time is very sensitive to the value of the scale height h. For this analysis, the value is the one at the chosen altitude (350 km) from [7].

5. *Time Limitation* For every debris of this mission the time frame for the removal is fixed at 25 years. The satellite will be removed with its last respective debris. The rocket stages will be left in specific orbit with a life-time shorter than 25 years. This value is the upper limit set for this mission.

D. Rocket

The satellite designed for this mission has a weight around 1500 kg. To bring this satellite to a LEO orbit a suitable rocket needs to be chosen. In the selection of the rocket, cost consideration was the primary concern. Research has been done and a launcher has been selected. The choice is the Polar Satellite Launch Vehicle (PSLV), because it is cheaper than any other commercially available launching system. The cost per launch is a quarter of what is required for a Falcon 9. This rocket is operated by the Indian Space Research Organization (ISRO). For this mission the XL version of the PSLV is selected to have margin if the mass of the satellite changes. Table II gives data to confront the PSLV and the Falcon 9.

Table II: Comparison between Falcon 9 and PSLV XL

Parameters	Falcon 9	XL
Manufacturer	Space X	ISRO
Country of Origin	USA	India
Cost per Launch	$62M	$15M
Size		
Height (m)	70	44
Diameter (m)	3.7	2.8
Mass (kg)	549,054	320,000
Stages	2	4
Capacity		
Payload to LEO (kg)	22,800	3,800

Payload to GTO (kg)	8,300	1,425

If the satellite's mass is less than PSLV's maximum payload, the cost of the launch can be decreased by sharing the launcher with other organizations interested in launching their satellites to a similar orbit. Table III displays the specifications of the four stages of PSLV XL.

Table III: Specification of all PSLV XL stages

	Stage 1	Stage 2	Stage 3	Stage 4
Thrust (kN)	4,800	799	240	15.2
I_{sp}sea level (s)	237	-	-	-
I_{sp}vacuum (s)	269	293	295	308
Burn time (s)	105	158	83	425

1. *Launch Simulation*

In the first part of the flight, the rocket flies vertically. The rocket's motion is described by the following equation (adapted from [8] p.231 with a drag term D added):

$$\frac{dV}{dt} = \frac{T}{m} - \frac{D}{m} - g \quad (10)$$

Where

$$T = \dot{m_e}\, I_{SP}\, g_0 \quad (11)$$

$$D = \frac{1}{2}\rho V^2 C_D S \quad (12)$$

In the formulas above V is the velocity of the rocket and m is its mass. Re is the Earth's radius, g_0 is the acceleration of gravity at ground level while g is the acceleration of gravity that varies with altitude following the formula below:

$$g = \left(\frac{g_0}{1 + \frac{h}{Re}}\right)^2 \quad (13)$$

The mass flow rate $\dot{m_e}$ is assumed to be constant and equal to:

$$\frac{dm_e}{dt} = \frac{m_{0s} - m_{fs}}{t_{burn}} \quad (14)$$

Where m_{0s} is the initial mass of the stage, m_{fs} is the final mass of the stage when all the propellant is burned, and t_{burn} is the burnout time of the fuel in the tank.

After some height, the rocket is tilted to perform a gravity turn and save some fuel. Hence the rocket equations become (adapted from [8] p.234, with the extra speed V_{extra} due to the Earth rotation included):

$$\frac{dV}{dt} = \frac{T}{m} - \frac{D}{m} - \left(\mathrm{g} - \frac{\dot{X}^2}{Re + H}\right)\sin(\gamma) \quad (15)$$

$$\frac{d\gamma}{dt} = -\frac{1}{V}\left(\mathrm{g} - \frac{\dot{X}^2}{Re + H}\right)\cos(\gamma) \quad (16)$$

$$\frac{dX}{dt} = V\cos(\gamma) + V_{extra}\sin(\gamma) \quad (17)$$

$$\frac{dH}{dt} = V\sin(\gamma) + V_{extra}\cos(\gamma) \quad (18)$$

Here, X and H are the coordinates of the rocket in the local horizon frame (round Earth approximation), and $\gamma$is the flight path angle of the vehicle. The system of differential equations above can be solved with MATLAB for all four stages. Here the initial conditions of stage (n+1) depends on the final conditions of stage n. The tilting angle γ, the height where the tilt is performed and the time during which the final stage is thrusting are the adjustable parameters. Their values are set to get the right altitude with the right speed and the right flight path angle when reaching the orbit of the first debris.

