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DEPLOYABLE DRAG DEVICE FOR LAUNCH VEHICLE UPPER STAGE DE-ORBIT

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Orbital debris is a growing problem in low Earth orbit; it has crossed a threshold of critical density where the number of debris objects will grow exponentially unless mitigated. Spent launch vehicle upper stages represent a problematic category of orbital debris in highly utilized orbits. They can stay in orbit for well over 100 years if left to deorbit naturally, and they represent a significant fraction of large space debris in low-Earth orbit. It is estimated that removing a few large objects per year will mitigate the exponential growth of debris. To address the debris problem, a trade study was conducted to determine a deployable drag device to accelerate the orbit degradation of upper stages. Following the operation of the upper stage, the drag device will be deployed to decrease the orbit lifetime of the system. The design is targeted toward upper stages launched into orbital altitudes ranging from 650-850 km. Three categories of deployable drag devices are being investigated: drag sails, inflatable aerodynamic decelerators, and electrodynamic tethers. These are compared to the option of using residual propellant in the upper stage to perform a burn to initiate a deorbit trajectory. The device will be mounted to the upper stage using a standardized secondary payload launch interface, such as a CubeSat deployer device or the EELV Secondary Payload Adapter (ESPA). The trade study compared the drag device configurations based on cost, risk, and deorbit time. A maximum deorbit period of 25 years is a performance design requirement. The propulsive option was shown to be the lowest cost option, however the drag device is more mass efficient and has less of an impact to the payload capability of the launch vehicle. An aerostable drag sail design is proposed as a baseline design for the device.

I. INTRODUCTION

Orbital debris is a growing problem in low Earth orbit; it has crossed a threshold of critical density, known as Kessler Syndrome, where the number of debris objects will grow exponentially unless mitigated as a result of objects colliding and creating more debris. When the Cosmos and Iridium satellites crashed in 2009, 2000 trackable objects and on the order of 100,000 untracked objects were added to orbit [1]. It has been shown that removing five large objects from Low Earth Orbit (LEO) per year will mitigate Kessler Syndrome, if started by 2020 [2]. There have been many proposed systems for active removal of debris from orbit. A more efficient, and far less costly approach is to accelerate the orbital decay of large space systems through the use of passive drag devices.

Spent launch vehicle upper stages represent a problematic category of orbital debris in highly utilized orbits. They can stay in orbit for well over 100 years if left to deorbit naturally, and they represent a significant fraction of large space debris in low-Earth orbit [3]. This research is focused on accelerating the orbit degradation of launch vehicle upper stages by using a deployable drag device that can be launched as a secondary payload and deployed using a standard deployment system for secondary payloads. Following the operation of the upper stage, the drag device will be deployed to passively decrease the orbit lifetime of the system. This paper discusses the trade study that was conducted to compare the drag device configurations based on cost, risk and deorbit time. The selected baseline drag device is described.

II. TRADE STUDY PARAMETERS

The trade study involved five main areas: device type, launch vehicle, target orbit altitude, design decay time, and packaging volume. The different options in each category can be seen in the Morphological Matrix in Table 1.

II.I Device Types

There are four main device types that are considered for orbit debris removal. The first is a drag sail, which is similar in concept to a solar sail. For the initial trade study, it was assumed to be a square planar sail comprised of four booms that support a thin membrane, as seen in Figure 1. Additional hardware includes a deployment motor and electronics to initiate deployment.

The second device type is an inflatable balloon. It was assumed to be a thin membrane that is inflated with a gas to form the shape of a sphere [4], as seen in Figure 2. It was decided not to have the membrane rigidized because collisions with the non-rigidized balloon have a lower risk of creating more debris in the event of a collision [5].

The third device is an electrodynamic tether. The electrodynamic tether interacts with the Earth's

Architecture Decision	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6
Device Type	Drag Sail	Inflatable Balloon	Tether	Propulsive		
Launch Vehicle	Falcon 9	Delta IV	Atlas V			
Target Orbit Altitude	High LEO (850-1000 km)	Mid LEO (700-850 km)	Low LEO (600-700 km)			
Design Decay Time	25 years	15 years	10 years	5 years		
Packaging Volume	3U PPOD	6U PPOD	12U PPOD	27U PPOD	1/2 ESPA	Full ESPA

Table 1: Morphological Matrix for drag device trade study

magnetic field in such a way that it creates a drag force that decreases deorbit time [6], as shown in Figure 3.

