

# The Space Superhighway: Enabling Active Debris Remediation Through an In-Space Logistics Infrastructure

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The Space Superhighway is a future space infrastructure concept intended to support civil, commercial, and national security space interests by providing In-Space Servicing, Assembly, and Manufacturing (ISAM) services across low Earth orbit (LEO), geosynchronous orbit (GEO), and cislunar space. This concept was originally developed by an interagency working group and commissioned by the Executive Office of the President. The Space Superhighway is comprised of three primary components: regional hubs, a sustainable transportation network, and Earth-to-orbit logistics. This study establishes methods which may be used to quantify the cost-savings from use of the Space Superhighway infrastructure and interrogates the effects of the use of this logistics network on a specific use case – removal of 26 pieces of large space debris within LEO. Through application of the established methods and assuming an emplaced Space Superhighway infrastructure with no cost implications related to deployment of infrastructure-related spacecraft, this study found that the cost to use an established Space Superhighway infrastructure to remove the targeted debris may be cheaper than removal of the targeted debris through traditional methods when the  $\Delta V$  between a regional hub hosting propellant and the debris field is less than 1500 m/s. Through determining optimized locations of regional hubs within LEO, this study estimates that such a  $\Delta V$  is within expectations for a LEO environment supported by a fully evolved Space Superhighway logistics infrastructure. This study provides a blueprint for future Space Superhighway value proposition studies for other use cases which, when combined, may provide the ultimate benefit and justification for the proliferation of an interconnected Space Superhighway.

## I. Introduction

The Space Superhighway (SSH) is a space logistics architecture concept which could provide an interconnected low Earth orbit (LEO) to cislunar space ecosystem capable of supporting on-orbit refueling, satellite repair and augmentation, and logistics support to on-orbit assets. In 2021, at the request of the Executive Office of the President, an interagency working group with participation from NASA centers (Langley, Goddard Space Flight Center, Marshall Space Flight Center, and NASA Headquarters), other government agencies (U.S. Space Force and the Air Force Research Lab), and the Aerospace Corporation, developed the concept of the SSH [1]. An interconnected space logistics architecture such as SSH would benefit commercial space entities and the defense sector by providing a means to extend the lifetime of on-orbit assets, expand situational awareness, and maneuver satellites without concern of propellant availability. The SSH ecosystem incorporates three core components: regional hubs, a sustainable in-space transportation network, and Earth-to-orbit logistics. This architecture could extend satellite lifetime, reduce

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delivery costs for propellant used in space, and reduce the total quantity of space debris and additional debris generation.

Space debris is growing at an alarming rate, fueled by growth in the number of satellite launches and numerous debris generating events [2]. Current space debris mitigation methods are primarily focused on encouraging international cooperation in limiting debris contributions and ensuring satellites move to a graveyard orbit or deorbit when appropriate. To date, removal of an uncooperative, pre-existing piece of space debris from LEO by a debris remediation satellite has not been demonstrated. Concepts for future Active Debris Remediation (ADR) typically involve the use of standalone ADR satellites or constellations of ADR satellites which have a finite lifespan. This lifespan is often dependent on the rate of fuel consumption, which is directly related to the number of debris mitigated. With an SSH ecosystem, ADR concepts could leverage the readily available propellant at regional hubs, the in-space transportation network to move propellant to the debris field, and refueling operations to replenish and extend the lifetime of ADR spacecraft. This would in turn increase the capability in terms of number of debris mitigated per ADR vehicle, reduce the overall number of ADR spacecraft required by the concept, and may reduce overall expenditure for long term ADR implementation.

This study establishes a method for comparing SSH-enabled and traditional ADR concepts, discusses the development of SSH infrastructure vehicle models using NASA’s Exploration Architecture Model for the IN-space and Earth-to-orbit modeling (EXAMINE) [3], and explores the benefit of an SSH architecture in its support of a single use case – the removal of 26 pieces of large space debris in LEO. The developed methods and models are applicable to a wide variety of space-infrastructure-enhanced projects, such as geosynchronous orbit (GEO) satellite end-of-life services; deployment of persistent Earth-orbiting platforms or large, assembled telescopes; and cislunar assembly of Mars transit vehicles.

## II. Concept of Operations

Two concepts of operation (con-ops) were developed to explore the benefit of using an SSH infrastructure: 1) a baseline con-ops in which ADR is performed without refueling and 2) an SSH-enabled con-ops using an in-space refueling infrastructure. The purpose of both of these con-ops is to remove a cluster of 26 pieces of debris within LEO considered to be highly concerning [4]. These debris, which are shown in Fig. 1, are located at ~840 km altitude and ~71° inclination. The targeted debris are primarily rocket upper stages, each with a mass of ~9,000 kg. In this study, spacecraft use nodal precession to account for the differences between right ascension of the ascending node (RAAN) between debris within the debris field.

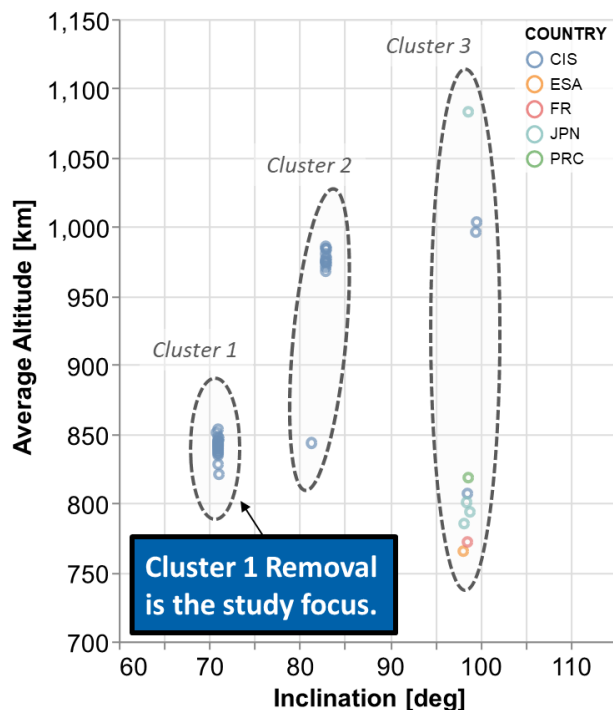


Fig. 1 Debris of concern within LEO with identification of targeted cluster.