E. Launch

1. *Launch site:* Since PSLV XL is operated by ISRO the Launchpad is in Satish Dhawan Space Centre (Sriharikota, Andrade Pradesh, India). The coordinates are: Latitude 13°43' N and Longitude 80°13' E.

2. *Trajectory:* Since all the debris are in orbit with inclination around 98° this is the target for the final orbit. The final altitude is the altitude of the first debris (758 km). The Earth rotates in the eastward direction. At the equator, this speed is 465 m/s, and a fraction of it can be exploit to burn less fuel. At the launch site the speed from the rotation of the Earth is the value at the equator times the cosine of the latitude, hence 452 m/s.
The target orbit is located at an altitude of 758 km. Because this orbit is circular, the required speed to stay on the orbit is:

$$V_{objective} = \sqrt{\frac{\mu}{(Re + h)}} = 7.48\ km/s \quad (19)$$

Where Re is the radius of the Earth (6375 km) and μ is the Earth's gravitational parameter (398600 km^3/s^2).
The inertial launch azimuth A can be calculated from the launch site latitude l and the orbit's inclination *i* =98.38°:

$$\sin(A) = \frac{\cos(i)}{\cos(l)} \quad (20)$$

The value of A is then:

$$A = -8.62°$$

The azimuth is negative because the orbit inclination is greater than 90°. Using this azimuth, the rocket would be launched westwards and the Earth's rotation would slow it down. To exploit the Earth's rotation and save fuel the rocket should be launched eastwards. Hence the inertial azimuth to use is:

$$A_{East} = 180° - |A| = 171.37° \qquad (21)$$

With this value the objective speed in the Earth's rotational frame is calculated. From this value, the amount of Earth's rotation speed at the launch site an in the launch direction can be obtained (see Fig. 4). This velocity is used as extra speed for the rocket.

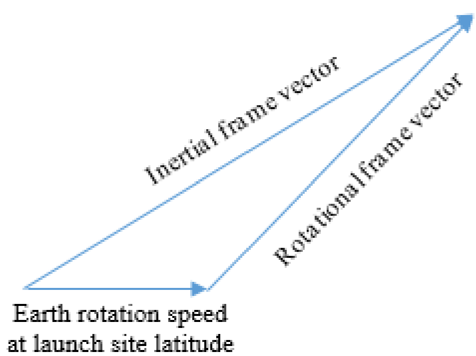

Fig.4 Calculation of Earth rotation speed used during launch

From Figure 4, the objective speed in the Earth's rotational frame is:

$$|\boldsymbol{V}_{rot}| = 7.42\ km/s$$

Hence, launching eastwards with a 171.37° azimuth saves 53 m/s to reach the orbital velocity. This value is used in the equations 17 and 18, as V_{extra}.

F. *Cost Estimation*

For PSLV XL the cost per launch is around $15 million. This cost is a quarter of the $62 million necessary to use the Falcon 9. Since the satellite weight less than 1.5 tons and the capacity of the PSLV is 3.8 tons to LEO, this cost can be further reduced. This can happen sharing the space in the payload area of the rocket with another mission. For the satellite the cost is estimated in around $22.5 million. This value is reached with the hypothesis of cost around $15000/kg of the satellite. This value is from [9] and is in accordance with other similar satellites.

G. *Risk Analysis*

1. *Rocket*
Since the rocket has four stages the chances of failure are high. But till now 14 launches out of 14 have been completed without any problem. This testifies that the rocket has a robust design. Nevertheless, some problems during launch may always occur in the future and safety must remain a pivotal point. Some problems may also arise from the left stages. Indeed, they remain in orbit with no fuel, and hence without control. Especially, stages two to four contain tanks for their pressurized liquid propellant. These tanks are made of thick metal walls, and is not certain that they will burn up entirely crossing the atmosphere, as reported in ref. [10], [11] and [12].

2. *Approach of the Satellite to the Debris*
This is the trickiest part because of the high risk that approaching an object with unknown attitude may pose. This phase creates high threat to the integrity of the satellite, and because of that during this phase the satellite uses several sensors to avoid collision. The sensors include RADAR, LIDAR, infrared sensors and a magnetometer. A manual backup is always available. The grabbing maneuver is performed with robotic arms. This allows the satellite to leave on the debris the device that will deploy the foam safely.