The fourth approach to deorbit is to utilize the launch vehicle upper stage on-board propellant and guidance system to perform a controlled deorbit. This approach is generally viable, however, allocation of propellant for deorbit reduces the payload mass capability of the launch system. In evaluating propulsive deorbit in this trade study, propellant mass was sized to ensure deorbit within each of the discrete decay times in the morphological matrix.

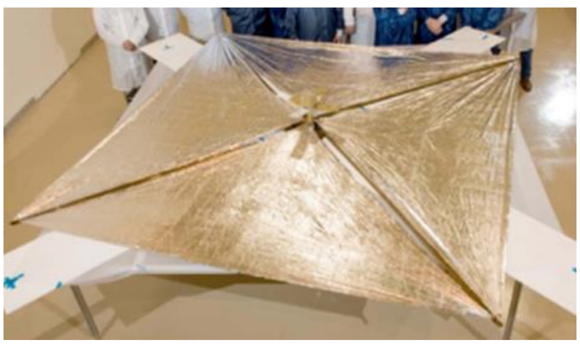

Fig 1: NanoSail-D solar sail, similar design to drag sail in trade study [7].

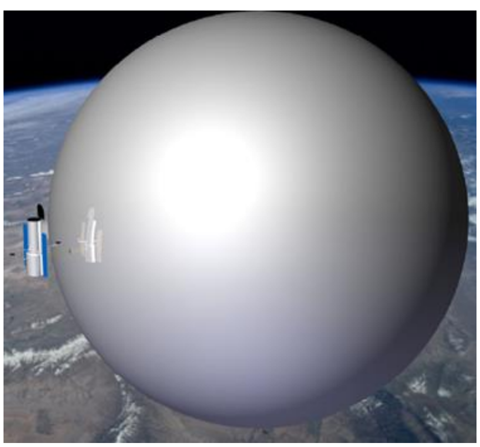

Fig. 2: Gossamer Orbit Lowering Device (GOLD), similar to inflatable balloon used in trade study [4].

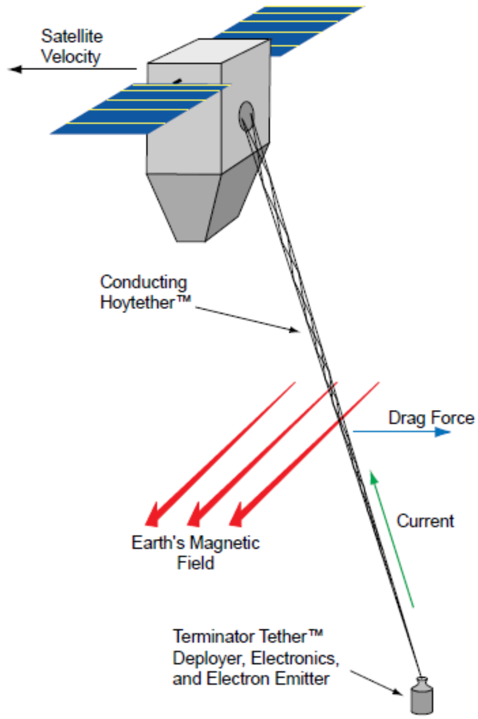

Fig. 3: The Terminator Tether, similar to the electrodynamic tether used in the trade study [6].

II.II Launch Vehicles

The launch vehicles were selected for this study (Falcon 9, Delta IV, Atlas V) because they frequently send payloads to highly utilized low-Earth orbits, and they are capable of deploying secondary payloads using standardized deployment devices.

II.III Target Orbit Altitude

Low Earth Orbit (LEO) is generally defined as altitudes of 600-1000 km. This was divided into three ranges: Low LEO (600-700km), Mid-LEO (700-850 km), and High LEO (850-1000 km). The upper limit of each altitude range for the target orbit altitude was investigated.