The two con-ops rely on Active Debris Remediation Vehicles (ADRVs), which are spacecraft capable of grapples and moving pieces of debris through space. In both con-ops, the ADRVs move the pieces of debris from LEO into a disposal orbit at 300 km altitude. After the ADRV towing the piece of debris reaches the disposal orbit, it releases the debris and boosts itself back to the debris cluster. The ADRVs are designed to mitigate a discrete number of debris, ranging from one to 13, which alters design parameters of the vehicle such as the launch mass and fuel capacity.

### A. Traditionally Implemented Debris Remediation Mission

In the traditionally implemented debris remediation con-ops, several ADRVs are launched from Earth to the debris field. This con-ops uses traditional means of operating in space, i.e., that refueling and space infrastructure are unavailable. The mission is accomplished through launching a discrete number of ADRVs which are self-sufficient through the full duration of the mission. After initiation, the ADRVs begin to move pieces of debris from the debris field to the disposal orbit at 300 km altitude. After releasing the debris, the ADRVs will boost to the next piece of debris and continue the process until all 26 pieces of debris are removed. As there are a total of 26 pieces of targeted debris, the ADRVs in this con-ops may remove a different number of total debris. For example, if four ADRVs are launched, two of the ADRVs will address six pieces of debris each and the remaining two ADRVs will address seven pieces of debris each. A single design is used for such ADRVs, meaning the ADRVs which addressed six pieces of debris each did not fully deplete the available propellant. At end of life (EOL), each of the ADRVs will complete its mission by remaining in the disposal orbit after the final piece of debris has been removed from the targeted cluster. This con-ops is visualized in Fig. 2.

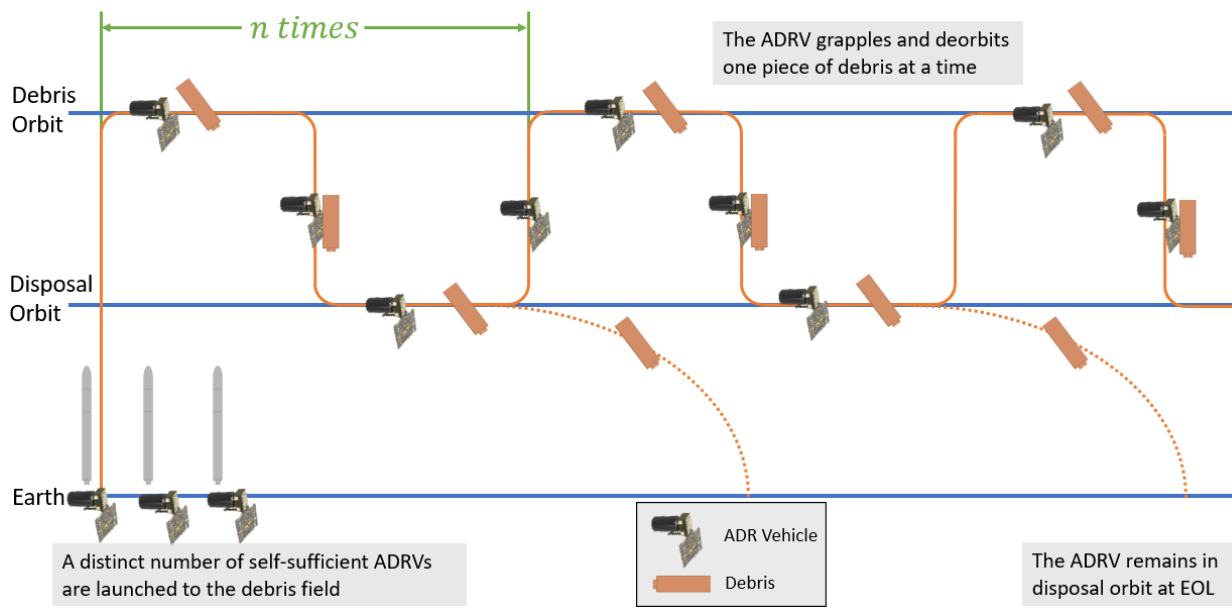


Fig. 2 Traditionally implemented ADR co-ops.

### B. Space-Superhighway-Enabled Debris Remediation Mission

The SSH-enabled debris remediation con-ops involves the removal of the 26 pieces of debris through use of an ADRV similar in design to those used in the traditional con-ops. In the SSH-enabled con-ops, a single, refuellable ADRV is launched to the debris field. This refuellable ADRV will remove pieces of debris, one at a time, until propellant is depleted, at which time propellant is delivered to the ADRV through the SSH infrastructure. Propellant, which is contained in propellant modules with varying traded inert mass fractions (IMFs), is delivered from Earth to a Regional Hub (RH) near the debris field. RHs are SSH infrastructure elements which host a variety of commodities on orbit, such as propellant, orbital replacement units (ORUs), or payloads. The distance between the regional hub and the debris field is a critical factor in the total cost of using the SSH infrastructure and is discussed in later sections.

The propellant modules, when required by the ADRV, are moved from the RH to the ADRV by a Transit Element (TE). TEs are components of the SSH infrastructure which are capable of moving logistics mass throughout the SSH ecosystem. In this study, a TE moves propellant modules, one at a time, from the RH to the ADRV until additional

propellant is no longer required by the ADRV. The propellant modules are sized to fully replenish the ADRV propellant. After delivery of a propellant module to the ADRV, the empty propellant module remains joined to the ADRV until reaching the disposal orbit. The empty propellant module is released along with the debris into the disposal orbit and the ADRV boosts back to the debris cluster. At the end of the con-ops, the ADRV boosts back to a stable altitude in LEO, because the vehicle may have future use in a space environment with readily available propellant. The SSH-enabled debris remediation con-ops is visualized in Fig. 3.

