COST ANALYSIS OF ACTIVE DEBRIS REMOVAL SCENARIOS AND SYSTEM ARCHITECTURES

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ABSTRACT

Active debris removal (ADR) has various options from various viewpoints, such as the architecture of removal activity, the propulsion technology for de-orbit, the orbit and mass of target debris, and so on. In order to find the best ADR scenario consisting of these available options, we have developed a scheme to make a quantitative trade-off on ADR cost. In this paper, we outline this scheme, and the results of case studies are shown and discussed.

1 INTRODUCTION

The Inter-Agency Debris Coordination Committee (IADC) predicts that the number of debris will continue to increase due to collisions between space debris [1]. If the number of small debris of 1 mm to 10 cm which can neither be avoided nor defended is increased as predicted by the IADC, it may seriously limit the human space activities in the future. Liou [2] claimed that the active removal of large and massive debris in crowded orbits can effectively prevent the collisions which are major causes of the increasing tendency. With a good implementation of the commonly adopted mitigation measures, active debris removal (ADR) of five objects per year is supposed to stabilize the population growth. The effective target of ADR is massive objects with high collision probabilities. Many (but not all) of the potential targets in the current environment are spent rocket upper stages.

In order to realize ADR, cost consideration is important. This is because if the cost of ADR exceeds the benefits obtained by it, it cannot be an ongoing activity from an economic point of view. Then, how much does it cost to implement ADR? It is necessary to consider a great many things to answer this, because there are many parameters that make up an ADR scenario. The parameters include, for example, the number of target debris, the mass of debris, the trajectory distribution of the target debris group, the number of removed debris per an ADR satellite, the type of removal device and propulsion system, and the launch system, and so on. With these parameters, the ADR scenario is constructed. Depending on the ADR scenario, the ADR cost fluctuates greatly. Therefore, quantitative trade-off consideration of various ADR scenarios is indispensable for understanding the cost of implementing ADR. For example, it is valuable to analyse the following things: Which is more advantageous between the architecture where an ADR satellite removes one debris and the architecture where an ADR satellite attaches ADR kits to multiple debris? How superior is the use of electric propulsion for orbital transfer between debris compared with using chemical propulsion? How superior is the electrodynamic tether (EDT) as a debris removal device? How will the ADR cost change between removal of the light Cosmos-3M upper stage and the heavy Zenit upper stage? Analysis results that answer these questions are effective in considering ADR scenarios that are advantageous in terms of cost.

In this research, we attempted to construct a scheme to make a trade-off of various ADR scenarios to find the lowest cost one. We have defined parameters that make up an ADR scenario. A mathematical model that uses the ADR scenario as input and outputs the ADR cost has been constructed. In that model, the optimum combination of debris visited by ADR satellites is obtained by solving the traveling salesman problem (TSP) to compute the total ΔV amount required for the efficient ADR mission. Then, by using a satellite system model, a removal device model, and a propulsion system model, properties of the ADR satellite are calculated. Then, by inputting the properties of the ADR satellite to the spacecraft cost model, the cost required for the development and manufacture of the ADR satellite is calculated. By adding launch cost to this, ADR mission cost is obtained at last. By using this scheme, we can make a trade-off between various ADR scenarios from a cost perspective. Useful analysis results can be provided for determining a policy toward future ADR realization and building an ADR technology development strategy.

In this paper, we describe the purpose, overall picture and modelling of the ADR scenario trade-off scheme. In addition, we present the results of the ADR scenario trade-off analysis with the theme of removing the large debris group in a crowded low earth orbit. Furthermore, based on the results, we discuss ADR scenario and system architecture, which are advantageous in terms of cost.

2 ADR SCENARIO PARAMETERS

The purpose of the trade-off study is to find the optimal scenario by calculating the cost of removing one space

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debris in various ADR scenarios and comparing them with each other. An overview of the process of the assumed ADR mission is to launch ADR satellites with a rocket, rendezvous to the debris, capture it, and lower the altitude of the debris. As mentioned above, there can be various parameters in the scenario, and the options are diverse. The authors organized the parameters constituting the ADR scenario as shown in Table 1.

Table 1. ADR scenario parameters and options

Paremeter		Option	
Symbol	Description	Symbol	Description
architecture	Architecture	SINGLE	SINGLE architecture
		MOTHERSHIP	MOTHERSHIP architecture
		SHUTTLE	SHUTTLE architecture
n_debris	Number of debris removed by an ADR satellite	1 - 20	MOTHERSHIP/SHUTTLE: Number of debris removed by an ADR satellite
			SINGLE: Number of debris removed by an ADR satellite cluster launched by a Rocket
Mdebris	Debris mass	8000, 1500, 200	Debris mass [kg]
sc_size	ADR satellite size	MICRO	Satellite whose "base mass" (the mass excluding tank and kits) is 80 kg
		SMALL	Satellite whose "base mass" (the mass excluding tank and kits) is 250 kg
		LARGE	Satellite whose "base mass" (the mass excluding tank and kits) is 2000 kg
ep_type	Electric propulsion type	NONE	
		HALL	Hall thruster
		EDT	Electrodynamic tether (only for SINGLE architecture)
kit_type	ADR kit propulsion type	NONE	
		EDT_KIT	Electrodynamic tether (only for MOTHERSHIP and SHUTTLE architecture)
		SRM	Solid rocket motor
kit_size	ADR kit size	KIT200	ADR kit is scaled for removal of 200 kg debris
		KIT1500	ADR kit is scaled for removal of 1500 kg debris
		KIT8000	ADR kit is scaled for removal of 8000 kg debris
flag_inj_err	Rocket injection error due to launch window	INJ_ZERO_WINDOW	Launch window is 0 min
		INJ_15MIN_WINDOW	Launch window is ±15 min
flag_Hdest	Debris destination orbit	HDEST_25YRS	Orbit where debris will naturally reentry within 25 years
		HDEST_HIGH	Higher orbit than the 25 years orbit
flag_rocket	Launch vehicle	HIIA	H-IIA rocket (Japan)
		FALCON9	Falcon 9 (US)

Here, in order to organize the structure of the ADR scenario, the terms "architecture", "tour" and "campaign" are defined. Figure 1 shows the conceptual explanation.

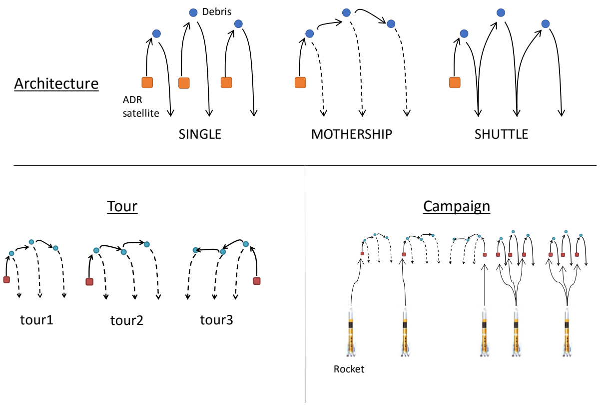

Figure 1. Concept of architecture, tour, and campaign

"Architecture" is a concept that expresses the process by which the ADR satellite removes debris. Based on reference [3], we defined three architectures that could be considered as ADR processes. In the "SINGLE" architecture, an ADR satellite removes one debris. In the "MOTHERSHIP" architecture, an ADR satellite has multiple ADR kits, visits multiple debris one by one, and attaches the kits to the debris. The ADR kit may be electrodynamic tether (EDT) or solid rocket motor (SRM). Then, the ADR kit lowers the debris and removes it from the original orbit. In the "SHUTTLE" architecture, an ADR satellite approaches the debris, captures the debris, lowers it, then it again ascents to the original altitude and heads to the next debris. Repeating this, an ADR satellite removes multiple debris. This “architecture” is one of the major and important ADR scenario parameters.

The "campaign" and "tour" are concepts expressing the structure of the ADR activities. The entire activity to remove a target group of debris is called campaign. This includes the launch of multiple rockets and the manufacturing of multiple ADR satellites. On the other hand, a certain activity that removes debris that an ADR satellite is responsible for is called a tour. One ADR satellite conducts one tour. One campaign consists of multiple rocket launches and multiple tours. What we want to know is the cost required to remove one debris, which can be computed by dividing the total cost of the campaign by the number of removed debris.

Other ADR scenario parameters are shown in Table 1. By selecting pre-prepared option for each parameter, one ADR scenario is completed. Our aim is to create multiple ADR scenarios assuming various cases and to calculate the cost of removing one debris for each case. By analysing the results, you can know which choice affects the increase and decrease of the cost, which leads to the search for the optimal ADR scenario.

3 A SCHEME TO COMPUTE ADR COST

A scheme was constructed in which the ADR scenario parameters shown in Table 1 were used as input and the ADR campaign cost was calculated to output the cost required for removing one debris. This chapter explains the scheme and the ADR cost model used therein. The overall picture of the scheme is shown in Figure 2.