II.IV Design Decay Time

Across the world, many space organizations are creating guidelines for how long defunct objects can remain in space. Across the board, that limit is 25 years. This analysis was hoping to make deorbit time as small as possible to reduce risk. The times are 25 years, 15 years, 10 years, and 5 years.

II.V Packaging Volume

It was decided to use secondary payload mass and volume requirements consistent with standardized secondary payload deployment systems. Each of the launch vehicles listed in Table 1 are capable of deploying secondary payloads. Therefore, treating the deployment device as a secondary payload does not pose any new design requirements on the launch system.

Six different types of secondary payload packaging were investigated. The first four are different sizes of the Poly-Picosatellite Orbital Deployer (PPOD), which is the original CubeSat launching platform. One unit of a CubeSat, or 1U, has dimensions of 10 cm x 10 cm x 11 cm. A 3U PPOD holds a satellite with three of these in line for dimensions of 10 cm x 10 cm x 34 cm [8]. The 6U PPOD is two 3Us next to each other, and so on [9]. With increasing volume, there is an increasing amount of mass allowed as well. The 3U has a maximum mass of 4 kg, and the 6U has a maximum mass of 12 kg.

The mass and volume requirements of the different packaging can be seen in Table 2.

Packaging	Dimensions (m)	Volume (m^2)	Mass (kg)
3U PPOD [8]	0.10 x 0.10 x 0.34	0.0034	4
6U PPOD [9]	0.12 x 0.24 x 0.36	0.0104	12
12U PPOD [9]	0.23 x 0.24 x 0.36	0.0199	24
27U PPOD [9]	0.34 x 0.35 x 0.36	0.0428	54
½ ESPA [10]	0.50 x 0.50 x 0.60	0.1500	90
Full ESPA [10]	0.61 x 0.71 x 0.91	0.3587	181

Table 2: Dimensions for the secondary payload packaging.

The final two stowing packaging are the Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) class payloads. They come in full and half sizes. ESPA payloads have less strict shape requirements than PPODs, but the volume dimensions listed in Table 2 are the general space envelope each payload is given on the launch vehicle [10].

III. ANALYSIS

There were three main variables that were used in a pareto evaluation: risk, deorbit time, and cost. In order to estimate the pareto variables for each configuration, the drag area and mass were also estimated.

III.I Drag Area

The drag area is one of the most important characteristics of the drag sail and the inflatable for this analysis because it is used to estimate deorbit time, collision risk, and cost. The first step in the analysis was to use historical data to estimate the drag area that could be stowed in the different packaging.

III.I.I Estimating Drag Sail Drag Area

The historical missions used as benchmarks were all square solar sails. NanoSail-D is a mission developed by NASA Marshall Spaceflight Center. It had a deployed area of 10 m^2 and was packaged in a 3U CubeSat [7]. CubeSail is a mission by the University of Surrey to demonstrate solar sailing. It has a deployed area of 25 m^2 and is packaged in a 3U CubeSat [11]. LightSail is another solar sailing demonstration mission sponsored by The Planetary Society. It has a deployed area of 32 m^2 and was packaged in a 3U CubeSat [12]. Sunjammer is a mission by L'Garde, Inc. to demonstrate a mission capable solar sail. It has a deployed area of 1200 m^2 and is packaged in a full ESPA [13].

In order to compare the deployed area to the packaging volume, the packing coefficient was calculated by dividing the deployed area by the stowed volume. The values ranged from 5,000 for NanoSail-D to 21,000 for Sunjammer. The estimated deployed areas for each packaging were estimated using a packing coefficient of 16,000 m^{-1}. The values can be seen in Table 3. It was assumed that 70% of the volume would be taken up by the sail and the remaining 30% by other subsystems. Since the drag sail is assumed to be flat, there is no guarantee that it will trim to a maximum drag attitude perpendicular to the flow. To account for this, the drag sail normal was assumed to be oriented 60° away from the flow, so the drag area is estimated as the deployed area multiplied by sin(30°). These values are also shown in Table 3.