3. *Foam expansion*
The foam used in this project can increase its volume to 100 times its initial one. The expansion is assumed ideal. The foam will firmly stick to the debris due to the opposite charges of debris' surface and the foam.

4. *Re-entry of the Debris*
The reentry of debris can also pose harm to other satellites due to the increased area of the debris. The release altitude of the debris is 350 km. Around this altitude, there are several satellites and the International Space Station orbiting. Therefore, when crossing this area of space to reach lower altitude, great attention is needed not to crash into another object, which would make the mission fail and increase the number of debris instead of decreasing it.

III. RESULTS

A. *Rocket*

The equations 15 to 18 implemented in MATLAB give the values of velocity and altitude of the rocket during the launch phase. The rocket starts vertically with respect to the ground. At a certain height (h = 187.4 m), using the thruster in the upper part, the rocket is tilted to reach a flight path angle γ of 88.69°. After some time, the first stage separates and the other stages continue the mission. The other stages will burn out one after the other, until the fourth stage places the satellite into the final orbit. This is the first debris' orbit. The altitude of the first target is 758 km. The velocity in this orbit is 7.48 km/s, from formula (19). To reach this value the rotation of the Earth can be used to decreased the fuel required. From the simulation, after the launch the rocket arrives at the right altitude, with the right speed, the final angle is 3.68° greater than the orbit's inclination. This can be corrected using the fuel left in the tank of the fourth stage. Indeed, the stage has a burnup time of 525 s, and during this mission its engine are used for 488 s. When the satellite is placed in the right orbit the fourth stage is placed in an orbit with life span of less than 25 years. The graphs of altitude and velocity over time of the rocket are given in Figures 5 and 6, respectively.

B. Satellite

The design of the satellite is based on the SMART-OLEV specification. The propulsion system is a low thrust ion engine called NASA Evolutionary Xenon Thruster (NEXT). This engine is under construction, with the first mission scheduled for 2019. It has been tested for 43000 hours without any failure. The engine can provide 236 mN of maximum thrust using 6.9 kW of power. All with an I_{SP} of 4190 s [13]. The engine can be throttled down to 0.5 kW. The engine will use only a fraction of the power required, to produce 200 mN of thrust T.

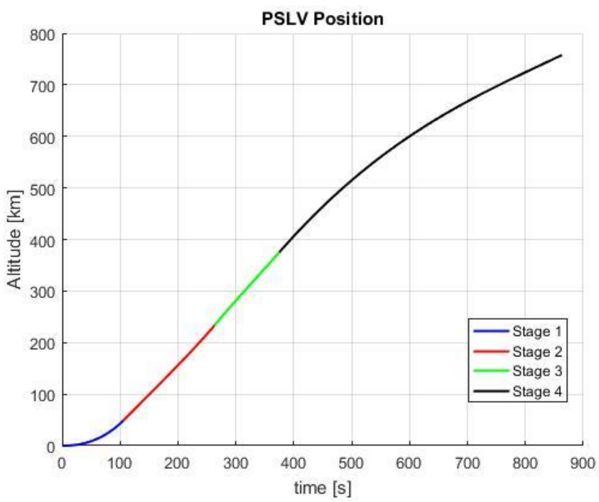

Fig. 5 Altitude over time for the launch

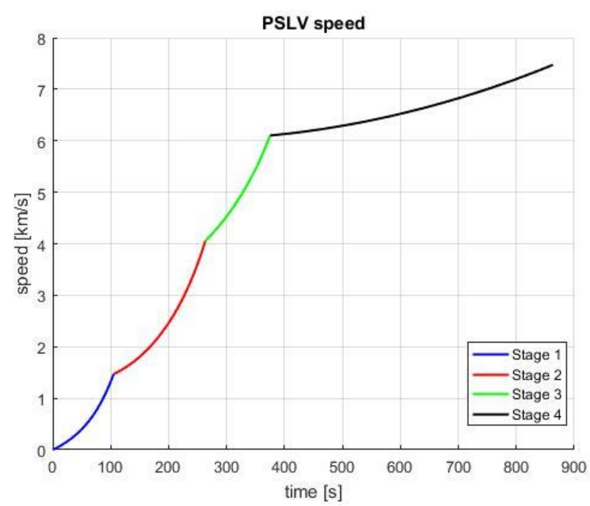

Fig. 6 Velocity over time for the launch

To support the power requirement of this system, some solar panels are used. The best cells currently available have efficiencies between 20 and 25%, with power density of $P_\rho = 300$ W/m^2. Accounting for all the satellite's systems and keeping a safety margin the power required is $P_r = 6.5$ kW. The area needed to get that power is given by the formula hereunder:

$$A = \frac{P_r}{P_\rho} = 21.6\ m^2 \tag{22}$$

This area is covered with two lines of solar arrays, each one with an area of 10.8 m^2. The dry mass is around 1000 kg.
To calculate the ΔV required, an I_{SP} of 4190 s and trust T of 200 mN are set. The final value is 5.7 km/s.
To compute the time, once the value of ΔV is known, the formula (4) is used. The mass in every case is the satellites' mass at that moment plus the mass of the debris. For the whole mission 210 days are necessary. The fuel required to complete the mission calculated with the Tsiolkovsky equation is 160 kg.

C. Debris Removal Technology

A bit of time after the satellite leaves the debris at the final altitude the foam will deploy, and surround the debris completely. A Polyurethane foam is used due to its simple production and its high expansion ratio (order of 100 to 1), following suggestion of [12]. The use of the foam increases the area and so decreases the burn up time. In case of collision with other objects, due to the property of expandable foam, they can be encompassed by the foam. This reduces the risk of increasing the number of debris as consequence of an impact. Since five debris need to be removed, five removing devices containing the foam are necessary. The final density is around 2 kg/m^3. The final volume is around 14 m^3, the mass of foam in each device is then 28 kg. To this weight, 10 more kg is added for the tanks, electronics and case containing the systems. Thus the final weight of each device is 38 kg.

D. Debris Decay Time

The decay time of an object is calculated with formula (8). For the calculation, the coefficient of drag $C_d$is set at 5, due to the roughness of the surface with the foam deployed. The final value depends among other things on the mass and the area of the debris. Based on this value, each debris will have the same decay time. The time of decay for every debris of 7 and a half years.

IV. Discussion

A. Possible Improvements

The mission described in the previous paragraphs uses a launcher, PSLV XL, that has four stages. The last two stages do not fall into the ocean after they have burnt-up. While the fourth stage has enough fuel to re-enter the atmosphere, the third will remain in orbit, adding one more debris to those currently in orbit. So there is room for improvement in our mission. The third stage needs to re-enter the atmosphere, because otherwise the effort to remove debris would be useless. Recovering the first stages to re-use them can reduced further the cost.

B. Safety and Reliability

1. Rocket

Even if PSLV XL has never had any failures during launch, safety during launch must remain an important point. During the fall of the last three stages they may not burn-up completely. This can happen to the tanks for the liquid fuel, as reported in [10] and [12]. If these debris reach the ground, they can cause serious harm to the people living in the area. Once the stages have burnt-up, if any fuel is left in the tank, it could be used for re-entry.

2. *Satellite*

The satellite's operation is automated but there is always a manual backup available. In the approaching phase the risk of collision with the debris is high. All the onboard systems are used to prevent this from happening. After the satellite has moved the final debris to the right altitude, it stays attached to it and the foam is deployed. Then the satellite's tank will be emptied to prevent explosion due to collision with other debris. A clever design of the satellite would ensure that it would burn up completely during re-entry. Research on this issue are currently ongoing.

The probability of a person on Earth being hit by a debris is low, in the order of 10^{-12}. But this event already happened as reported in ref. [11], and many objects have reached the ground during the years [10] and [12]. They were mainly liquid fuel tanks. If this kind of object hits a person it will cause serious harm. Even if the risk is low, further development could make sure that no debris can reach the ground after crossing the atmosphere. This would lower the risk of harming people.

V. Conclusion

As discussed in the previous paragraphs the mission is feasible in the time frame of one year from launch. The satellite is reliable and able to perform the mission. The satellite will carry five de-orbiting devices, one for each debris. They will have separate tanks for the foam component and all the electronics to control the foam expansion. The use of foam for the removal allows faster decay time, and better fuel economy. The release height is 350 km. With the use of foam with higher expansion ratio the release altitude could be further increased. The satellite has an empty weight of 1180 kg and will use 160 kg of fuel. This value is the result of the high efficiency of the ion thruster. A similar mission with chemical propulsion would have required around 16 tons of fuel, assuming a specific impulse I_{SP} of 300 s.