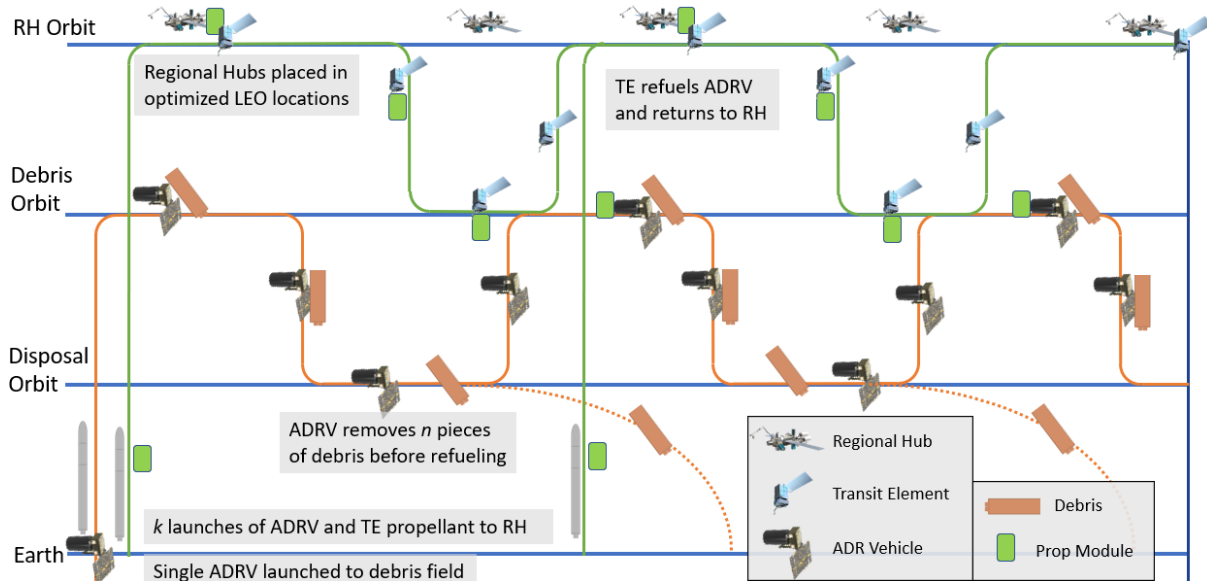


Fig. 3 SSH-enabled ADR con-ops.

### III. Methods

#### A. Methods of Comparison

A method of determining the cost for use of the SSH infrastructure was developed to effectively compare the results of the traditional and SSH-enabled concepts. This cost is split into two categories: utilization cost and deployment cost. The utilization cost includes any cost related to a single instance of using the SSH infrastructure, including the cost of any propellant used by the infrastructure and the cost of delivering that propellant to the appropriate orbit. The deployment cost refers to the cost incurred for developing, constructing, and launching components of the SSH infrastructure, such as RHs or TEs. Vehicle cost estimates within this study are generated through the Project Cost Estimating Capability (PCEC), a parametric cost model developed by NASA. Inputs to PCEC are provided by the EXAMINE subsystem component requirements for each vehicle. The outputs of PCEC used within this study include Design, Development, Testing, and Evaluation (DDT&E) costs and unit production costs. Due to uncertainty in mission timeline and required services, satellite operational costs are not considered in this analysis.

As this study targets a single, relatively small debris field, the deployment cost is not considered and only the utilization cost is used in comparisons to the cost of a traditional ADR concept. This is equivalent to assuming the SSH infrastructure is deployed and available to use prior to the start of this mission. It is expected that an in-space logistics infrastructure such as SSH would not be deployed to support a single mission (such as the described ADR mission), but instead to establish a thriving ecosystem which provides enhancing and cost saving services to any missions within cislunar space. In future exploration of the SSH, it is expected that the benefits across multiple use cases can be aggregated to show a net benefit of deploying components of the SSH infrastructure.

#### B. Active Debris Remediation Vehicle Development

The ADRV, which is used in both the traditional and SSH-enabled concepts, was developed using NASA's EXAMINE. For simplicity within the SSH infrastructure, all vehicles are assumed to use Nitrogen Tetroxide/Monomethylhydrazine (NTO/MMH) propellant to reduce complexity in the commodity flow through the space ecosystem. The designed ADRV uses turbopump-fed main propulsion system (MPS) engines which share

common pressurization, fuel, and oxidizer tanks with the 100 lbf class reaction control system (RCS) thrusters. The MPS engines are sized based on the variable inputs of the model.

Thirteen models were constructed for the traditional con-ops ADRV, with the number of debris mitigated per ADRV ranging from one to 13. The effect of the change in the number of debris mitigated is the total  $\Delta V$  capability of the spacecraft. The model generated outputs for each of the 13 vehicles, with outputs including dry mass, inert mass, propellant mass, total launch mass, vehicle length, and vehicle diameter. Table 1 displays the outputs for the traditional ADR con-ops ADRV.

**Table 1 Traditional ADR Con-Ops ADRV Properties**

<b>Number of Debris Targets</b>	<b>Dry Mass (kg)</b>	<b>Inert Mass (kg)</b>	<b>Prop. Mass (kg)</b>	<b>Total Mass (kg)</b>	<b>Total Length (m)</b>	<b>Max Diameter (m)</b>
1	1661	1724	1106	2830	4.22	1.04
2	1784	1925	2537	4461	4.93	1.36
3	1912	2147	4309	6456	5.52	1.61
4	2054	2408	6533	8940	6.08	1.85
5	2216	2720	9341	12060	6.64	2.08
6	2407	3103	12930	16030	7.23	2.31
7	2621	3564	17550	21120	7.87	2.55
8	2882	4150	23640	27790	8.57	2.81
9	3208	4914	31830	36750	9.36	3.10
10	3628	5943	43210	49160	10.3	3.43
11	4193	7388	59670	67060	11.4	3.82
12	5371	10080	88000	98080	13.6	4.04
13	8366	16420	150700	167100	19.1	4.04

A new ADRV model within EXAMINE was generated for the SSH-enabled ADR con-ops due to the return of the ADRV to a stable LEO orbit. The SSH-enabled ADR con-ops vehicle differs from the traditional con-ops ADRV only in this additional  $\Delta V$ . Thirteen ADRVs cases were generated with the number of debris mitigated between refueling operations ranging from one to 13. Table 2 displays the outputs for the SSH-enabled ADR con-ops ADRV.