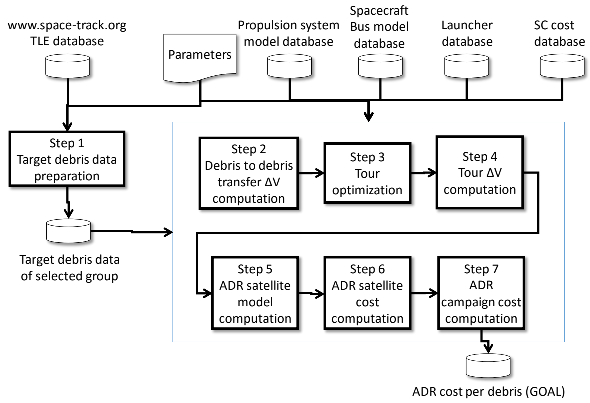

Figure 2. A scheme to compute ADR campaign cost

This scheme has a total of seven steps of processing. As a result of the processing, the cost required for removal of one debris is calculated. Each step will be explained one by one in the following subchapters.

3.1 Step 1: Target Debris Data Preparation

In this step, a group of debris to be removed is determined, and its orbit data is prepared. As typical target debris, for example, a group of Russian rocket upper stages that are densely present in orbits where the inclination i is 83°, or a group of large debris in sun synchronous orbits (SSO) can be considered. This step is carried out manually by humans. In the web database of JSpOC [4], conditions such as the orbit and the type of the objects are set, and a list of space objects matching the conditions is searched. Then, based on the list, the latest two-line element (TLE) orbit data is retrieved, and the data is extracted as a csv file. This file becomes an input to subsequent steps as the orbit data of the removal target debris.

3.2 Step 2: Debris to Debris Orbit Transfer ΔV Computation

In this step, for all the debris extracted in the step 1, the ΔV required for the transition from an orbit of one debris to that of another one is calculated for every possible pair combination. This calculation is preparation for the optimization process in the subsequent step 3. For example, when there are N debris to be removed, there are N × N combinations of all transitions. However, since the diagonal components are transitions to themselves, they are invalid. Therefore, there are N × N - N possible combinations. For each of the possible orbital transitions, required ΔV is computed.

Since it is necessary to calculate ΔV many times, it is important to simplify a calculation method. Therefore, we devised a simple calculation method of ΔV, focusing only on the semi-major axis a, the inclination i, and the right ascension of the ascending node (RAAN) Ω. In this method, the eccentricity e, the argument of periapsis ω, and the mean anomaly M are ignored. However, in this paper, only the space debris in the circular orbits with small eccentricity are handled. Also, the required ΔV for the proximity operation including the orbital phase adjustment and the control to capture the target is separately considered and added in the subsequent step 4. Therefore, we think that this is a good approximation as a calculation method roughly to estimate ΔV amount.

Various ways can be considered for the method of transition between orbits. The simplest is to change a, i, and Ω directly by impulse manoeuvres. However, the orbit of the target debris group of the low earth orbit (LEO) which is handled in this paper has a feature that the variation of the inclination is small, but the variation of the RAAN is very large. Therefore, it is not realistic to perform orbit transition by the method because the necessary ΔV becomes too large.

As a method to solve this, there is a method of indirectly changing the difference of the RAAN between two orbits using the nodal regression due to the gravity potential J_2 term. The nodal regression rate $\dot{\Omega}$ is a function of a and i. Therefore, by waiting for a while in a waiting orbit where the difference of a and i between the two orbits are intentionally set, it is possible to absorb the difference of the RAAN. The specific process is as follows. First, the ADR satellite changes a and i by the first impulse maneuver and moves to the waiting orbit. Next, it stands by for a long time on the waiting orbit and changes the difference of the RAAN by utilizing the difference in the nodal regression rate. Finally, in the second impulse maneuver, it moves to the a of the target orbit. We refer to this method as the indirect impulse transfer (IIT) method.

Also, instead of performing the transition between debris with impulse maneuvers, there may be an ADR satellite system that performs it with finite time maneuvers by low thrust electric propulsion. Even with the use of the efficient electric propulsion, a large amount of propellant and significantly long life of the thruster are required to directly absorb the difference of the large RAAN. Therefore, it is realistic to use the nodal regression rate as in the case of the impulsive maneuver. There is an analytical solution named Edelbaum equation [5] for obtaining the required ΔV for the orbital transition by low thrust propulsion from a circular orbit to a circular orbit. It is often used to calculate rough estimates. We will call the orbital transition approach which uses both the orbital transition by the Edelbaum equation and the orbital plane rotation due to the nodal regression [6] as a split Edelbaum transfer (SET) method. Figure 3 shows a schematic diagram of orbit transitions by the IIT method and the SET method.

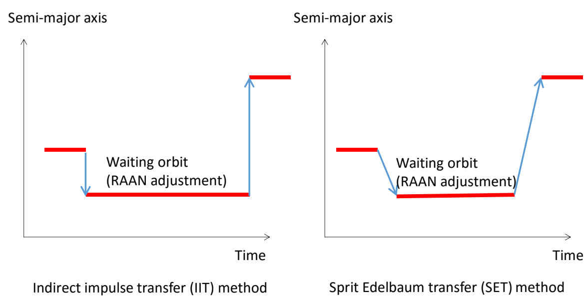

Figure 3. Concept of orbit transfer using IIT method and SET method

When the IIT method is applied, firstly an orbital transition to the semi-major axis of the waiting orbit a_w is made by the two impulses of the Homan transfer (ΔV_{t1A} and ΔV_{t1B}). After passing through the waiting period T_w at the waiting orbit, the second transition to the target semi-major axis a_t is made by another two impulses of the Homan transfer (ΔV_{t2A} and ΔV_{t2B}). It is necessary to select the proper semi-major axis a_w so that the difference of the RAAN becomes zero after the waiting period T_w passes. The difference in the inclination is directly absorbed by an out-of-plane maneuver (ΔV_n). Eqn. (1) - (8) show the calculation formula of the transition ΔV in the IIT method. Here, n is the mean motion, R_e is the Earth's equatorial radius, δ means the difference of the orbital element, the subscript o means the initial orbit, w means the waiting orbit, and t means the target orbit, respectively.

$$\Delta V_n = n_o a_o \delta i \tag{1}$$

$$\frac{\partial \delta \dot{\Omega}}{\partial a} = \frac{21 \gamma n_o}{2 a_o} \cos i_o , \ \ \gamma = \frac{J_2}{2} \left(\frac{R_e}{a_o}\right)^2 \tag{2}$$

$$a_w = a_t - \delta \Omega / \left(\frac{\partial \delta \dot{\Omega}}{\partial a} T_w \right) \tag{3}$$

$$\Delta V_{t1A} = \sqrt{\frac{\mu}{a_o}} \left(\sqrt{\frac{2 a_w}{a_o + a_w}} - 1 \right) \tag{4}$$

$$\Delta V_{t1B} = \sqrt{\frac{\mu}{a_w}} \left(1 - \sqrt{\frac{2 a_w}{a_o + a_w}} \right) \tag{5}$$

$$\Delta V_{t2A} = \sqrt{\frac{\mu}{a_w}} \left(\sqrt{\frac{2 a_t}{a_w + a_t}} - 1 \right) \tag{6}$$

$$\Delta V_{t2B} = \sqrt{\frac{\mu}{a_t}} \left(1 - \sqrt{\frac{2 a_t}{a_w + a_t}} \right) \tag{7}$$

$$\begin{aligned} \Delta V = |\Delta V_n| + |\Delta V_{t1A}| + |\Delta V_{t1B}| \\ + |\Delta V_{t2A}| + |\Delta V_{t2B}| \end{aligned} \tag{8}$$

When the SET method is applied, the semi-major axis a and the inclination i are corrected at the same time with a finite time manoeuvre. By solving the nonlinear optimization problem with a_w and i_w as parameters, the required total ΔV is minimized under the equality constraint that the difference of the RAAN at the end of the waiting period T_w becomes zero. Equations for the transition ΔV calculation in the SET method are shown in Eqn. (9) - (13). Eqn. (10) and (11) are the Edelbaum equations. The authors solve this nonlinear optimization problem using the matlab's fmincon function.

