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デブリ除去シナリオの定量的トレードオフ

A Parametric Study on Active Debris Removal Scenarios

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スペースデブリ環境の維持・改善には「混雑軌道に存在する大型デブリ」の積極的除去が効果的であるが、要するコストが得られる便益を上回るのは簡単ではなく、課題となっている。デブリ除去コストは、「対象デブリ群の軌道分布」「対象デブリの数」「デブリ質量」「廃棄軌道高度」「除去衛星 1 機が除去するデブリ数」「除去衛星システムのサイズ」「除去用推進系のタイプ」「打ち上げ方式」等の多くのパラメータに依存する。本研究では、このパラメータセットを「除去シナリオ」と呼び、除去システムやそのコストを定量化・数学モデル化して、除去シナリオを設定するとデブリ除去にかかるコスト概算値が算出できるツールを構築した。本発表では、除去シナリオ、除去システムおよびコストのモデル化手法について述べるとともに、様々な除去シナリオをコストや成立性の観点で比較検討した結果を紹介する。

Active Debris Removal (ADR) has variety of options in various aspects: such as a de-orbit propulsion technology, architecture of removal activity, selection of an orbit and mass of the targets, and so on. To search the best ADR scenario that consists of a set of the best selections from these available options, we have developed a scheme to perform a quantitative trade-off study between probable ADR scenarios from the viewpoint of required ADR cost. In this paper, a summary of the scheme and the implemented ADR scenario model is explained, as well as some results of preliminary case-studies are shown and discussed.

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Motivation

- COST is essential for realization of ADR
- Because, to justify ADR campaign, cost of it must be smaller than expected economical loss due to space debris

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Motivation

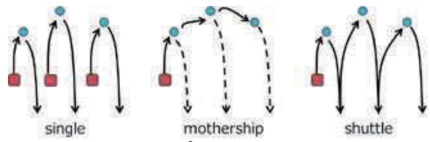
- Then, how much is the ADR campaign cost?
- This is actually a big question. To answer this, we have to consider many things!
  - Number of debris to be removed
  - Distribution of the target debris orbital elements
  - Mass of debris to be removed
  - Number of removed debris per a single ADR spacecraft
  - Number of ADR spacecraft launched by a rocket
  - Type of a deorbit device
  - etc...
- ADR cost per a debris significantly changes depending on this
- Therefore, a quantitative parametric study on ADR cost is necessary
- This is essential analysis for establishment of strategic technology development plan to realise cost-effective ADR campaign

Objective

- Establish a framework of a quantitative parametric study to answer “Which ADR scenario is the most low cost one?”
  - Define ADR scenario options as parameters
  - Construct a mathematical model to compute ADR cost using the parameters as inputs
  - Compare various ADR scenarios
  - Use results as material to investigate strategic technology development plan for cost-effective ADR

Analysis on ADR scenario, architecture and cost

- Construct a mathematical model to compute ADR cost
- Search the cheapest combination of options and parameters that represents the cost-effective and technically feasible ADR mission



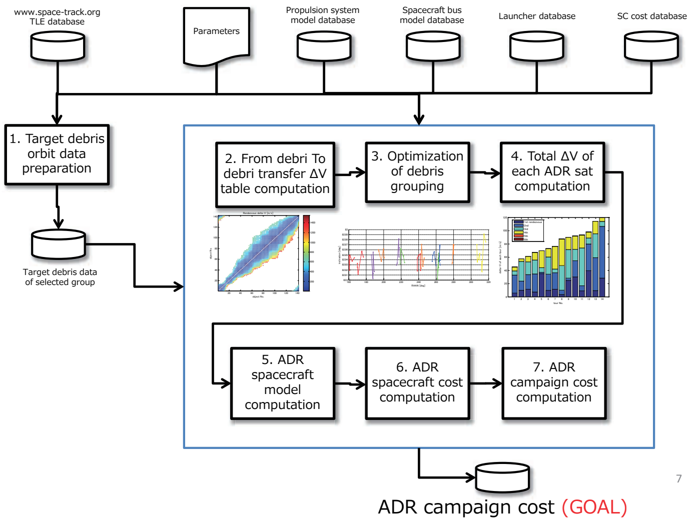
Architecture

LARGE : large cargoship (DRY 2700kg)
SMALL : small satellite (DRY 250kg)
MICRO : micros atellite (DRY 100kg)