**Table 2 SSH-Enabled ADR Con-Ops ADRV Properties**

<b>Number of Debris Targets</b>	<b>Dry Mass (kg)</b>	<b>Inert Mass (kg)</b>	<b>Prop. Mass (kg)</b>	<b>Total Mass (kg)</b>	<b>Total Length (m)</b>	<b>Max Diameter (m)</b>
1	1675	1747	1257	3004	4.31	1.08
2	1800	1951	2740	4691	5.00	1.39
3	1930	2180	4583	6764	5.59	1.65
4	2076	2450	6907	9356	6.16	1.88
5	2245	2776	9857	12630	6.73	2.11
6	2442	3177	13650	16830	7.34	2.35
7	2666	3664	18580	22240	8.00	2.60
8	2943	4291	25130	29420	8.72	2.87
9	3293	5119	34080	39190	9.55	3.17
10	3752	6255	46720	52970	10.5	3.52
11	4383	7886	65440	73320	11.7	3.94
12	6056	11530	102200	113700	14.8	4.04
13	9587	19030	176500	195500	21.3	4.04

### C. Transit Element Vehicle and Response Model Development

The SSH TE is considered a component of the SSH infrastructure. However, details such as the propellant use of the TE must be established in order to appropriately estimate the utilization cost for the SSH-enabled ADR con-ops. To this end, an EXAMINE model was created for a TE capable of moving propellant modules of varying IMF from a RH to the ADRV located at the  $\Delta V$  centroid of the debris field. Similar to the ADRV, the TE uses NTO/MMH for both the MPS and RCS. The TE uses three pump-fed MPS engines which are sized according to the variable inputs of the model, whereas the RCS engines are 100 lbf class. The MPS and RCS use standalone pressurization gas, fuel, and oxidizer tanks with separate feed subsystems.

The TE EXAMINE model utilizes two input parameters: the mass of the propellant module delivered from the RH to the ADRV and the  $\Delta V$  between the RH and the ADRV. The model was interrogated across 1100 sets of inputs, with transported mass ranging from 1000 kg to 20,000 kg in steps of 1000 kg and  $\Delta V$ s ranging from 500 to 3200 m/s in steps of 100 m/s. Of note, a vehicle input  $\Delta V$  of 500 m/s equates to a total  $\Delta V$  capability of 1000 m/s due to the need to return to the RH from the ADRV after delivery of propellant. The output parameters for the TE model include total propellant mass, total vehicle mass, vehicle length, and vehicle diameter. The outputs from the 1100 input sets represent distinct vehicles optimized to perform the mission as prescribed by the input parameters.

With the output parameters for each of the 1100 input sets, response models were generated to enable rapid access to expected vehicle parameters without the need of rerunning the EXAMINE model. Each of the response models is based on a third-order polynomial fit to the dataset found through using Python scikit-learn, an open-source machine learning library, with a 75/25 train/test split of the data. As the  $\Delta V$  and payload capacity increase, there is a transition of the propellant tanks from spheres to cylinders, which creates a discontinuity in the output parameters. The response model is split into two regimes to handle this discontinuity. The transition from spherical to cylindrical propellant tanks can be identified as the intersection of the regime 1 vehicle diameter response model with the maximum vehicle diameter of 4.52 m. This is provided by the inequality found in inequality (1). In the equations presented in this section, Y represents the  $\Delta V$  between a RH and the debris field and X represents the mass carried by the TE from the RH to the debris field.

$$\begin{aligned}
 &7.25 * 10^{-14} * X^3 + 1.15 * 10^{-14} * Y^3 - 5.52 * 10^{-13} * X^2 * Y - 4.12 * 10^{-12} * Y^2 * X \\
 &- 3.34 * 10^{-9} * X^2 - 4.32 * 10^{-7} * Y^2 + 4.55 * 10^{-8} * X * Y + 7.81 * 10^{-5} * X \\
 &+ 1.53 * 10^{-3} * Y - 0.770 \text{ m} \leq 4.52 \text{ m}
 \end{aligned} \tag{1}$$

If the provided inequality is met, the input  $\Delta V$  and input payload mass generate a vehicle within regime 1, in which the fuel and oxidizer tanks are spherical. If the inequality is not met, the generated vehicle falls within regime 2, in which the fuel and oxidizer tanks are cylindrical. The propellant used by the TE when completing the input  $\Delta V$  and carrying the input payload mass is the most impactful parameter in the analysis, as it drives the total cost of transporting propellant to and from the ADRV. The response model for the propellant used by the TE is defined by a series of equations derived from the TE EXAMINE model output. The response model equations are captured in Eq. (2) and Eq. (3). The relevant regime is determined through use of inequality (1).

Regime 1:

$$f(x, y) = C_9 X^3 + C_8 Y^3 + C_7 X^2 Y + C_6 Y^2 X + C_5 X^2 + C_4 Y^2 + C_3 X Y + C_2 X + C_1 Y + C_0 \tag{2}$$

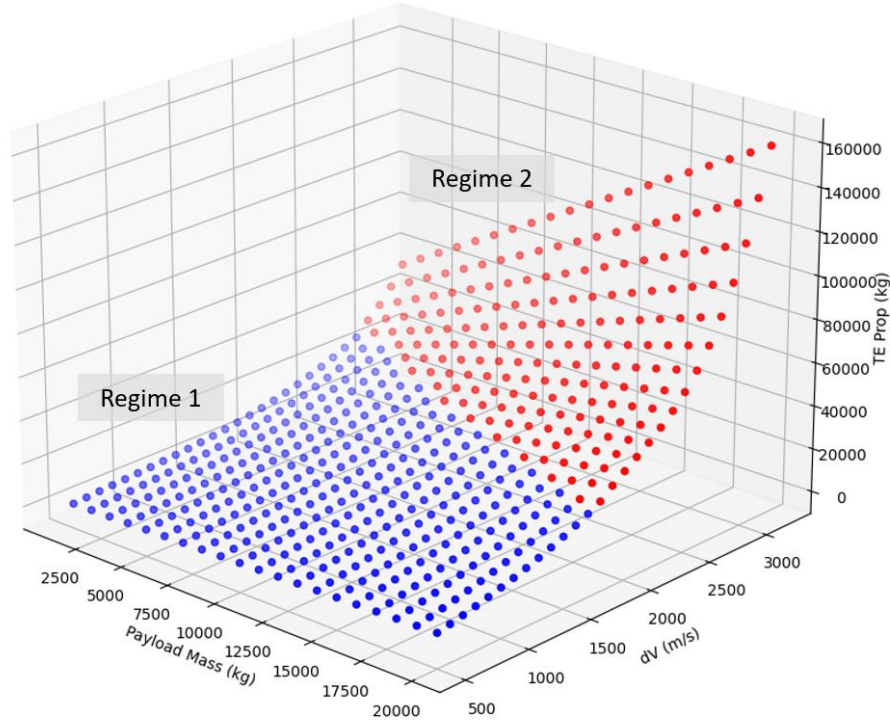
$$\text{where } [C_0 \dots C_9] = [-2290, 8.73, 7.89 * 10^{-2}, 1.82 * 10^{-4}, -6.21 * 10^{-3}, -3.52 * 10^{-7}, 2.71 * 10^{-7}, -3.40 * 10^{-9}, 2.27 * 10^{-6}, 1.14 * 10^{-10}]$$