With the IIT method or the SET method, the required ΔV of all possible debris to debris orbital transitions can be calculated in a relatively short time.

$$\min_{a_w, i_w} f(a_w, i_w) \ \ s.t. \ ceq(a_w, i_w) = 0 \tag{9}$$

$$\Delta V_1 = \sqrt{V_o^2 + V_w^2 - 2 V_o V_w \cos\left(\frac{\pi}{2}(i_w - i_o)\right)} \tag{10}$$

$$\Delta V_2 = \sqrt{V_w^2 + V_t^2 - 2 V_w V_t \cos\left(\frac{\pi}{2}(i_t - i_w)\right)} \tag{11}$$

$$f(a_w, i_w) = \Delta V_1 + \Delta V_2 \tag{12}$$

$$ceq(a_w, i_w) = \delta \Omega (t = T_w, a_w, i_w) \tag{13}$$

3.3 Step 3: Tour Optimization

When considering a ADR campaign to remove N_{deb} debris with N_{sat} ADR satellites, one ADR satellite should remove N_{deb}/N_{sat} debris in the average. Assigning the target debris randomly to each ADR tour will generally results in that pairs of debris where the orbits are remarkably distant from each other can be placed in the same ADR tour. This significantly increases the required ΔV capability of the ADR satellites. Therefore, it is important to assign "near" debris to each ADR tour as much as possible from the viewpoint of the ΔV reduction. For this purpose, this step optimizes the allocation of the target debris to each ADR tour.

In the case of the MOTHERSHIP or SHUTTLE architecture in which one ADR satellite removes multiple debris, optimization is performed so that the maximum orbit transition ΔV among all the tours is minimized. In other words, the ΔV of the worst tour is minimized. This is intended to equalize the necessary ΔV to each ADR satellite as much as possible. Since the ADR satellite to be developed requires the ability to carry out this ADR campaign, the ΔV of the worst tour becomes the orbit transition capability required for the ADR satellite.

On the other hand, in the SINGLE architecture, we assume that one rocket accommodates and launches a satellite cluster consisting of multiple ADR satellites. The rocket injects all the loaded ADR satellites in the same orbit. From this initial orbit, each ADR satellite departs toward their assigned debris. We optimize the assignment of the debris to each rocket so that the maximum orbit transition ΔV among all the ADR satellites is minimized. Again, as with the MOTHERSHIP and SHUTTLE architectures, we intend to equalize the required ΔV for each ADR satellite. The optimization concept described above is illustrated in Figure 4.

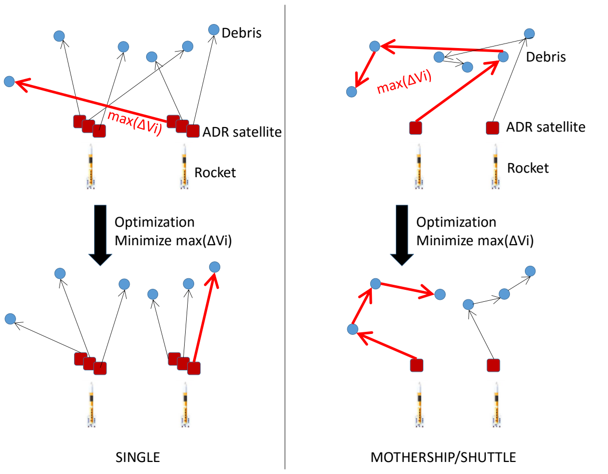

Figure 4. Concept of ADR tour optimization

This optimization calculation is a type of so-called traveling salesman problem (TSP), and it is possible to obtain a quasi-optimal solution using a genetic algorithm. References [7] and [8] can be cited as previous studies that solved similar problems using TSP.

Examples of the optimization results in the MOTHERSHIP architecture are shown in Figure 5 and Figure 6. These are the calculation results on the ADR campaign for removing the 90 Russian rocket upper stages at the inclination i = 83° by 14 ADR satellites. Each ADR satellite is walking across multiple debris one after another. Debris with the closer RAAN values are grouped because the difference of the RAAN is the dominant factor determining orbital transition ΔV. Since each ADR satellite removes about five debris on average, the number of orbital transitions for each tour is about four. In this example, the ADR tour requiring the largest ΔV needs a total of about 120 m/s for orbit transitions between debris.

Similarly, examples of optimization results in the case of the SINGLE architecture are shown in Figure 7 and Figure 8. It is the calculation result of the ADR campaign which removes the 90 Russian rocket upper stages by launching 14 rockets with five ADR satellites. Unlike the MOTHERSHIP architecture, each ADR satellite is spreading towards the responsible debris from its initial orbit.

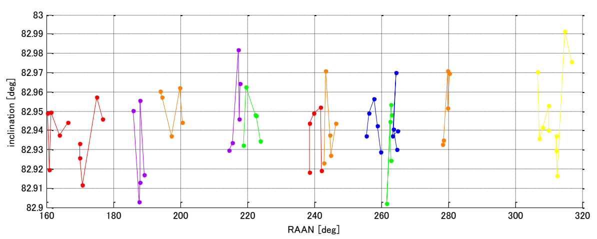

Figure 5. Distribution of debris RAAN and inclination as a result of ADR tour optimization (MOTHERSHIP architecture)

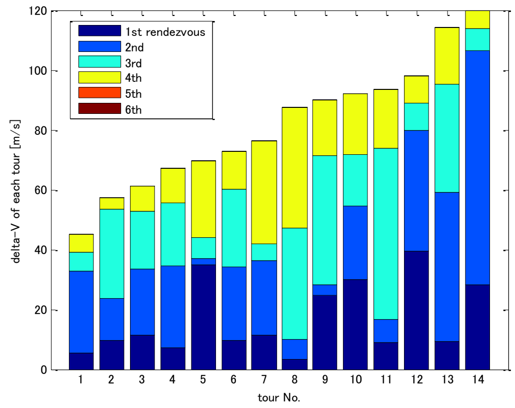

Figure 6. Orbital transfer ΔV allocated for each tour as a result of ADR tour optimization (MOTHERSHIP architecture)

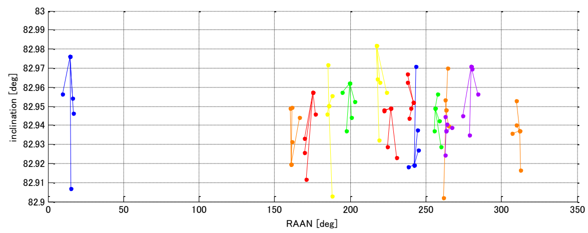

Figure 7. Distribution of debris RAAN and inclination as a result of ADR tour optimization (SINGLE architecture)

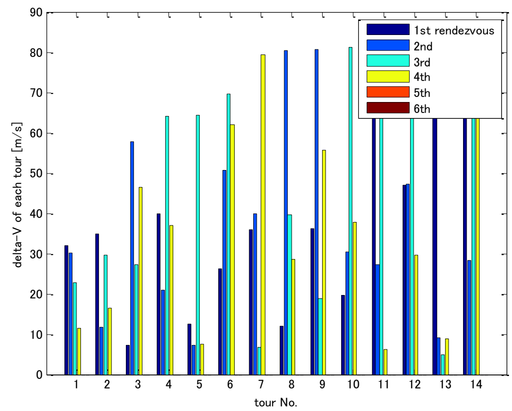

Figure 8. Orbital transfer ΔV allocated for each tour as a result of ADR tour optimization (SINGLE architecture)

3.4 Step 4: Tour Δ V Computation

The ADR satellite consumes propellant not only in orbit transition between debris. First of all, it is necessary to perform a correction maneuver to compensate for the launch injection error. Also, after arriving in the vicinity of the target debris, it is necessary to perform the proximity operation including the orbital phase adjustment and the relative position control to capture the target. Furthermore, for the SINGLE and SHUTTLE architecture, we need to perform a descent maneuver to lower the debris. In addition, in the case of the SHUTTLE architecture, once we have lowered the debris to a sufficiently low altitude, we need to perform an ascent maneuver back to the altitude of the next debris again. Finally, when the ADR tour ends, the ADR satellite itself needs to move to a graveyard orbit. Therefore, the structure of ΔV consumed by the ADR satellite is summarized as shown in Figure 9. For the MOTHERSHIP and SHUTTLE architectures, the sum of all ΔV in the table in Figure 9 is the total ΔV required for the ADR satellite. In the case of the SINGLE architecture, the sum of ΔV in one row of the table is the total ΔV required for each ADR satellite.

ADR sat No.	INJ	TRN	PRX	DES	ASC
1	✓	✓	✓	✓	
2	✓	✓	✓	✓	
3	✓	✓	✓	✓	
⋮	⋮	⋮	⋮	⋮	⋮
N	✓	✓	✓	✓	

SINGLE

Debris No.	INJ	TRN	PRX	DES	ASC
1	✓	✓	✓		
2		✓	✓		
3		✓	✓		
⋮	⋮	⋮	⋮	⋮	⋮
N		✓	✓	✓	

MOTHERSHIP

Debris No.	INJ	TRN	PRX	DES	ASC
1	✓	✓	✓	✓	✓
2		✓	✓	✓	✓
3		✓	✓	✓	✓
⋮	⋮	⋮	⋮	⋮	⋮
N		✓	✓	✓	

SHUTTLE

Figure 9. Structure of ADR tour ΔV (INJ: injection, TRN: transfer between debris, PRX: proximity operation, DES: descent, ASC: ascent)

In this step, the ΔV of injection, proximity operation, descent, and ascent are calculated. And the total ΔV of each tour, that is, ΔV per the ADR satellite is calculated. The injection maneuver ΔV is calculated assuming that the launch injection errors in a, i, Ω are corrected by impulsive burns by RCS. The proximity operation ΔV is a fixed value of 20 m/s per one time. Also, for ΔV required for descent or ascent, it is calculated as performing only decreasing or increasing the semi-major axis, respectively.