Spacecraft size

EDT : ElectroDynamic Tether
EP : Electric Propulsion
CP : Chemical Propulsion

De-orbit propulsion type



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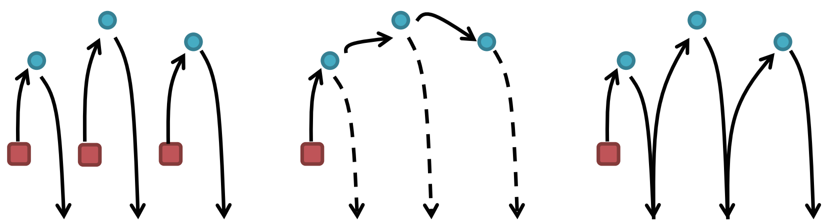
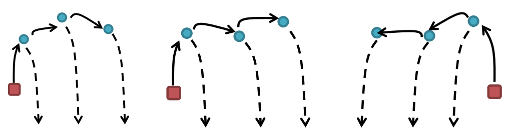
Concept of “Architecture”, “Tour” and “Campaign”

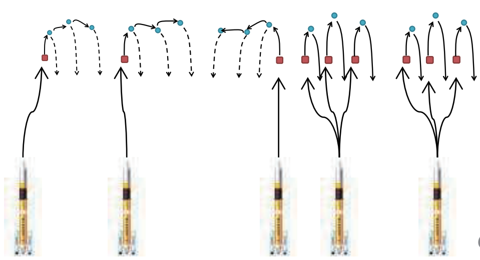
Architecture



Tour A process which an ADR spacecraft travels and removes debris. One tour corresponds to one ADR spacecraft.



Campaign An activity consists of tours and launches to remove a group of target debris.



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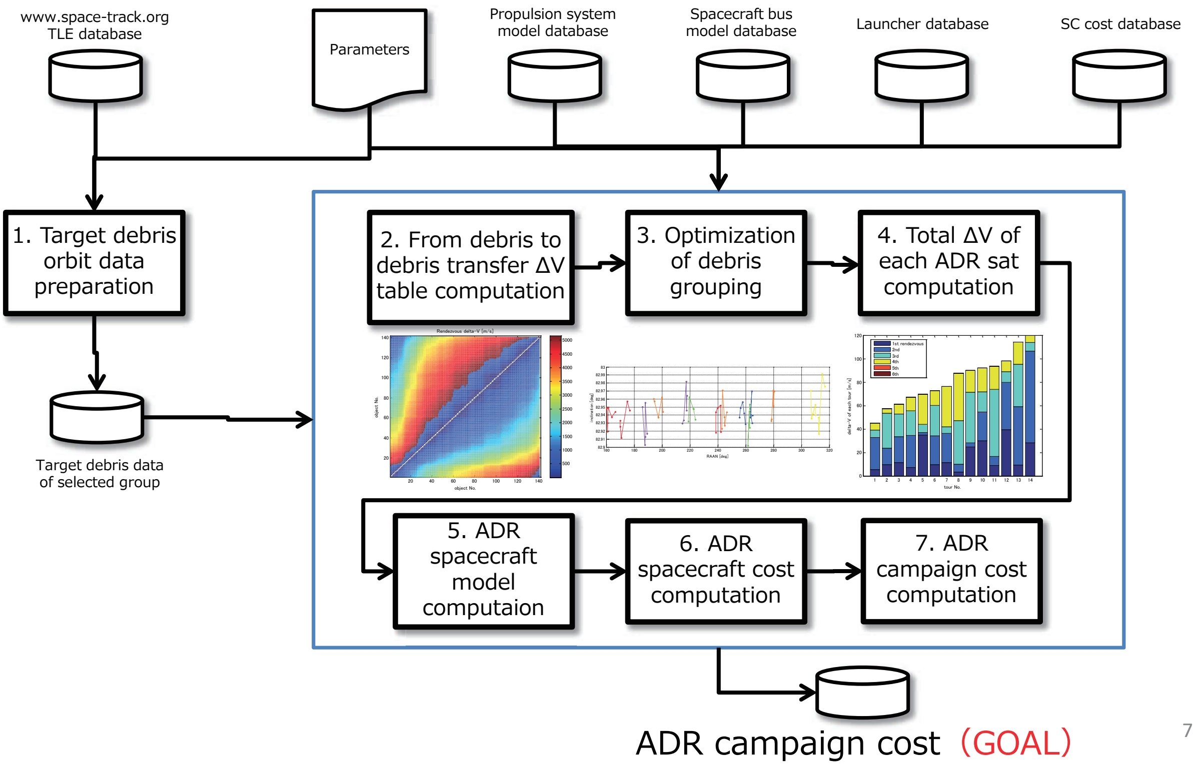
Framework to compute ADR cost