Regime 2:

$$f(x, y) = C_9 X^3 + C_8 Y^3 + C_7 X^2 Y + C_6 Y^2 X + C_5 X^2 + C_4 Y^2 + C_3 X Y + C_2 X + C_1 Y + C_0 \tag{3}$$

$$\text{where } [C_0 \dots C_9] = [-816000, 950, 17.7, -0.0145, -0.369, -1.36 * 10^{-5}, 3.36 * 10^{-6}, 5.28 * 10^{-9}, 4.87 * 10^{-5}, -7.51 * 10^{-11}]$$

With the response model defined by Eq. (2) and Eq. (3), the propellant used by the TE can be treated as a variable without the need to rerun the time and computationally expensive EXAMINE model. The output from a set of  $\Delta V$  and payload mass inputs represents the propellant used by a TE during the prescribed transit for a TE designed to complete the maneuver with only marginal remaining propellant. The EXAMINE model propellant use output divided among the two regimes is shown in Fig. 4. The coefficient of determination,  $R^2$ , value is 0.9998 for the regime 1 data and 0.9996 for the regime 2 data.



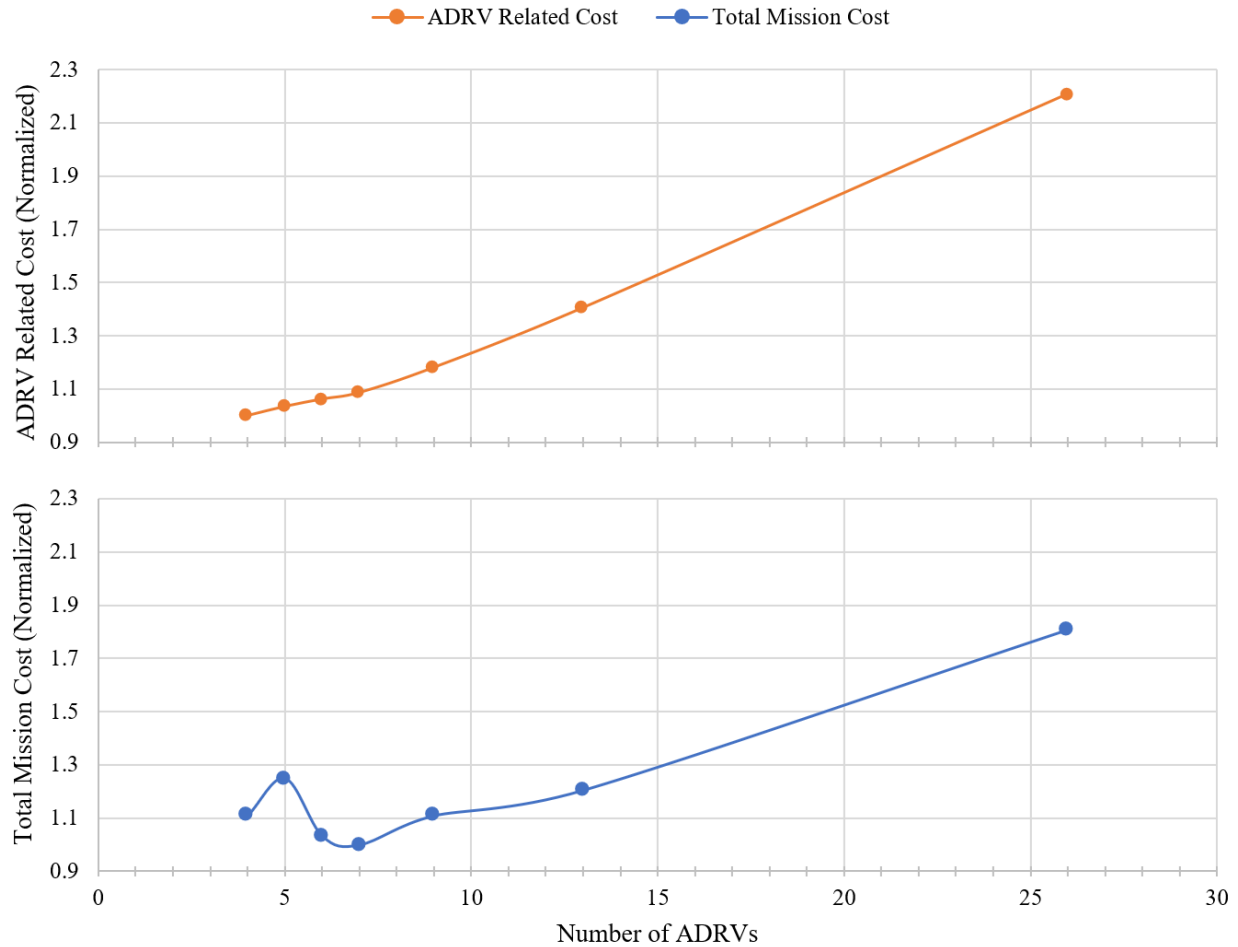
**Fig. 4 Two regimes of EXAMINE Transit Element propellant use.**

## IV. Results and Discussion

### A. Traditionally Implemented Debris Remediation Mission

The traditional implementation of the debris remediation mission described in Section II.A. uses a discrete number of ADRVs, as defined in Table 1, to remove the targeted 26 pieces of debris within LEO. The design space explored for the traditionally implemented mission includes a varying number of debris mitigated per ADRV, ranging from one to 13, and the use of one of three expected commercially available launch vehicle options for delivery of each ADRV to the debris field. The total cost associated with the traditionally implemented mission is determined by summing the cost of the ADRVs and the expense to launch the ADRVs to the debris field.