3.5 Step 5: ADR Satellite Model Computation

In this step, the mass and power of each subsystem constituting the ADR satellite system are calculated. In addition, we also calculate the satellite dry and wet mass. The input is the worst value of the ΔV of the ADR tours calculated in the step 4, and the parameters set for the scenario such as the satellite size, the propulsion system type, the removal kit type, etc. Table 2 outlines the model used for the calculation.

Three kinds of satellite sizes, MICRO, SMALL and LARGE, shown in Table 2 are set as options for the ADR satellite size. The ratios of the propellant weight to the tank weight, the ratio of each subsystem weight to the total weight of the satellite, and the weight of the electric propulsion subsystem are set with reference to data from multiple satellites of JAXA and the reference [9]. In this model, as the required ΔV increases, the propellant mass, tank mass, and mass of its support structure increase, resulting in an increase in the satellite dry mass. Since the ADR satellite should perform the proximity operation to the target debris, the chemical RVS is necessarily equipped. The hall thruster was assumed as the electric propulsion device. The presence or absence of the electric propulsion device and the ADR kits is determined by the ADR scenario parameter. In the case of satellites that do not have the electric propulsion device or the ADR kits, their masses are not added.

Table 2. Summary of ADR satellite mass and power model

Symbol	Spacecraft Size			Unit	Remark
	MICRO	SMALL	LARGE		
Mbase	80	250	2000	kg	Dry mass excluding tank and kits
Pbase	100	300	1000	W	Power excluding electric propulsion
Mfuel_rcs	Computed from ΔV for maneuvers using RCS			kg	Fuel mass for RCS maneuver
Mfuel_ep	Computed from ΔV for maneuvers using HALL			kg	Fuel mass for HALL maneuver
Mrcs_tank	= Mfuel_rcs*0.1			kg	RCS tank mass
Mep_tank	= Mfuel_ep*0.16			kg	HALL tank mass
Mep	= Mep_sys + Mep_tank			kg	HALL subsystem mass
Pep	120	1200	12000	W	Power for HALL
Mkit	Depending on target debris mass			kg	Kit mass
Mbus	= Mbase + Mrcs_tank			kg	Bus mass
Mdry	= Mbus + Mep + Mkit × Nkit			kg	Dry mass
Mwet	= Mdry + Mfuel_rcs + Mfuel_ep			kg	Wet mass
Ptot	= Pbase + Pep			kg	Total power
Maocs	= Mbus*0.12			kg	AOCS subsystem mass
Mttc_dh	= Mbus*0.08			kg	COM subsystem mass
Mtherm	= Mbus*0.05			kg	THERMAL subsystem mass
Meps	= Mbus*0.25			kg	POWER subsystem mass
Mstr	= Mbus*0.40			kg	STRUCTURE mass
Mrcs	= Mbus*0.10			kg	RCS mass

3.6 Step 6: ADR Satellite Cost Computation

In this step, the recurrent cost of the ADR satellite is calculated by the cost model based on the reference [9]. In the reference, nonrecurring costs are denoted by research, development, test and evaluation (RDT&E) and recurring by the theoretical first unit (TFU). The mass and power of each subsystem constituting the ADR satellite obtained in the step 5 are inputs. Table 3 outlines the model.

Table 3. Summary of ADR satellite cost model

No.	Symbol	RDT&E [K$]	TFU[K$]	Remark
(1)	Cost_kit	= Mkit*191*TRLfactor	= Mkit*64	KIT cost
(2)	Cost_str	= 157*Mstr^0.83*TRLfactor	= Mstr*13.1	STRUCTURE cost
(3)	Cost_therm	= (1.1*Mtherm^0.61)*((Mdry)^0.943)*TRLfactor	= 50.6*Mtherm^0.707	THERMAL cost
(4)	Cost_eps	= 2.63*(Meps*Ptot)^0.712*TRLfactor	= 112*Meps^0.763	EPS cost
(5)	Cost_ttc_dh	=	= 635*Mttc_dh^0.568	TTC&DH cost
(6)	Cost_aocs	=	= 293*Maocs^0.777	AOCS cost
(7)	Cost_rcs	= (65.6+2.19*Mdry^1.261+1539 + 434*log(Vbus) + 4303 - 3903*Nthruster^(-0.5))*2/3*TRLfactor	= (Cost of RDT&E)/2	RCS cost
(8)	Cost_ep	= Mep*191*TRLfactor	= Mep*64	HALL cost
(9)	Cost_subtot	= sum of (1) to (8)		
(10)	Cost_iat	= 0.139*Cost_subtot*2/3	= (Cost of RDT&E)/2	Integration and test cost
(11)	Cost_prog	= 0.229*Cost_subtot*2/3	= (Cost of RDT&E)/2	Program cost
(12)	Cost_gse	= 0.066*Cost_subtot*2/3	= (Cost of RDT&E)/2	GSE cost
(13)	Cost_loos	= 0.061*Cost_subtot*2/3	= (Cost of RDT&E)/2	
(14)	Cost_tot_FY00	= (sum of (1) to (13))*(1 + rate_contractor_fee)		Cost at FY2000
(15)	Cost_tot_CURR	= Cost_tot_FY00*rate_infration		Cost at FY2016

If the technology of the subsystem is immature, its development tends to cost more. In order to reflect this, we adopted a model that weights RDT&E based on technology readiness level (TRL) of each subsystem with reference to the literature [3]. Specific values of the weighting factor "TRLfactor" and the setting of the evaluated value of the TRL for each subsystem are shown in Table 3. We evaluated the TRL low for ADR kits and AOCS that can deal with non-cooperative targets.

Table 4. TRLfactor and TRL value of each subsystem

TRL	TRLfactor
3	1.75
4	1.75
5	1.32
6	1.32
7	1
8	0.82
9	0.68

Subsystem	TRL
KIT	4
STR	7
THERM	7
EPS	6
TTCDH	7
AOCS	4
RCS	7
EP	5

3.7 Step 7: ADR Campaign Cost Computation

In this last step, we first decide the number of ADR satellites N_{sat} necessary to remove all the target debris and the number of rockets N_{rocket} necessary to launch those ADR satellites. Furthermore, using the ADR satellite recurrent cost $Cost_{sat}$ and the rocket cost $Cost_{rocket}$, the ADR campaign cost $Cost_{campaign}$ is calculated according to Eqn. (14). The ADR campaign cost corresponding to the ADR scenario parameter can be calculated through the process of the above seven steps. By dividing it by the number of target debris N_{debris}, the ADR cost per one debris $Cost_{per\_deb}$ is obtained.

$$Cost_{campaign} = Cost_{sat}N_{sat} + Cost_{rocket}N_{rocket} \tag{14}$$

Since the calculation of the mass, power, cost of the ADR satellite is based on a simple model described above, the cost calculation error is not considered to be small. Therefore, it is important to note that the absolute value of cost is only an approximate value. However, the purpose of this study is to compare various ADR scenarios in terms of cost, and it is sufficient if it can simulate the sensitivity of cost variation to parameters. Therefore, we believe that it is appropriate to represent the ADR cost, which is the output of this scheme, as relative values normalized by the cost of a certain case instead of using it as they are. It is a reasonable use of this scheme to discuss the cost advantage of each scenario based on the normalized values.

4 ADR SCENARIO TRADE-OFF ANALYSIS RESULTS

The ADR scenario trade-off study was performed using the developed scheme described in the previous chapter. In this chapter, the analysis results are shown and discussed.

4.1 Cases and Parameters

Groups of cases to be analysed is set as shown in Table 5. Parameters of interest are the target debris, the architectures, the ADR satellite size, and the debris mass. As a target debris, we selected a group of Russian rocket upper stages that are densely present in orbits where the inclination i is 83°, and designed the case groups A to F with the intention of investigating the difference by architecture. In the case of the SINGLE architecture, since the number of removed debris per the ADR satellite is limited to be one, the case of the larger ADR satellite which is obviously inferior in economy is omitted, and only the case of the MICRO size satellite is set up. As MOTHERSHOP architecture, realization is severe with the MICRO size satellites, so we considered only the SMALL size satellites. As a SHUTTLE architecture, I tried various ADR satellite sizes. Also, in order to examine the difference due to the target debris, we set the case group G to remove large debris existing in SSO. By comparing the case group D and G we can see how the ADR cost changes depending on the target debris orbits.