Packaging	Drag Sail Deployed Area (m^2)	Drag Sail Drag Area (m^2)	Inflatable Drag Area (m^2)
3U PPOD	38	19	50
6U PPOD	116	58	151
12U PPOD	223	111	289
27U PPOD	479	240	621
½ ESPA	1680	840	2176
Full ESPA	4017	2009	4882

Table 3: Calculated deployed and drag areas for the drag sail and inflatable that can be packaged in each packaging size.

III.I.II Estimating Inflatable Balloon Drag Area

The historical data used was the Gossamer Orbit Lowering Device designed by the Global Aerospace

Corporation. It is a 37 m diameter sphere with a mass of 39 kg packaged in a volume slightly larger than a 27U PPOD [4].

It was assumed that the inflatable balloon would package similar to parachutes by using a constant packing density. The packing density is the amount of "parachute" mass that can be packaged into 1 cubic meter of volume [14] . The mass was divided by the packaging volume to get the packing density. The estimated packing density used was 746 kg/m^3. To estimate the drag areas, the packing density was multiplied by the stowing volume to get the mass, which was in turned divided by the areal density of 0.009 kg/m^2 to get the surface area. The drag area is the area of the circular cross section of the deployed sphere. The drag areas are shown in Table 3.

III.II Mass

For each packaging, the maximum mass allowed based upon the constraints of the secondary payload deployment device was assumed.

For the propulsion option, it was necessary to use the rocket equation to calculate the mass of propellant needed to perform a deorbit burn to ensure specified deorbit times. This mass was then used to calculate the cost of this option for each launch vehicle based upon their price per kilogram of payload mass that can be delivered to the specified orbit.

III.III Risk

Risk is an important parameter for decision making, but it is difficult to quantify. This analysis was divided into two halves that were recombined at the end to have a quantitative value for each option. The first half used the Analytical Hierarchy Process (AHP) to conduct a series of piecewise comparisons. The second half was calculating the area time product.

III.III.I Analytical Hierarchy Process for Risk

Each device type was evaluated based on four different criteria: how well the device adheres to secondary payload requirements, the risk of creating new debris, the risk it will not fully deploy, and the risk that it will not stay deployed. Table 4 shows the first step which is to create a matrix of comparing the criteria to each other in terms of importance. Then, for each criterion, a matrix is created to compare each device to each other. These can be seen in Tables 5, 6, 7 and 8.

These matrices were created by assigning a value to one option over another. The value in each cell is the value of the option on the left divided by the value of the option on the top. For example, in Table 4, adhering to secondary payload requirements is twice as important as creating new debris, therefore the second cell in the first row is 2, and the first cell in the second row is 0.5.

The next step is calculating the normalized vectors of each matrix by squaring the matrix, calculating the row sum, and then normalizing that vector. This is repeated until the vector does not changed between iterations. These will be used at the end of the risk analysis to combine these comparisons into a single numerical value.

	2nd P/L Req'ts	New Debris	Fully Deploy	Stay Deployed
2nd P/L Req'ts	1	2	3	3
New Debris	0.5	1	2	2
Fully Deploy	0.3333	0.5	1	1
Stay Deployed	0.3333	0.5	1	1

Table 4: Relative weighting of risk criteria (type)

The comparison numbers in Table 4 were determined by importance. The secondary payload requirements were determined to be more important than creating new debris because adherence to secondary payload requirements determines the ease in which the device is integrated into the launch vehicle with the other payloads. It is also more important than fully deploying and staying deployed because increasing integration complexity increases cost. Creating new debris is more important than fully deploying and staying deployed because the purpose of this device is to decrease debris, not create more. Staying deployed and fully deploying are equal because they both determine how effective the device is while in orbit.