The most cost-effective solution for the traditionally implemented debris remediation mission uses seven ADRVs, which can mitigate four pieces of debris each. Two of the seven ADRVs will only mitigate three pieces during the mission. From the data in Table 1, the optimum ADRV has a total launch mass of 8400 kg, propellant mass of 6300 kg, length of 6.01 m, and diameter of 1.8 m. The total  $\Delta V$  capability of each vehicle is approximately 1700 m/s, with half of this  $\Delta V$  capability including transportation of pieces of debris. The total cost of this traditional ADR concept is used as a baseline for comparison with the SSH-enabled ADR concept. Fig. 5 shows the ADRV related costs, including DDT&E and production, normalized to the minimum ADRV related cost and the total cost of the traditionally implemented ADR mission normalized to the minimum mission cost. To note, the significant differences in mission cost between two seemingly similar con-ops, such as using 5 vs 6 ADRVs, are due to the packing efficiency on launch vehicles, varying launch vehicle mass capabilities, and resulting total cost.

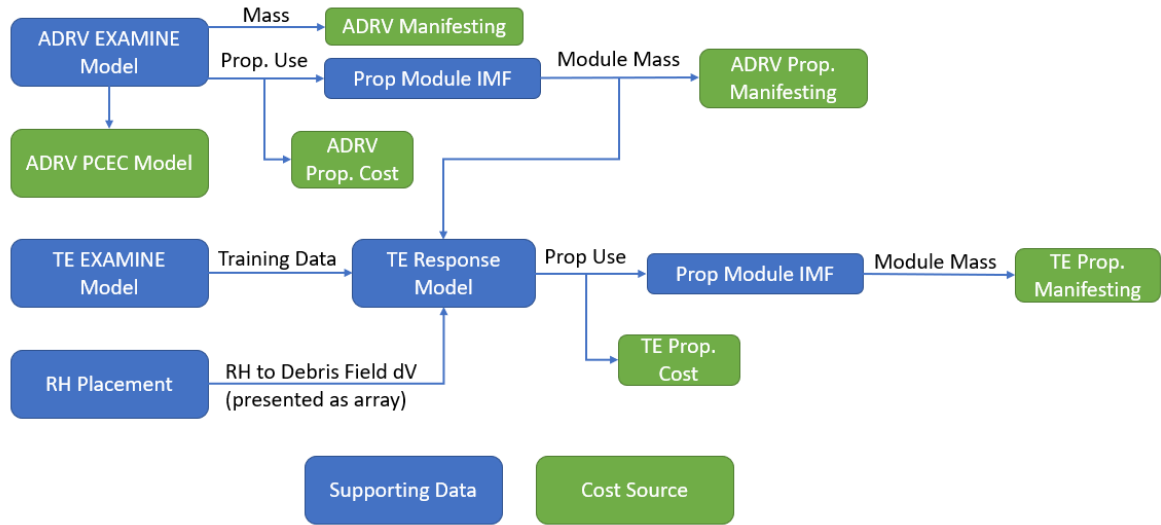


**Fig. 5 Vehicle cost and total cost of traditionally implemented ADR mission.**

### B. Space-Superhighway-Enabled Debris Remediation Mission

In the SSH-enabled debris remediation mission, a single ADRV is launched to the targeted debris field and removes a number of debris until refueling is required, at which point the ADRV receives propellant through the SSH infrastructure. In this study, the total cost considered for this con-ops includes the cost to deploy the single ADRV and the utilization cost, as described in Section II.A. The cost of deploying the SSH infrastructure, including DDT&E, construction, and launch of the RH and TE, is not considered as it is unlikely that a single use case will justify the deployment of such an architecture. Instead, benefits across several use cases will be necessary to justify the installation of SSH infrastructure.

The costs considered for the SSH-enabled ADR mission are divided into ADRV costs and SSH utilization costs. The ADRV costs include the cost of the ADRV, the cost to launch the ADRV to the debris field, the cost of the additional propellant supplied to the ADRV through the SSH infrastructure, and the cost of launching the additional ADRV propellant. The SSH utilization costs include the cost of the propellant used by the TE to transport the additional ADRV propellant from the RH to the ADRV and the cost to launch the propellant used by the TE. These costs are visualized in Fig. 6.



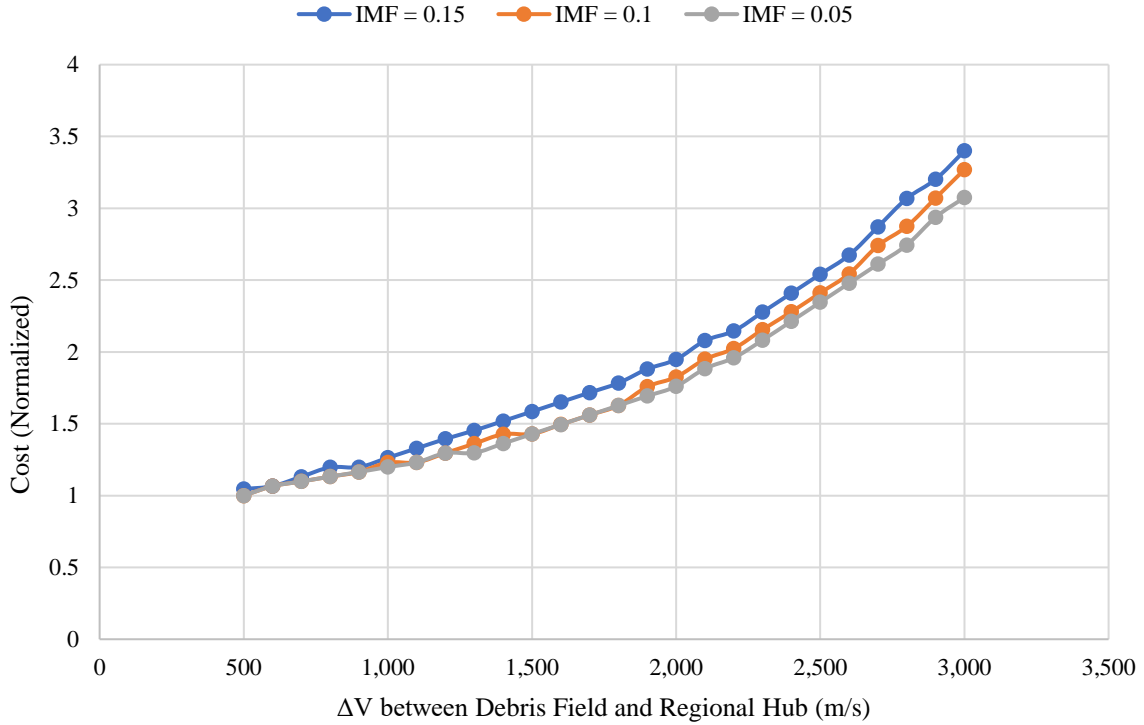
**Fig. 6 Cost of SSH-enabled con-ops.**

The variables explored in the SSH-enabled debris remediation design space include the selection of an ADRV from those outlined in Table 2, with capability to deorbit between one and 13 pieces of debris; selection of an available TE as defined through the response model in Section III.C; placement of a RH at a set  $\Delta V$  from the debris field; definition of an IMF for the structure required to contain the propellant delivered through the SSH infrastructure; and selection of a launch vehicle from three expected commercially available launch providers for launch of the ADRV, ADRV additional propellant, and TE propellant. The sizing of the ADRV from the available options in Table 2 is intertwined with the sizing of the TE, as described in Section III.C, since the frequency of ADRV refueling and resulting ADRV propellant capacity dictates the payload capacity required for the TE.