Table 5. Case groups of ADR scenario trade-off analysis

Case group ID	Target debris	Architecture	ADR satellite size	Debris mass [kg]
A	Russian rocket upper stage (i = 83 deg)	SINGLE	MICRO	1500
B				8000
C				200
D		MOTHERSHIP	SMALL	1500
E				8000
F		SHUTTLE	MICRO, SMALL, LARGE	200, 1500, 8000
G	SSO debris	MOTHERSHIP	SMALL	1500

Table 6. Choices of ADR scenario parameters for ADR scenario trade-off analysis

Parameter	Choice
Mdebris	200 kg (similar to typical mega-constellation satellite) or 1500 kg (similar to SL-8 COSMOS-3M upper stage) or 8000 kg (simlar to SL-16 ZENIT upper stage)
flag_inj_err	INJ_ZERO_WINDOW
flag_Hdest	HDEST_25YRS
flag_rocket	H-IIA (3300 kg to SSO) or Falcon-9 (7000 kg to SSO)

Other prerequisites are summarized in Table 6. We set three kinds of debris mass: a SL-16 Zenit upper stage (8000 kg), a SL-8 COSMOS-3M upper stage (1500 kg), and 200 kg as a typical mega constellation satellite. The rocket was supposed to be launched toward the orbital plane of the debris to be removed first. The graveyard orbit is set to have an altitude at which the debris re-enters the earth naturally in 25 years. Basically, we select the H-IIA of Japan as the launcher, but if the ADR satellite is too heavy, the Falcon-9 can also be an option as well. In calculating the number of ADR satellites that can be installed in the rocket, fifty percent of the ADR satellite mass is added as the support structure plus margin necessary for the rocket side. In addition, the maximum operating time of the hall thruster is set to be 8000 hours, and if it is more than that, decided that the ADR satellite is supposed to be technically difficult to realize.

4.2 Target Debris and its Orbit

In this subchapter, characteristics of the target debris orbits are described. Figure 10 shows the histogram of the orbital elements of the Russian rocket upper stages that are densely present in orbits where the inclination i is 83°. The total number is 142. A remarkable feature is that the distributions of the semi-major axis a and inclination i are very narrow. This feature seems to work advantageously for the efficiency of orbital transfer. The RAAN Ω is widely distributed.

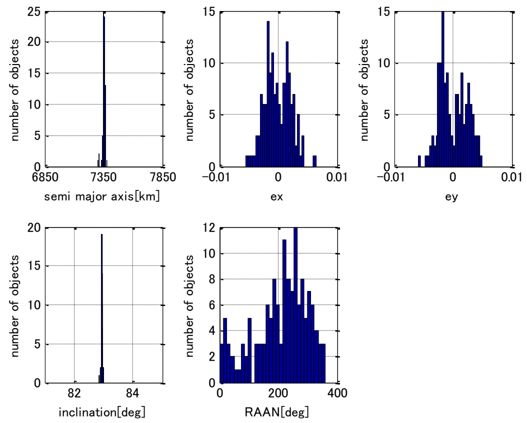

Figure 10. Orbital elements histogram of 142 Russian rocket upper stages at i = 83°

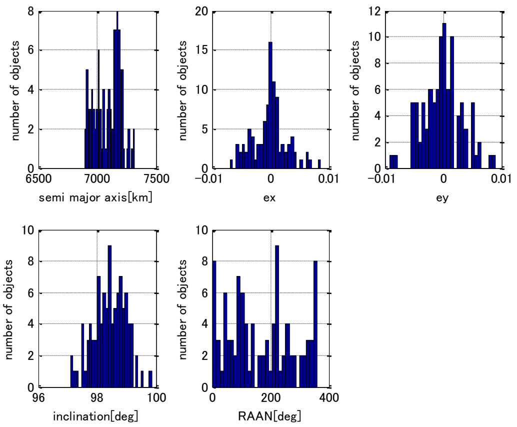

Figure 11. Orbital elements histogram of 98 large debris at SSO

Figure 11 shows the distribution of the large debris in SSO. Not only the spent upper stages, but also some typical satellite debris, such as ENVISAT, ADEOS, ADEOS-2, and ALOS are also added into this debris group. The total number is 98. One characteristic is that the distribution of the semi-major axis a and inclination i is relatively wide. This feature may be disadvantageous in terms of the required period and ΔV for orbital transfer.

4.3 Russian Upper Stage Removal Scenario

This subchapter describes the analysis results of the Russian rocket upper stage case groups (case group A to F). Figure 12 shows the debris-to-orbit orbit transition ΔV table computed by the IIT method described in the subchapter 3.2. The orbital transition period is fixed to six months. Both the horizontal axis and the vertical axis are ID numbers of 142 debris. The ID number is sorted in ascending order with respect to the RAAN. From this figure, the required ΔV for the orbit transition from one debris (horizontal axis) to another debris (vertical axis) can be found. The diagonal white line is a transition to itself, so it is null. The fact that this figure shows a clean gradation indicates that the orbit transition ΔV is almost determined by the difference of the RAAN. There is a boundary where the required ΔV jumps on the left side of the diagonal white line. This is because the lower limit of the waiting orbit altitude is restricted to 400 km. On the left side of the boundary, the ADR satellite does not make a transition to a low waiting orbit, but conversely it transitions to a very high waiting orbit and attempts to correct the difference of the RAAN in the opposite direction.

Figure 13 shows an example of the debris-to-debris orbit transition ΔV table by the SET method. The white area shows that there is no feasible solution. The reason why the white area is conspicuous compared with the figure of the IIT method is that the orbit transition using the hall thruster with small thrust may not make a transition to a distant orbit within a defined orbital transition period.

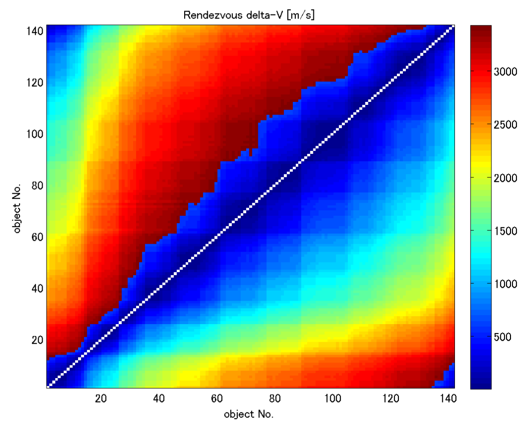

Figure 12. Orbital transfer ΔV table of Russian rocket upper stages at i = 83°, by IIT method, transfer duration is six months.

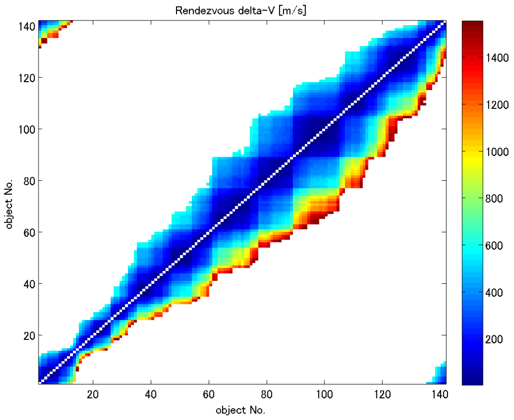

Figure 13. Orbital transfer ΔV table of Russian rocket upper stages at i = 83°, by SET method, transfer duration is six months, acceleration is $1e^{-4}\ m/s^2$

Figure 16 shows the ADR scenario trade-off analysis results for each case in the case group A. These cases are the SINGLE architecture, the ADR satellite is the MICRO size, and the mass of debris is that of the SL-8 COSMOS-3M upper stage. It is important to note that costs in all analysis results (Figure 16 to Figure 22) are represented by values normalized with respect to the case A-1. From the ADR cost per one debris, the case A-4 in which debris is lowered by the hall thruster is found to be the lowest price. However, in this case, the operation time of the hall thruster exceeds 8000 hours, which is difficult to realize. This case may become feasible by relaxing the objective of the ADR. As an example of a possible way, for example, the altitude of the destination graveyard orbit may be increased from the altitude at which debris naturally re-enters in 25 years to a higher altitude aimed only to remove debris from the crowded orbit. Except for the case A-4, the case A-2 is the lowest cost. In this case, the EDT is used as a debris removal device, and the chemical propulsion RCS is used for other manoeuvres. The cases of using SRM as a removal device are expensive.

Figure 17 shows the results of the case group B in which the mass of the target debris is changed to 8000 kg from that of the case group A. The cases B-2 and B-5 using EDT as a removal device are considerably lower in cost than the cases using other removal device types (RCS, SRM, and HALL). This is the result of the EDT's characteristic that the fuel consumption does not increase even if the debris mass increases. The cases B-4 and B-6 which uses hall thrusters are not realistic because the electric propulsion operation time is too long. When SRM is used as a removal device, the mass of the ADR satellite greatly increases and it is expensive.

In the case group C, as a thought experiment, the debris mass is reduced to 200 kg assuming a mega constellation. The analysis results are shown in Figure 18. It can be seen that the difference between the removal device types has shrunk. With this debris mass, the ADR satellite using SRM seems reasonable in terms of cost.