VI. Division of Work

During this project, Ali Taghavi and Vishal Hayagrivan investigated on Active Debris Removal technologies and the feasibility of a magnetic removal system. Federico Rorro and Mathieu Schincariol worked on low-thrust orbital maneuvers, debris decay and cost analysis. Harianas Dewang and Pierre Arrou-Vignod were in charge of the launcher selection and launch trajectory simulation.

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Appendix

Feasibility Study of Magnetic Debris Removal

***Abstract*—This section contains the calculation for the magnetic ADR technology. This was our first choice, but has proved to be impossible to use with the current material. Since a lot of time and effort was spent to study this idea, an appendix to describe it was necessary. This technology, with a careful selection of target, can reduce the fuel required to move between different orbits.**

A.1 Technology description

With this concept onboard of the satellite is generated a magnetic field with an electromagnet. For this technology to work properly, the target should be made of metal. Every satellite today in orbit have a certain percentage of metal in them, and this will be used as described below. Once this system is turned on, the debris will slow down and will move towards the satellite. Since we are in free space even the satellite will move towards the debris. A certain time after the electromagnet is turned on it will be shut down. This to prevent the two object from colliding. The magnetic field is assumed to start and stop instantaneously. When the electromagnet is turned off, the debris will have less velocity than at the start, and so will move to an orbit with smaller radius. Opposite thing will happen to the satellite. It will accelerate and so moved to an orbit with greater radius. If the time this system is working is well calibrated two things will happen. The debris will reach a lower enough altitude to burn in the atmosphere without any other intervention. The satellite will move to the next debris' orbit without using any more fuel, but only exploiting the effect of the magnetic force.

A.2 The basic design

The electromagnet is a solenoid, a coiled wire around the core. This kind of design can produce a magnetic field. The magnitude of this magnetic field B can be calculated with the formula below:

$$B = nI\mu \int_0^l \cos\theta d\theta = nI\mu(sin\theta_1 - sin\theta_2) \quad \text{(A1)}$$

Where n is the number of coils per unit length, I is the current passing through the wire, μ is the magnetic permeability of the material of which the coiled are made. The angles θ_1 and θ_2 are marked in the picture below. D is the distance from the target.

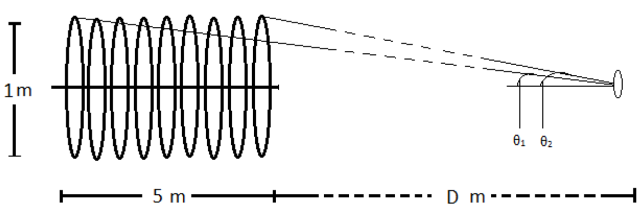


Fig. A1 Solenoid dimensions and angles definition

When the magnitude of the magnetic field is known, the force F generated can be calculated with the following formula:

$$F = \frac{B^2 A}{2\mu} \quad \text{(A2)}$$

Where A is the area of the coils, modelled as a cylinder.

A.3 Results

A.3.1 Force and Time Required

Using the following parameter for the material of the wire:

Table A.I Characteristics of the Solenoid's core material

Magnetic Permeability (μ)	1.26	[H/m]
Relative Permeability (μ/μ_0)	10^6	[-]
Density	7180	[Kg/m^3]

Where μ_0 is the permeability vacuum.

The parameter above refers to *Metglas 2714A* (A3) the material with the highest magnetic permeability today available. This material has a magnetic permeability a million times higher than the vacuum.

With formulas A1 and A2 results the magnetic field strength and the force generated by the solenoid are computed. The magnetic field, and hence the force generated, depends on the inverse of the square of the distance. The final speed is determined by the final altitude set for the debris (250 km). The initial velocity is the velocity at 700 km altitude. The magnitude of the ΔV necessary to reach the desired final altitude can be calculated with formula (1), setting a_2 as the final altitude and a_1 as the initial one. To achieve this value of ΔV some time is needed. This is called time required. Another time, called time available, estimates the time before the two objects collide. All the information above are reported in the following graphs. Two graphs is reported because of scaling issues.