As the location of future RHs is unknown and RHs within LEO may be providing services to several clients simultaneously, a RH may not be within close proximity to the debris field during the outlined mission. To this end, the  $\Delta V$  between the RH and the debris field is maintained as a variable in this analysis to explore the impacts of the varying  $\Delta V$  on the total cost of the mission. In addition, results for the analysis are calculated with the IMF for the propellant modules at varying levels to observe sensitivity of the mission cost to this factor.

The approach used to find the cost of the mission across varying  $\Delta V$ s between the RH and debris field and varying IMFs is to first calculate the mass of the propellant module that must be delivered by the TE to the ADRV for each of the ADRV options in Table 2. This propellant module is sized such that a single module will fully replenish the ADRV. These resultants along with the RH-to-debris-field  $\Delta V$  array are supplied to the TE response model. The output of the response model provides the propellant used by the TE during each propellant delivery operation. This propellant quantity is then manifested among the available launch vehicles.

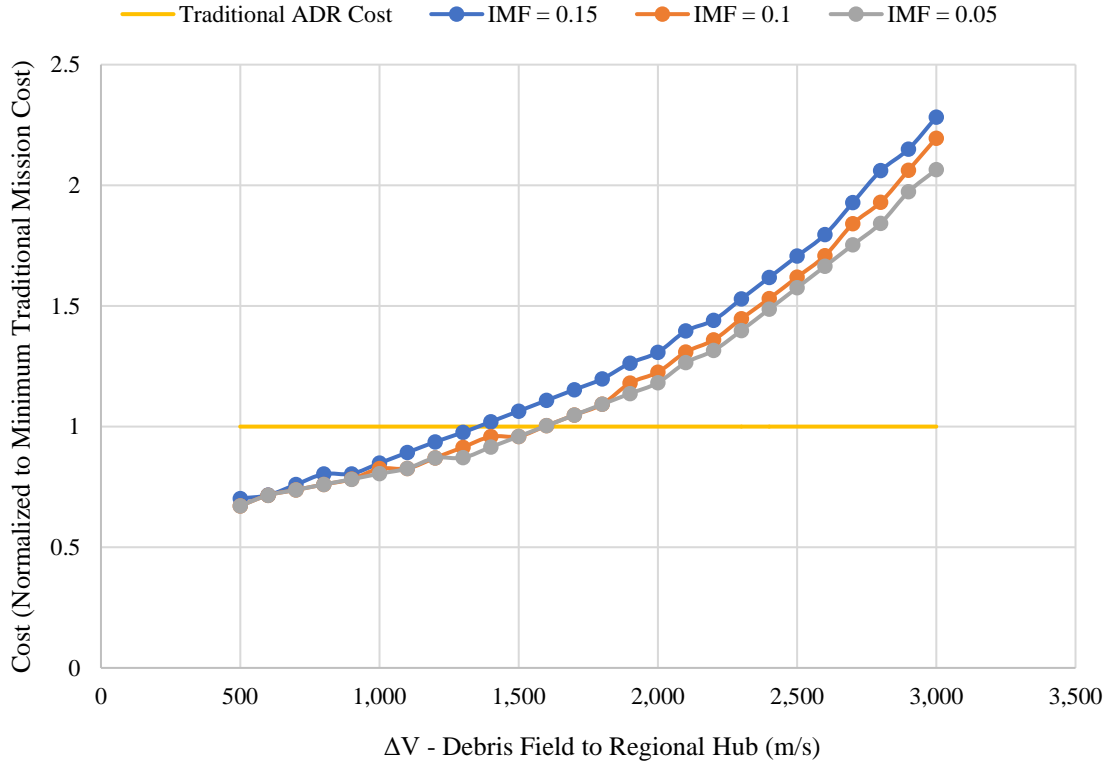
This process was used to find the most cost-effective solution at the minimum extent of the explored  $\Delta V$ s between the RH and the debris field and the minimum explored IMF for the propellant module, 500 m/s and 0.05 respectively. With these inputs, the optimum solution used an ADRV with the ability to remove 2 pieces of debris from the debris field between refueling operations. This results in 12 total refueling operations during the outlined mission. At the greatest explored extent of  $\Delta V$  between the RH and the debris field, the most cost-effective solution was found to be the use of an ADRV which has the ability to remove 4 pieces of debris from the debris field between refueling operations and requires 6 refueling operations during the mission timeline. The cost of the SSH-enabled ADR mission (normalized to the minimum cost) as a function of  $\Delta V$  between the RH and the debris field and the propellant module IMF is provided in Fig. 7. As shown in the figure, the cost, which includes the utilization cost of the SSH infrastructure and the cost to deploy a single ADRV, increases as the  $\Delta V$  between the nearest RH and the debris field increases. This is as expected, since increasing this  $\Delta V$  will increase the propellant used by the TE, and this propellant has an associated cost and must be delivered to the RH from Earth. Additionally, we observe the IMF of the propellant modules which are used to carry propellant to the ADRV has a greater effect at greater  $\Delta V$ s between the RH and the debris field. From observation of the TE response model in Fig. 4, this trend is expected considering the response model shows a greater sensitivity to increases in payload capacity at the greater  $\Delta V$  extent of the model.