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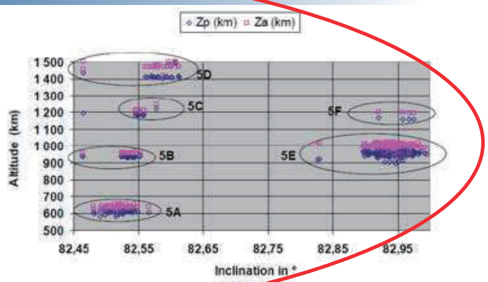
1. Target debris

As an example, a group consists of 142 russian upper stages at i=83deg is selected as targets

A) Upper stages in crowded orbits
- Typically russian upper stages
- Effective targets for space debris environment remediation

B) Domestic debris
- Domestic upper stages, ADEOS, ADEOS-II, etc.
- Possible to remove without international agreement

C) Mega constellation
- A lot of potential clients on the same orbital plane
- This large number of clients may cause significant change on ADR break-even point



Russian upper stages in crowded orbit (NASA)

H-IIA upper stage

ADEOS

ADEOS-II

OneWeb constellation (OneWeb)

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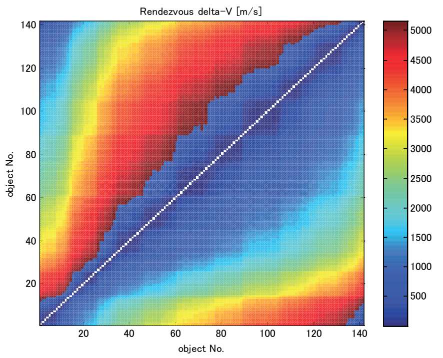
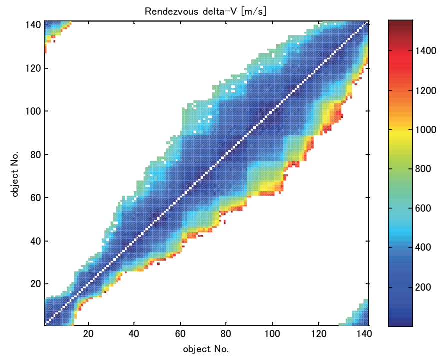
2. From debris to debris transfer ΔV table computation



Transfer ΔV table. Number of debris is 142. Object numbers are arranged in order of RAAN.



- Impulse transfer ΔV computation
  - ΔΩ is adjusted using nodal regression rate difference due to altitude difference between target and waiting orbits
  - Waiting orbit altitude > 400 km
  - Δa, Δi, and Δe vectors are adjusted directly by impulse maneuvers
  - Proximity operation needs 20m/s
- Electric transfer ΔV computation
  - Transfer ΔVs of both from original to waiting orbits and from waiting to target orbits are computed using Edelbaum equation (Split Edelbaum Strategy)
  - When RAAN difference is too large, a valid solution can not be obtained due to limitation of acceleration,