	Drag Sail	Inflatable	Tether	Propulsion
Drag Sail	1	0.5	1	2
Inflatable	2	1	2	3
Tether	1	0.5	1	2
Propulsion	0.5	0.3333	0.5	1

Table 5: Adherence to secondary payload requirements piecewise comparison of the devices (2pay)

Table 5 shows the comparison for adherence to secondary payload requirements. Propulsion is the least risky because it does not require any modifications to the launch vehicle itself. The inflatable is riskier than propulsion because its inflation mechanism will most likely require a waiver from the launch vehicle provider, and riskier than the drag sail because the drag sail will just need to prove proper inhibits. The tether is equal in risk as the drag sail because it will also only need proper inhibits. Both the drag sail and tether are riskier than propulsion.

	Drag Sail	Inflatable	Tether	Propulsion
Drag Sail	1	2	0.3333	0.6667
Inflatable	0.5	1	0.25	0.5
Tether	3	4	1	2
Propulsion	1.5	2	0.5	1

Table 6: Create new debris piecewise comparison of the devices (ndeb)

Table 6 shows the risk the device will create new debris. The drag sail is riskier than the inflatable because the drag sail has rigid booms supporting the flexible film and the inflatable is entirely a flexible film. If an objects hits the film, it will most likely not fracture into smaller pieces, but if it hits the rigid boom it will fracture. The propulsion is riskier than the drag sail and inflatable because the upper stage will be drifting after the burn, and the entire upper stage is rigid. The tether is the riskiest because it is very long and would cross the path of many satellites, and not all will have the ability to avoid it. It will also be hard to detect in order to avoid.

	Drag Sail	Inflatable	Tether	Propulsion
Drag Sail	1	2	0.3333	3
Inflatable	0.5	1	0.6667	2
Tether	3	6	1	9
Propulsion	0.3333	0.5	0.1111	1

Table 7: Risk it will not fully deploy piecewise comparison of the devices (fdep)

Table 7 shows the risk the device will not fully deploy. Propulsion is the least risky because the engines will only need to be restarted. Next is the inflatable, which is riskier than propulsion because the deployment is based on the effectiveness of the inflation mechanism and folding scheme. The drag sail is riskier than the inflatable because it requires unfolding the booms and the sail, which is complicated and precise. The tether is the riskiest because it has a much longer single length to deploy, and tethers in the past have often gotten tangled during deployment.

Table 8 shows the risk that the device will not stay deployed. This is trivial for the propulsion option because the burn would be a discrete event. The drag sail also is low risk because once it is deployed, the booms will lock in place ensuring it will stay deployed, and the sail film can be designed to minimize damage from debris. The inflatable is riskier than the drag sail because if it is struck by debris, no matter how small the hole, the inflation gas will leak, preventing it from staying deployed. The tether is the riskiest because it could be tangled or cut as a result of collisions with debris.

	Drag Sail	Inflatable	Tether	Propulsion
Drag Sail	1	0.5	0.3333	1
Inflatable	2	1	0.6667	2
Tether	3	1.5	1	3
Propulsion	1	0.5	0.3333	1

Table 8: Risk it will not stay deployed for the duration of deorbit piecewise comparison of the devices (sdep)

III.III.II Area-Time Product

Area-Time Product (ATP) is not a measure of the actual risk of creating new debris, but it is proportional to the risk and easier to calculate. In [5], Nock et. al describe how to calculate this using the collision cross sectional area instead of the drag area, as shown in Figure 4. The collision area assumes a nominal debris size of 2 m and adds a 1 m buffer to the outside of the object to create the collision area [5].

In order to combine this with the eigenvalues from AHP, the ATP values must be normalized by the range of values using Equation [1].

$$\left|ATP_i\right| = \frac{ATP_i - ATP_{\min}}{ATP_{\max} - ATP_{\min}} \quad [1]$$

The AHP eigenvalues were then combined with the normalized ATP for each option by Equation [2].

$$Risk = 2pay*type + fdep*type + sdep*type + ndeb*\left|ATP_i\right| \quad [2]$$

This gives a single value of risk for each option that is between zero and one, as shown in the pareto plots in Section III.IV.