Figure 19 shows the analysis results of the case group D, which is a scenario to remove the 1500 kg debris with the MOTHERSHIP architecture. The case D-4 is the lowest cost for removing the SL-8 COSMOS-3M upper stages among all the case groups A to G. This is a scenario where the SMALL size ADR satellites perform orbit transitions between debris by hall thrusters, and distribute EDT kits to each debris. This is considered to be a cost-effective method. The difference between the SRM kit and the EDT kit is not large with this mass of debris.

Figure 20 shows the results of the case group E in which the mass of the target debris is changed to 8000 kg from that of the case group D. As with the case group D, the case E-4 is the lowest cost for removing the SL-16 Zenit upper stages. On the other hand, it is found that the SRM kits are greatly disadvantageous to the EDT kits when the debris becomes heavy.

Figure 21 shows the analysis results of the case group F which tries various ADR satellite sizes in the SHUTTLE architecture. In this architecture, the size of the ADR satellites increases in all cases, resulting in a higher cost of removing one debris. The cases where many large debris are lowered with the LARGE size ADR satellites (the cases F-5 to F-8) with the SHUTTLE architecture can be feasible from the viewpoint of the electric propulsion operating time. However, as a result of the soaring price of the ADR satellite, it seems difficult to secure superiority in terms of economic efficiency.

4.4 SSO Large Debris Removal Scenario

In this section, analysis results of the SSO debris removal scenario (the case group G) will be described. Figure 14 shows the debris-to-orbit transition ΔV table by the IIT method. The debris ID No. is similarly sorted in ascending order by the RAAN. The orbital transition period was set as one year. This is because, in half a year, in most cases, there is no real solution in the orbit transitions by the SET method. The fact that the figure is not a clean gradation compared with Figure 12 indicates that the trajectory transition ΔV cannot be determined only by the difference between the RAAN. The ΔV is also influenced by the difference of the semi-major axis a and the inclination i which are relatively highly dispersed. Despite the long orbit transition period, the ΔV in Figure 14 is slightly larger than that of Figure 12. Therefore, the burden of orbit transition is larger in the SSO case.

Figure 15 shows an example of the debris-to-debris transition ΔV table by the SES method. As described above, the transition period is set to one year. As with the IIT method, it can be seen that the burden of the orbital transition is larger than the dense Russian rocket upper stage case.

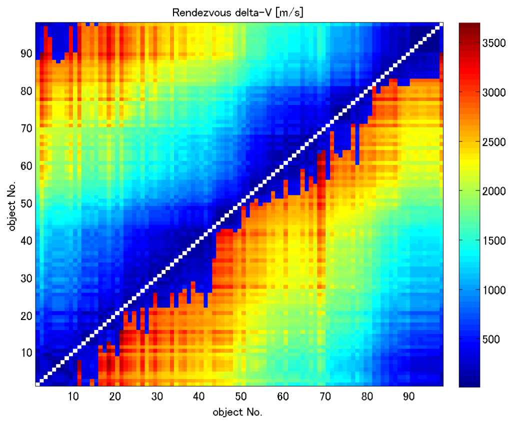

Figure 14. Orbital transfer ΔV table of SSO debris, by IIT method, transfer duration is one year

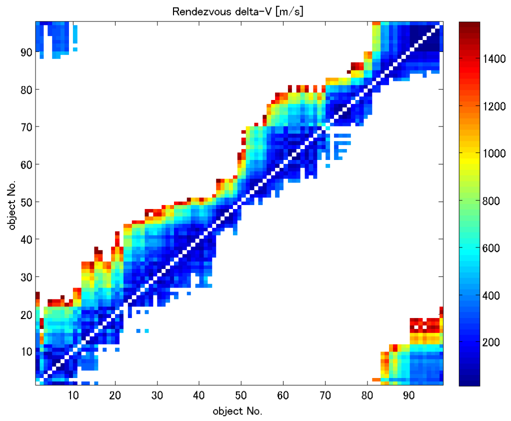

Figure 15. Orbital transfer ΔV table of SSO debris, by SET method, transfer duration is one year, acceleration is $1e^{-4}\ m/s^2$

Figure 22 shows the analysis results of the case group G. It is a scenario that the ADR satellite removes the 1500 kg SSO debris with the MOTHERSHIP architecture. As described above, the case group G has the larger required ΔV than the case group D. As a result, the ADR costs of one debris for the SSO cases are higher (about 5 to 13%) than that of the case group D. In other words, despite doubling the orbit transition period to the Russian rocket upper stage cases, the cost has increased rather than reduced. Therefore, it was found that the SSO debris removal scenario is considerably higher in terms of cost.

4.5 Findings

The trade-off analysis of the ADR scenario has been carried out for each of the Russian rocket upper stages removal and the SSO debris removal. Based on the results, the following findings are obtained.

The scenarios of the MOTHERSHIP architecture in which the SMALL satellites equipped with a hall thruster distributes EDT kits to the target debris are the most cost effective. In addition, if we relax the condition of the graveyard orbit altitude, the scenario of the SINGLE architecture, which the MICRO size satellite equipped with a hall thruster lowers debris, may be a low cost alternative. However, since hall thrusters for small satellites often have short lifetimes (typically 1000 to 2000 hours), technological innovation which extends that is the key to feasibility.

In the case of using the SRM as a removal device, if the removal target is about 200 kg of debris, it is reasonable. But if debris of more than 1500 kg is targeted, it is considered to be expensive compared with other means.

In addition, technically no fatal problem was found in the SHUTTLE architecture scenario where a large satellite has large power electric propulsion system and it removes multiple large debris. However, the ADR satellite costs soared, which led to an inefficiency in terms of economy.

The ADR in SSO is considered to be more costly than the removal of the Russian rocket upper stages located in the narrow bandwidth of orbital elements. The reason is that the required ΔV increases and/or the orbital transition period becomes longer. However, in the case of SSO, there may be many opportunities for ADR satellites to share a rocket with another satellite. From that perspective, there is a possibility that the economic advantage will increase.

5 CONCLUSIONS

We have constructed the scheme to make a trade-off of ADR scenarios in terms of costs. We used it to compute the ADR cost per one debris in various removal architectures, removal satellite sizes, removal device types, and we analysed the results to seek out cost superior options.

The cost model used in the scheme constructed this time is simple. In addition, there are costs that are missing, such as the operation cost of the ADR satellites, etc. Therefore, we think that the absolute value of the computed cost is not very reliable, but we think that as relative values for comparing scenarios it is sufficiently meaningful even at this stage. In the future, we will refine the model, and we will further study various scenarios and discuss which architecture, satellite size and combination of removal devices are considered suitable for practical ADR realization. We hope that the results will be useful for space agencies and private sectors to plan development strategies of the space debris removal technology.

6 REFERENCES

1. IADC (2013). Stability of the Future LEO Environment, IADC-12-08, Rev. 1.
2. Liou, J.-C. (2011). An active debris removal parametric study for LEO environment remediation, Advances in Space Research Volume 47, Issue 11, pp. 1865-1876.
3. Chamot, B., & Richard, M. (2012). Mission and system architecture design for active removal of rocket bodies in low earth orbit. *Master's thesis, Massachusetts Institute of Technology, US*.
4. Joint Space Operations Center, Space-Track.org, (2012). The Source for Space Surveillance Data, [www.space-track.org], USSTRATCOM.
5. Edelbaum, T. N. (1961). Propulsion requirements for controllable satellites. *ARS Journal*, *31*(8), pp.1079-1089.
6. Cerf, M. (2015). Low-Thrust Transfer Between Circular Orbits Using Natural Precession. *Journal of Guidance, Control, and Dynamics*, pp.2232-2239.
7. Cerf, M. (2015). Multiple Space Debris Collecting Mission: Optimal Mission Planning. *Journal of Optimization Theory and Applications*, *167*(1), pp.195-218.
8. Izzo, D., Getzner, I., Hennes, D., & Simões, L. F. (2015). Evolving solutions to TSP variants for active space debris removal. In *Proceedings of the 2015 Annual Conference on Genetic and Evolutionary Computation*, pp.1207-1214
9. Larson, W. J., & Wertz, J. R. (1999). *Space mission analysis and design, third edition*. Microcosm, Inc.