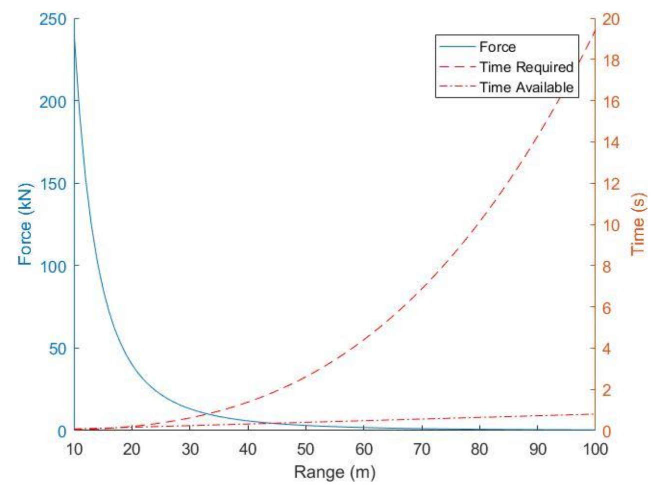
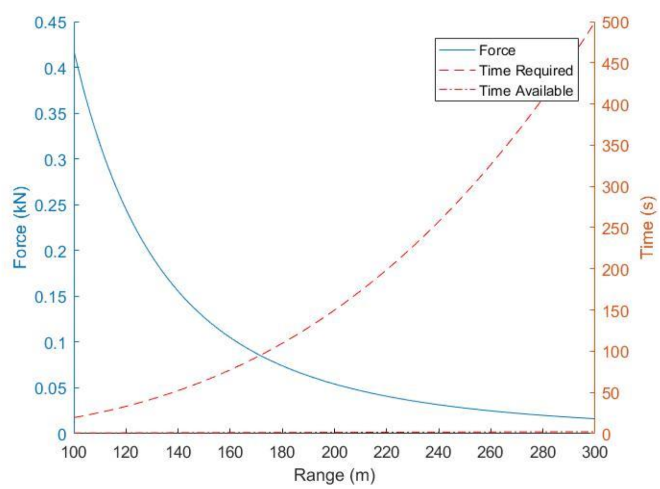


Fig. A2 Diagram of force and time from 0 to 100 m range

Fig. A3 Diagram of force and time from 100 to 300 m range



The only intersection between time available and time required, and hence the only solution for this problem is at 0.2 m range. This value is too low to ensure safety during operation. Also the force generated decreases significantly with distance, as explained above.

A.3.2 Mass Evaluation

In this section some calculation is performed to evaluate the mass of such a system. The hypothesis is to move a debris from an orbit with altitude of 700 km to a final altitude of 250 km.

To do so a ΔV calculated with formula (1) is necessary. The value is 125 m/s, in the opposite direction to the debris motion. With the current technology, a density n of 1000 coils per unit length is possible. With this density, the solenoid must have the dimension in figure A1, 5 m length and 1 m diameter. This will result in a solenoid that will weight around 28 tons. The current required to generate such a magnetic field is 100 A.

A.4 Discussion

The results obtained above demonstrate why, with the current technology is impossible to use this strategy for an ADR mission. The first problem is with the mass. A weight of 28 tons, for the solenoid alone, is too expensive to place into orbit. This because in this value is not included the satellite, its control system or the fuel needed to perform the necessary maneuver to target and remove debris. Another problem is the required current to make such a system works. This will need special cable that will add more weight, due to their increased diameter to handle this high current intensity. The third problem is about force. The force that such a system can generate are low at safety distance. A minimum distance must be maintained to avoid any unwanted interaction, that will result in an increase in the number of debris. And a final problem regards the time. To decelerate the debris till the right final velocity, some time is necessary. This value is simply of the ΔV divided by the acceleration, calculated as the force generated divided by the mass of the debris. This is the time required. Apart from distances lower than 0.2 m the time required is higher than the time available before the collision occurs. Is not possible to use such a system at this distance, because this is well below any safety distance necessary between satellite and debris. For all this reasons the use of this technology is today not possible.

A.5 Future Improvements and Implementation

With the development of the technology in the future will be probably possible to produce a solenoid with lower value of mass. This can be achieved with material that will have greater magnetic permeability. A considerable decrease in the material density is not predictable using metallic material for the wire. The use of superconductor cooled down to temperature near 0 K, will increased the performance of such a system. Today these electromagnets are not commercially available. When they will be available the mass and power required will decrease, and magnetic field generated will increase. This improvement can make the implementation of this ADR technology possible in the future years.

A.6. References

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