**Fig. 7 Cost of SSH-enabled ADR mission.**

### C. Comparison of the Missions

The cost of the SSH-enabled mission, as shown in Fig. 7, is normalized to the minimum cost of the traditionally implemented ADR mission, as shown in Fig. 5, for direct comparison. This comparison is depicted in Fig. 8. As observed in the figure, the use of the SSH infrastructure has the most benefit when the  $\Delta V$  between the RH and the debris field is at a minimum. The cost of the SSH-enabled concept is less than the cost of the traditionally implemented concept when the  $\Delta V$  between the RH and the debris field is less than approximately 1300 m/s or 1500 m/s, depending on the IMF of the propellant module. Recall that the cost considered for the SSH-enabled concept includes the cost of the ADRV and the cost to use the SSH-infrastructure but does not account for deployment of the infrastructure.



**Fig. 8 Normalized cost of SSH-enabled ADR mission relative to minimum traditional mission cost.**

When considering the benefit region of the SSH-enabled concept to be below 1500 m/s, comparisons are useful to gauge whether this  $\Delta V$  between the RH and the debris cluster is realistic. Using a satellite database maintained by the Union of Concerned Scientists [5], optimum locations for a set number of RHs were identified such that the overall  $\Delta V$  between those RHs and all 6570 satellites in LEO is minimized. This optimization was completed by leveraging expected symmetry and the Python SciPy open-source library to minimize a  $\Delta V$  function between all LEO satellites and the input number of RHs. The optimization was performed for up to 4 RHs within LEO and considered the varying inclination, RAAN, and altitude of the 6570 satellites within LEO. In the optimization, it is assumed that RAAN correction is accounted for by orbital precession. The results of the analysis are given in Table 3. The “Total  $\Delta V$ ” in the table refers to the sum of  $\Delta V$ s between all satellites in LEO and the nearest RH. As expected, this value is reduced with increasing number of RHs in LEO.

**Table 3  $\Delta V$ -optimum Regional Hub Locations within LEO**

Number of RHs	HUB LOCATIONS (I, RAAN, ALT) (°, °, KM)	TOTAL $\Delta V$ (KM/S)	$\Delta V$ BETWEEN DEBRIS FIELD AND RH (M/S)
2	A: (71.4, 141, 1600) B: (50.3, 308, 1600)	34002	A: 607 B: 1990
3	A: (81.0, 134, 1600) B: (58.1, 230, 1600) C: (52.2, 359, 1600)	26925	A: 1790 B: 1030 C: 1750
4	A: (53.6, 318, 1600) B: (94.8, 138, 938.8) C: (53.5, 73.2, 1600) D: (57.6, 207, 1600)	22622	A: 1580 B: 3550 C: 1590 D: 1090

From Table 3, it is apparent that  $\Delta V$ s below 1500 m/s between a regional hub and the targeted debris field may be reasonable in a space environment with an implemented space logistics architecture. When considering the results provided in Table 3 in the context of the benefits shown in Fig. 8, the SSH-enabled concept with two, three, and four regional hubs may provide 28%, 17%, and 17% cost savings, respectively, compared to the traditionally implemented ADR concept (assuming a 0.10 propellant module IMF). Increasing the number of RHs beyond four, it is expected that the  $\Delta V$  between the debris field and nearest RH would reduce; however, this trend is not apparent in the results up to four RHs. Although hubs on the scale of several dozen throughout cislunar space are expected by the authors in the implementation of a robust SSH ecosystem, this analysis shows that with as little as four RHs, there may be benefit to concepts such as the ADR use case addressed in this study.

## V. Conclusions

As the capabilities of in-space systems expand and the demand for in-space services and logistics infrastructure increases, justification for the deployment of large, persistent logistics assets in space must be provided. This work establishes methods to quantify the value of space logistics infrastructures and provides an example through application of these methods to a potential use case: removal of 26 pieces of debris from LEO. Through the application of the established methods, a quantifiable benefit is observed when a SSH RH is within a 1500 m/s of the debris field with the assumption of emplaced SSH infrastructure such as a RH and a TE. This application also highlights cost drivers for using an in-space logistics network, such as the  $\Delta V$  between available logistics infrastructure and possible clients and the IMF of payloads transported through the logistics network.

It is the expectation of the authors that similar methods must be developed for the capabilities other than refueling provided by the SSH infrastructure, including satellite servicing, large structure assembly, and commodity aggregation. The benefits of SSH infrastructure must be reduced to factors critical in justifying the existence of space infrastructure, such as cost as discussed in this work or time for deployment of assets, which may be critical for stakeholders such as industry and DoD. In addition, the use and publication of vehicle design response models, as demonstrated in this work, facilitates rapid access to vehicle parameters and provides a method of sharing vehicle parameters for future value proposition studies within the ISAM and space logistics community.

Through providing a general framework for cost comparisons, future use cases may be analyzed in the same manner as the use case explored in this work to show the benefits of the SSH infrastructure. Through separating mission-specific costs, such as the ADRV associated costs for this use case, and the utilization costs for use of the infrastructure, a suite of value proposition studies may be created which highlight the benefits of space infrastructure. These benefits may be combined to show the overall benefit of SSH infrastructure across multiple use cases, which will provide justification for deploying large assets, such as RHs and TEs, critical to a future vibrant space ecosystem enabled by the SSH infrastructure.

## References

- [1] Tomek, D., et al., "The Space Superhighway: Space Infrastructure for the 21<sup>st</sup> Century," *20<sup>th</sup> IAA Symposium on Building Blocks for Future Space Exploration and Development*, IAC-2022, 20 Sept. 2022, URL: <https://iafastro.directory/iac/paper/id/73702/summary/> [retrieved 27 November 2023]
- [2] "About space debris," URL: [https://www.esa.int/Space\\_Safety/Space\\_Debris/About\\_space\\_debris](https://www.esa.int/Space_Safety/Space_Debris/About_space_debris) [retrieved 27 November 2023]
- [3] Komar, D., Hoffman, J., Olds, A., and Seal, M., "Framework for the Parametric System Modeling of Space Exploration Architectures," AIAA 2008-7845. *AIAA SPACE 2008 Conference & Exposition*. September 2008.
- [4] McKnight, D., "Identifying the 50 statistically-most-concerning derelict objects in LEO," *Acta Astronautica*, Vol. 181, 2021, pp. 282-29, URL: <https://doi.org/10.1016/j.actaastro.2021.01.021> [retrieved 27 November 2023]
- [5] "UCS Satellite Database," URL: <https://www.ucsusa.org/resources/satellite-database> [retrieved 07 March 2023]