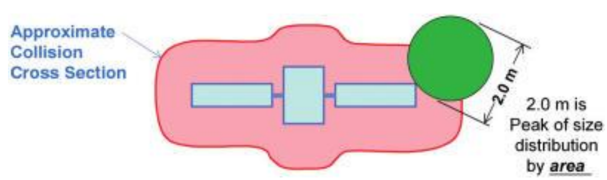

Fig. 4: Collision area used in the area-time product [5].

III.III.III Justification Against Tethers

According to Hoyt and Forward, an electrodynamic tether needs to be about 7.5 km long to deorbit a 1500 kg satellite. The interaction with the atmosphere makes tethers ineffective at inclinations above 75° [6].

These requirements lead to the conclusion that tethers are not appropriate for this scale since most of the upper stages investigated are larger than 1500 kg, i.e. the Falcon 9 upper stage is 4900 kg. The tether would pose a risk to other satellites in a similar orbit. The analysis also showed it to be the riskiest of the options. Based upon this, the electrodynamic tether was not considered as a candidate in the pareto evaluation.

III.IV Deorbit Time

The deorbit time was calculated using the NASA Debris Assessment Software 2.0.2 (DAS). The Science and Engineering utility can calculate the orbit lifetime of an object given certain parameters.

The start year is needed to determine the atmospheric properties during the deorbit period because of the variations of the 11 year solar cycle. The last solar maximum was in 2013. The chosen start year was mid-2015 roughly halfway between solar maximum and solar minimum. This is assumed to be a worst case deorbit time.

The initial orbit for each system is assumed to be circular. Initially, the highest of the three target orbit altitude ranges from Table 1 were evaluated (700 km, 850 km, and 1000 km).

The inclinations in LEO that have the highest concentration of debris are 71-74°, 81-83° and Sun-sync [1]. An inclination of 71° was chosen for the design as the worst case scenario for the most populated orbits since it has the longest decay time. The Right Ascension of the Ascending Node and the Argument of Perigee were set to 0° to simplify the analysis.

The final parameter is the area-to-mass ratio of the system. It was assumed that the mass was only from the upper stage since our mass estimate for the deorbit devices are only 1-3% of the upper stage mass. The area was assumed to be the drag area of the device because it is much larger than the drag area produced by the upper stage.

One thing to note about this analysis tool is that it stops propagating the orbits at 100 years. In the following results, if there is a deorbit time of 100 years, that means at least 100 years.

III.V Cost

The cost was estimated separately for the propulsion options and for the drag sail and inflatable options. Both used historical data for estimates.

III.V.I Propulsion Cost Estimation

The propulsion option was estimated using the price per kg to launch into LEO for each launch vehicle. This was calculated by dividing the cost per launch by the number of kg of payload that could be delivered to LEO. This can be seen in Table 9.

	Launch Cost	Mass to LEO (kg)	Price per kg
Falcon 9 [15]	$61,200,000	13,150	$4,600
Delta IV [16]	$80,000,000	12,900	$6,200
Atlas V [17], [18]	$100,000,000	9,800	$10,200

Table 9: Cost estimation of propulsion option for each launch vehicle.

III.V.II Drag Sail and Inflatable Cost Estimation

The cost estimation for the devices was based on the cost of LightSail and Sunjammer. The LightSail mission cost is estimated as $2 million while the Sunjammer cost is estimated as $27 million [19]. Both are technology demonstration missions so the cost includes more than the sail subsystem and deployment hardware, as well as the cost decreases once more than one is produced. LightSail is mostly a solar sail, so the cost of the sail subsystem for the first device was assumed to be 40% of the total mission cost, then 55% of that would be the recurring cost of one device, $440,000. Sunjammer is a more complicated system. The mission is composed of two spacecraft: the carrier to help it escape Earth orbit and the sailcraft which is the solar sail plus the electronics needed to make the sail work. The sailcraft is only 1/3 of the volume of the total mission [20], and since it has scientific instruments it was assumed that the cost of the first device was 15% of the total mission cost. With 55% of that cost is recurring, the cost of one device was assumed to be $2,200,000.

It was decided that the cost would scale according to the drag area with a logarithmic trendline. The plotted values are shown in Figure 5. The drag sail costs were extrapolated directly by using the equation of the trendline and the inflatable cost was 2 times the equation of the trendline since the surface area of the inflatable device is at least twice that of the drag sail.