Case ID	ADR sat. size	Architecture	ep_ type	kit_ type	Mdebris [kg]	Rocket	No. of launches	No. of ADR sats	Removed debris per an ADR sat	Mdry [kg]	Mwet [kg]	EP ops. time [hour]	one ADR sat TFU cost	Rocket total cost	ADR sat total cost	Cost per a debris
A-1	MICRO	SINGLE			1500	H-IIA	17	100	1	112	275	0	**1.0**	**1.0**	**1.0**	**1.0**
A-2	MICRO	SINGLE		EDT	1500	H-IIA	10	100	1	127	151	0	0.8	0.6	0.8	0.7
A-3	MICRO	SINGLE		SRM	1500	H-IIA	25	100	1	291	477	0	2.0	1.5	2.0	1.8
A-4	MICRO	SINGLE	HALL		1500	H-IIA	8	100	1	106	145	18483	0.7	0.5	0.7	0.6
A-5	MICRO	SINGLE	HALL	EDT	1500	H-IIA	15	100	1	139	159	0	0.9	0.9	0.9	0.9
A-6	MICRO	SINGLE	HALL	SRM	1500	H-IIA	20	100	1	279	317	16917	1.8	1.2	1.7	1.6

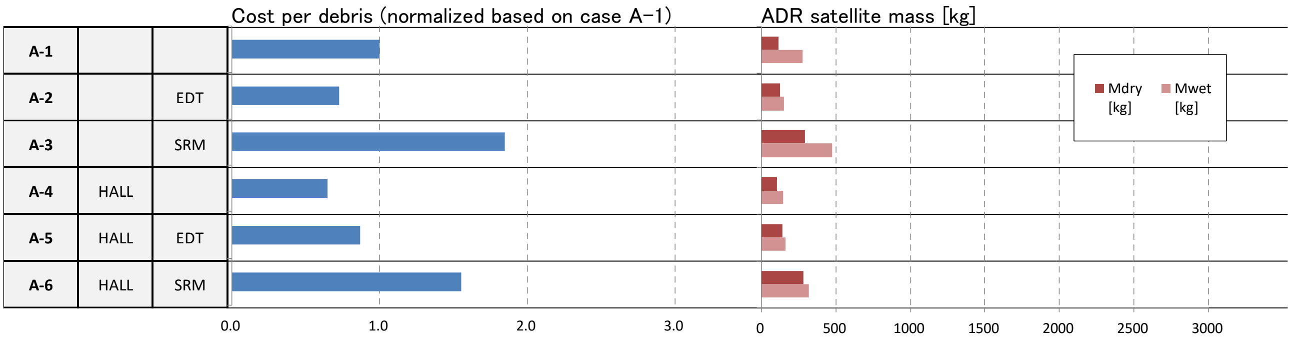

Figure 16. ADR scenario trade-off results (case group A). Cost is expressed as normalized value w.r.t. case A-1.

Case ID	ADR sat. size	Architecture	ep_ type	kit_ type	Mdebris [kg]	Rocket	No. of launches	No. of ADR sats	Removed debris per an ADR sat	Mdry [kg]	Mwet [kg]	EP ops. time [hour]	one ADR sat TFU cost	Rocket total cost	ADR sat total cost	Cost per a debris
B-1	MICRO	SINGLE			8.0ton	H-IIA	50	100	1	222	934	0	2.5	2.9	2.4	2.6
B-2	MICRO	SINGLE		EDT	8.0ton	H-IIA	10	100	1	127	151	0	0.8	0.6	0.8	0.7
B-3	MICRO	SINGLE		SRM	8.0ton	H-IIA	100	100	1	992	1781	0	6.5	5.9	6.4	6.3
B-4	MICRO	SINGLE	HALL		8.0ton	H-IIA	17	100	1	139	283	68404	1.2	1.0	1.2	1.1
B-5	MICRO	SINGLE	HALL	EDT	8.0ton	H-IIA	15	100	1	139	159	0	0.9	0.9	0.9	0.9
B-6	MICRO	SINGLE	HALL	SRM	8.0ton	H-IIA	100	100	1	900	1067	76044	5.4	5.9	5.3	5.5

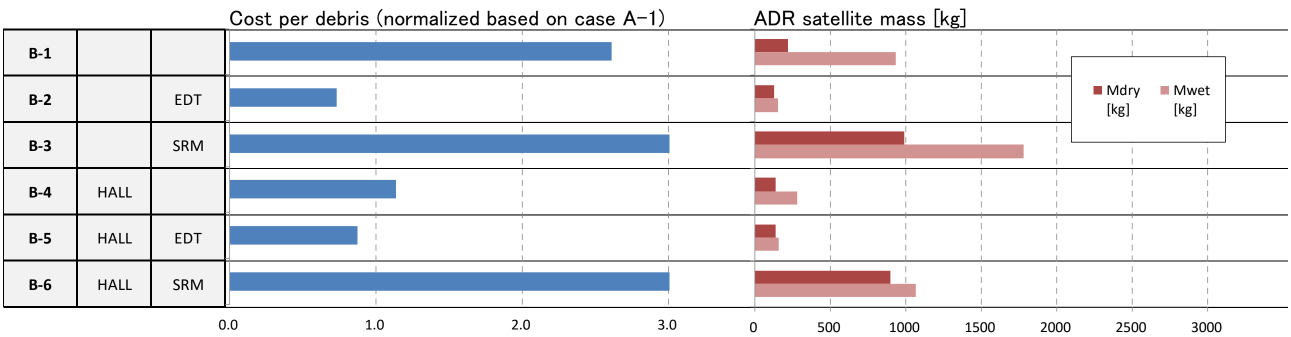

Figure 17. ADR scenario trade-off results (case group B). Cost is expressed as normalized value w.r.t. case A-1.

Case ID	ADR sat. size	Architecture	ep_ type	kit_ type	Mdebris [kg]	Rocket	No. of launches	No. of ADR sats	Removed debris per an ADR sat	Mdry [kg]	Mwet [kg]	EP ops. time [hour]	one ADR sat TFU cost	Rocket total cost	ADR sat total cost	Cost per a debris
C-1	MICRO	SINGLE			0.2ton	H-IIA	9	100	1	90	138	0	0.6	0.5	0.6	0.6
C-2	MICRO	SINGLE		EDT	0.2ton	H-IIA	8	99	1	127	153	0	0.8	0.5	0.8	0.7
C-3	MICRO	SINGLE		SRM	0.2ton	H-IIA	10	100	1	152	217	0	1.0	0.6	1.0	0.9
C-4	MICRO	SINGLE	HALL		0.2ton	H-IIA	6	100	1	97	109	5401	0.6	0.4	0.6	0.5
C-5	MICRO	SINGLE	HALL	EDT	0.2ton	H-IIA	10	100	1	143	183	0	0.9	0.6	0.9	0.8
C-6	MICRO	SINGLE	HALL	SRM	0.2ton	H-IIA	8	98	1	156	169	5177	1.0	0.5	0.9	0.8

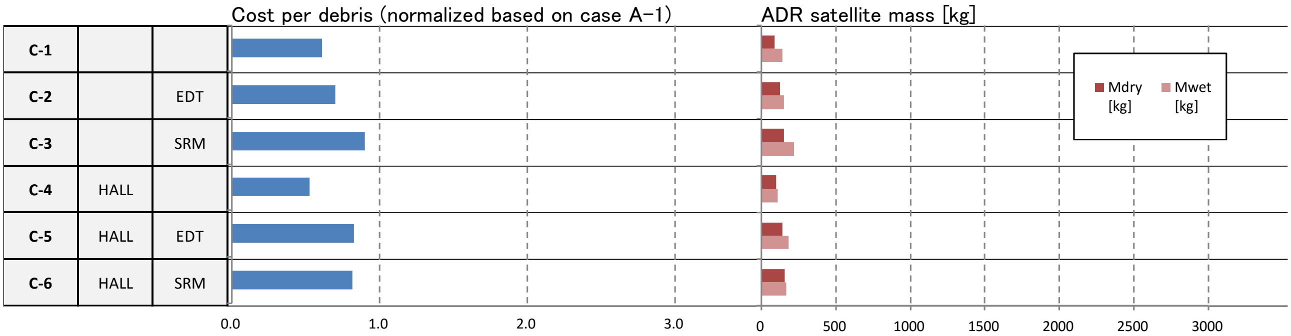

Figure 18. ADR scenario trade-off results (case group C). Cost is expressed as normalized value w.r.t. case A-1.

Case ID	ADR sat. size	Architecture	ep_ type	kit_ type	Mdebris [kg]	Rocket	No. of launches	No. of ADR sats	Removed debris per an ADR sat	Mdry [kg]	Mwet [kg]	EP ops. time [hour]	one ADR sat TFU cost	Rocket total cost	ADR sat total cost	Cost per a debris
D-1	SMALL	MOTHER SHIP		SRM	1.5ton	H-IIA	15	15	7	1548	1941	0	5.4	0.9	0.8	0.8
D-2	SMALL	MOTHER SHIP		EDT	1.5ton	H-IIA	13	13	8	1528	2068	0	5.5	0.8	0.7	0.7
D-3	SMALL	MOTHER SHIP	HALL	SRM	1.5ton	H-IIA	12	12	8	1972	2180	3231	6.7	0.7	0.8	0.8
D-4	SMALL	MOTHER SHIP	HALL	EDT	1.5ton	H-IIA	10	10	10	1840	2070	3988	6.3	0.6	0.6	0.6

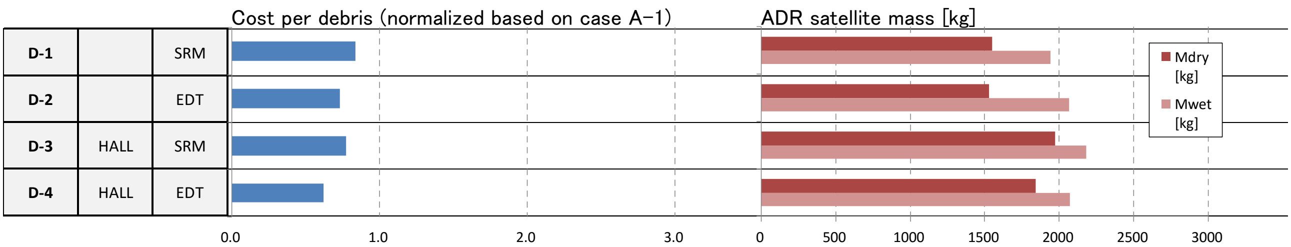

Figure 19. ADR scenario trade-off results (case group D). Cost is expressed as normalized value w.r.t. case A-1.

Case ID	ADR sat. size	Architecture	ep_type	kit_type	Mdebris [kg]	Rocket	No. of launches	No. of ADR sats	Removed debris per an ADR sat	Mdry [kg]	Mwet [kg]	EP ops. time [hour]	one ADR sat TFU cost	Rocket total cost	ADR sat total cost	Cost per a debris
E-1	SMALL	MOTHER SHIP		SRM	8.0ton	H-IIA	50	50	2	1796	1983	0	7.3	2.9	3.6	3.4
E-2	SMALL	MOTHER SHIP		EDT	8.0ton	H-IIA	17	17	6	1329	2171	0	5.6	1.0	0.9	1.0
E-3	SMALL	MOTHER SHIP	HALL	SRM	8.0ton	H-IIA	50	50	2	1879	1937	1444	7.9	2.9	3.9	3.6
E-4	SMALL	MOTHER SHIP	HALL	EDT	8.0ton	H-IIA	12	12	8	1726	1996	8083	6.2	0.7	0.7	0.7

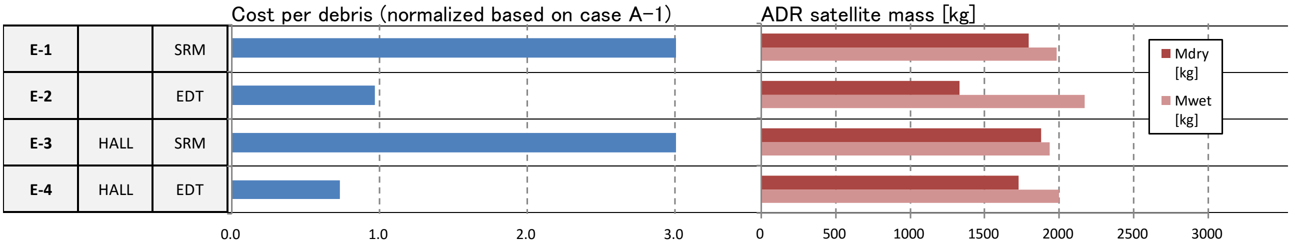

Figure 20. ADR scenario trade-off results (case group E). Cost is expressed as normalized value w.r.t. case A-1.

Case ID	ADR sat. size	Architecture	ep_type	kit_type	Mdebris [kg]	Rocket	No. of launches	No. of ADR sats	Removed debris per an ADR sat	Mdry [kg]	Mwet [kg]	EP ops. time [hour]	one ADR sat TFU cost	Rocket total cost	ADR sat total cost	Cost per a debris
F-1	MICRO	SHUTTLE			0.2ton	H-IIA	20	20	5	163	575	0	1.7	1.2	0.3	0.6
F-2	MICRO	SHUTTLE	HALL		0.2ton	H-IIA	50	50	2	98	112	6028	0.6	2.9	0.3	1.2
F-3	SMALL	SHUTTLE			1.5ton	H-IIA	25	25	4	497	1731	0	4.1	1.5	1.0	1.2
F-4	SMALL	SHUTTLE	HALL		1.5ton	H-IIA	34	34	3	389	494	5998	2.1	2.0	0.7	1.1
F-5	LARGE	SHUTTLE			1.5ton	FALCON9	34	34	3	2305	3831	0	8.7	1.4	2.9	2.5
F-6	LARGE	SHUTTLE	HALL		1.5ton	FALCON9	17	17	6	3401	4517	5836	17.1	0.7	2.9	2.2
F-7	LARGE	SHUTTLE			8.0ton	FALCON9	50	50	2	2351	4109	0	9.2	2.1	4.5	3.8
F-8	LARGE	SHUTTLE	HALL		8.0ton	FALCON9	34	34	3	3275	3945	3812	15.6	1.4	5.2	4.0

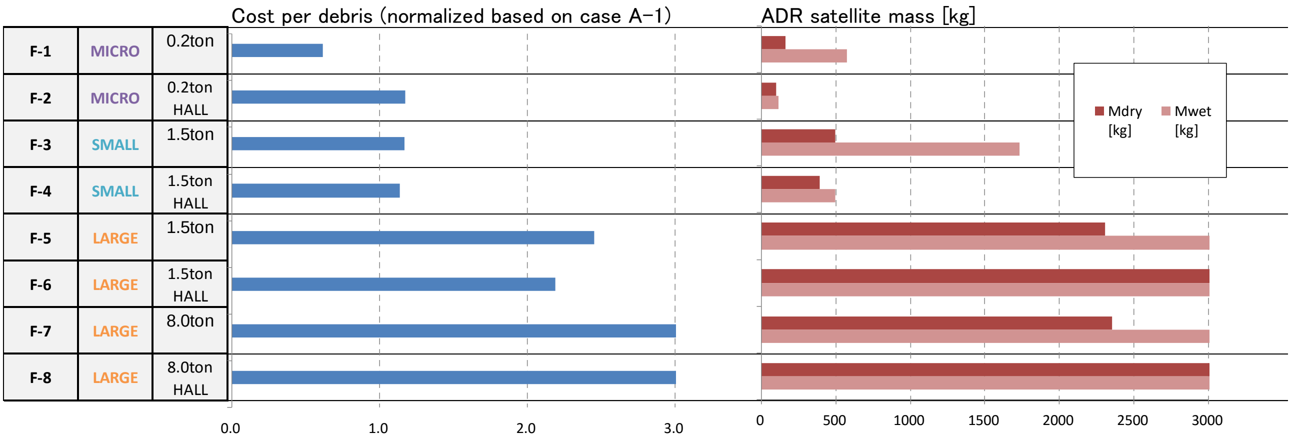

Figure 21. ADR scenario trade-off results (case group F). Cost is expressed as normalized value w.r.t. case A-1.

Case ID	ADR sat. size	Architecture	ep_ type	kit_ type	Mdebris [kg]	Rocket	No. of launches	No. of ADR sats	Removed debris per an ADR sat	Mdry [kg]	Mwet [kg]	EP ops. time [hour]	one ADR sat TFU cost	Rocket total cost	ADR sat total cost	Cost per a debris
G-1	SMALL	MOTHER SHIP		SRM	1.5ton	H-IIA	12	12	6	1413	2001	0	5.5	0.7	0.6	0.9
G-2	SMALL	MOTHER SHIP		EDT	1.5ton	H-IIA	11	11	7	1287	1923	0	5.1	0.6	0.6	0.8
G-3	SMALL	MOTHER SHIP	HALL	SRM	1.5ton	H-IIA	11	11	7	1621	1798	4865	5.8	0.6	0.6	0.8
G-4	SMALL	MOTHER SHIP	HALL	EDT	1.5ton	H-IIA	8	8	9	1728	2011	8053	6.2	0.5	0.5	0.6

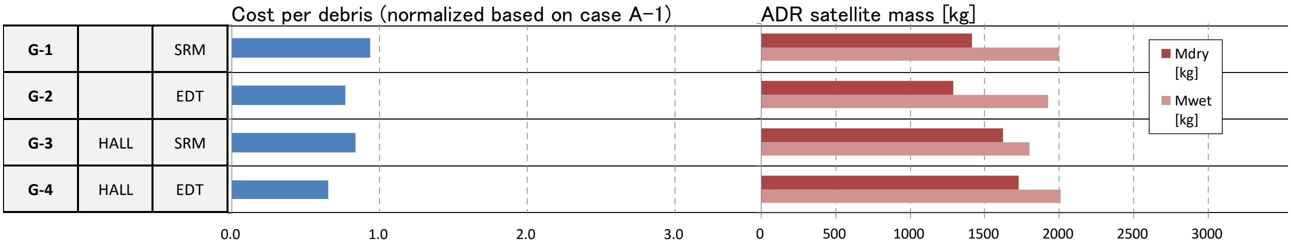

Figure 22. ADR scenario trade-off results (case group G). Cost is expressed as normalized value w.r.t. case A-1.