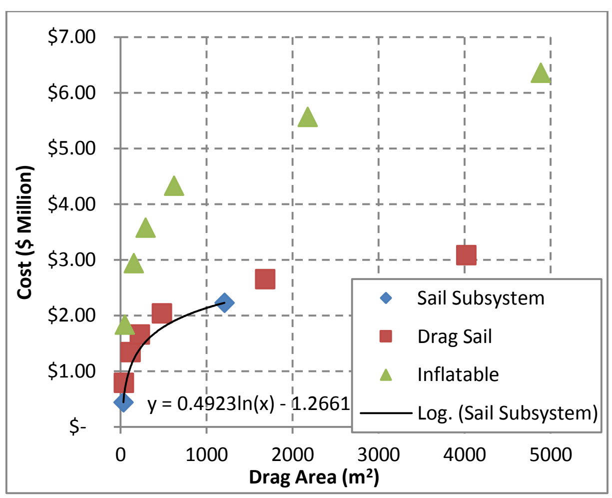

Fig. 5: Plot used to estimate the cost based on drag area.

III.IV Configuration Comparisons

It was quickly found that an altitude of 850 km is an appropriate choice for a baseline design because it may easily be scaled down for lower altitudes, and the drag force at 1000 km is too small for reliable deorbit based on drag. The different device options were compared for deorbiting from an altitude of 850 km.

The pareto plots that were created are shown in Figures 6-8.The grouping for risk and cost are due to the estimation procedure that was used. In all three plots, the propulsive deorbit approach appears to be favored. However, this approach would result in a significant reduction in payload delivery capability for the launch system. This is the primary motivation for flying low-mass deployable drag device. The goal of this research is to create a fully contained passive drag device system that would only need a single command to initiate deployment. It would require the least amount of work on the launch vehicle provider's part to meet the deorbit guideline of 25 years.

With that in mind, it was decided not to choose a configuration that tailored to a specific launch vehicle, but one that would deorbit all three upper stages investigated within the desired 25 years. The different launch vehicles with the same size device can be seen in the plots at three points close together. The chosen "family" is circled in each plot.

In Figure 6, these "families" are lines of positive slope because the larger launch vehicles have longer deorbit times which also is accounted for in the risk. The inflatable is higher risk than the drag sail for adherence to secondary payload requirements and staying deployed. It would require either a chemical reaction or pressure vessel to inflate, which in turn requires a waiver from the launch vehicle provider. Since the inflatable is not rigidized, it could be impacted by debris, causing holes that would prevent it from staying inflated.

In Figure 7, the families are horizontal lines because the cost was determined for each size device. It can be seen in Figure 7 that the best option where all three points in the family falls within the 25 year limit is the second largest drag sail, which is stowed in ½ ESPA packaging.

In Figure 8, they are vertical lines because the cost is now on the horizontal axis. This is harder to determine the best idea because the more ideal points, those with lower risk and lower cost, correspond to the longest deployment times.

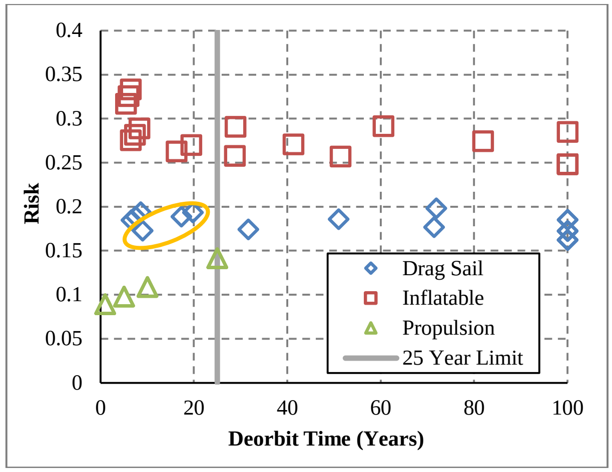

Fig. 6: Pareto plot comparing the risk and deorbit time of the various configurations.

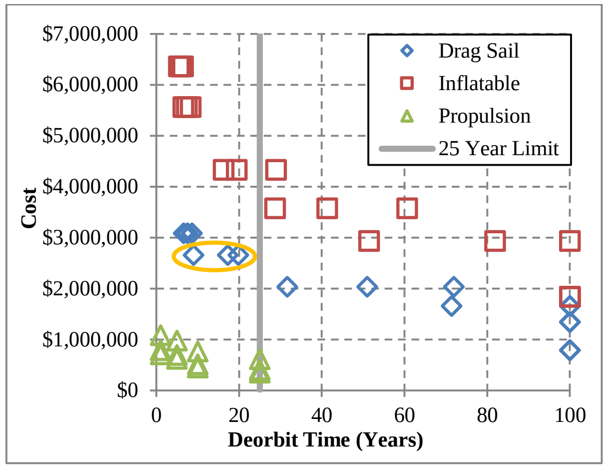

Fig. 7: Pareto plot comparing the cost and deorbit time of the various configurations.

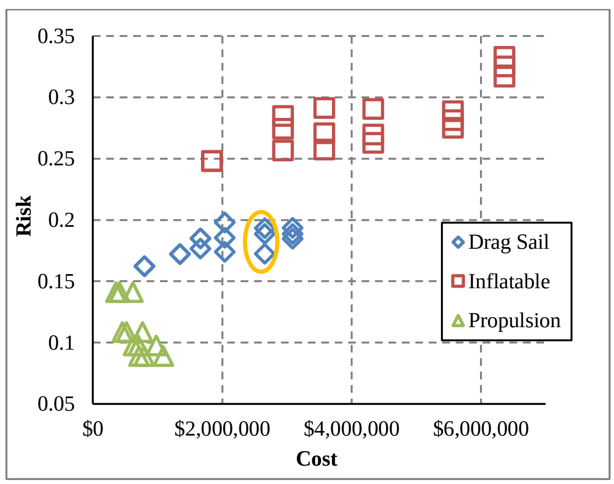

Fig. 8: Pareto plot comparing the risk and cost of the various configurations

IV. BASELINE DESIGN

After the trade study was concluded, the issue of passively ensuring the drag sail will create the maximum drag was investigated. To introduce an aerostable design, the flat square sail is modified so that if it is disturbed from its nominal maximum drag attitude, it will automatically create restoring moments. This design can be seen in Figure 9. The system is split into two separate devices mounted on either end of the upper stage. An aerostable design allows for smaller sails than what was predicted in the trade study. Each device would be deployed from a 27U CubeSat deployer. The drag sails have a main central boom with smaller booms extending from the top and bottom to support two sail panels.

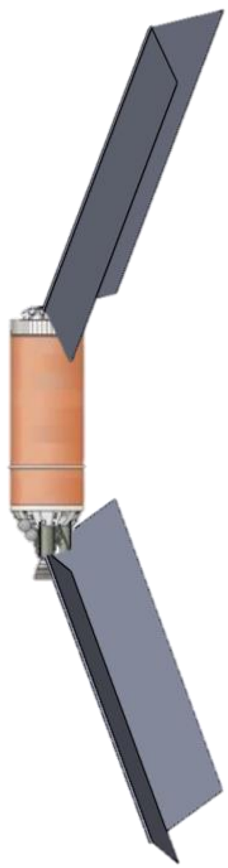

Fig. 9: Baseline design with two devices, angled for stability.

V. CONCLUSION

Orbital debris in Low Earth Orbit can no longer be ignored, and one of the most prevalent categories of objects is launch vehicle upper stages. This research investigated the different options for designing a passive deployable drag device to attach to launch vehicles before launch in order to ensure deorbit within 25 years. It was decided that the initial design should be a drag sail with the ability to deorbit the upper stages of the three main American launch vehicles, the Falcon 9 the Delta IV and the Atlas V, within 25 years. The baseline design is two drag sails mounted on either end of the upper stage with various angles to ensure that it is aerostable.

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