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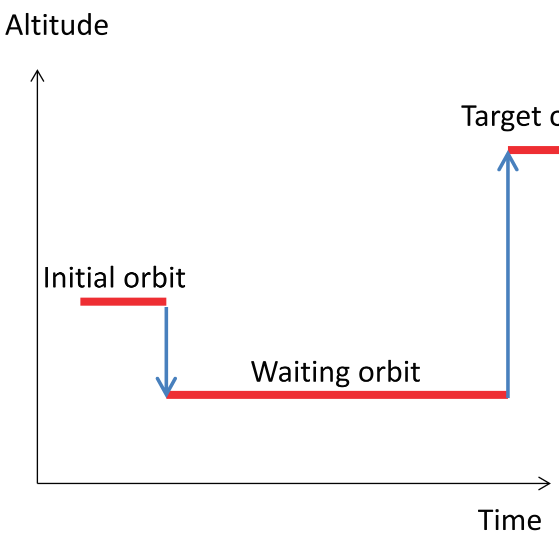
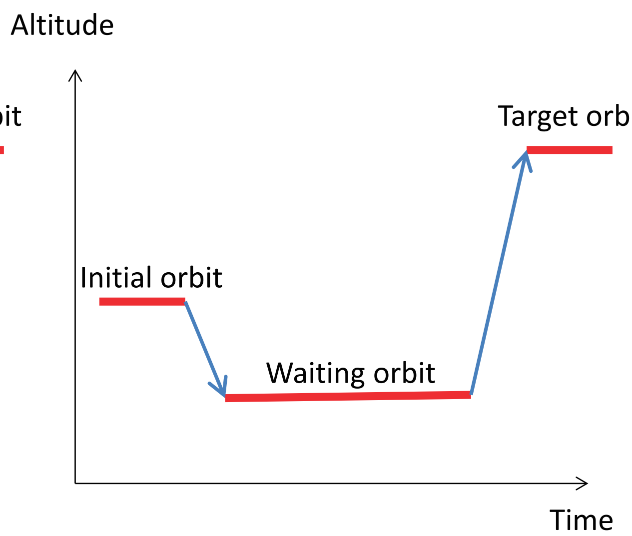
2. From debris to debris transfer ΔV table computation



Impulse transfer ΔV computation



Electric transfer ΔV computation

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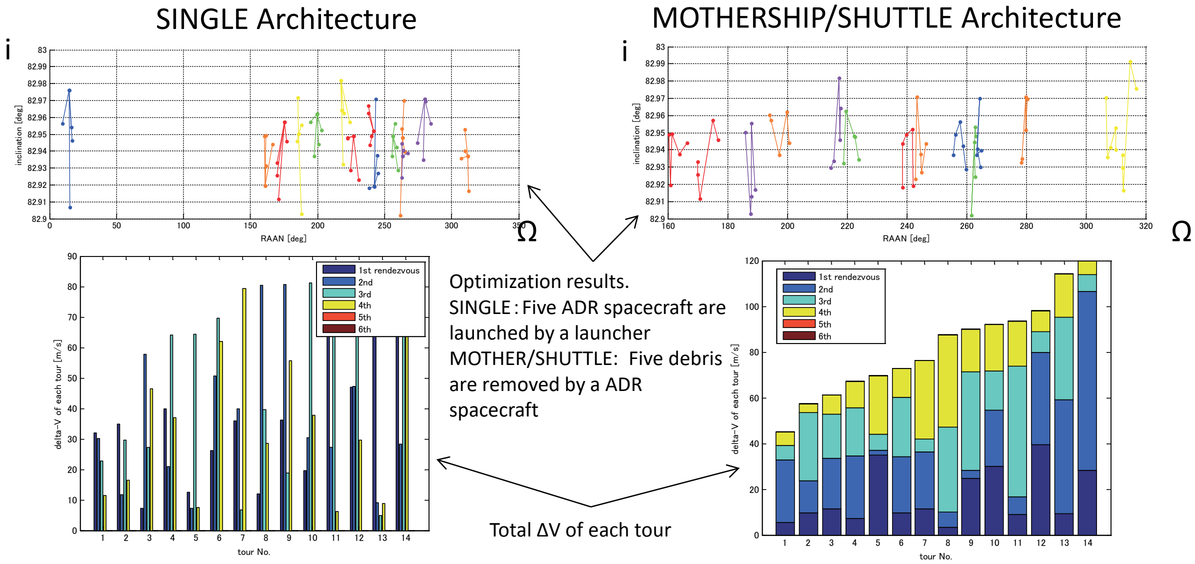
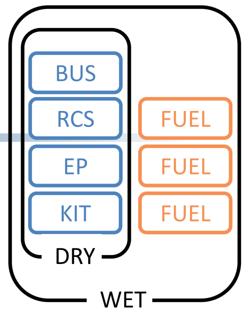
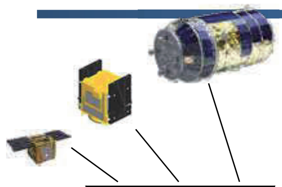
3. Optimization of debris grouping by generic algorithm



- A problem “minimize transfer ΔV when N ADR spacecraft visit M debris” can be formulated as the famous traveling salesman problem
- A suboptimal solution can be obtained by optimization using generic algorithm
- ΔV of a tour is a sum of “initial orbit correction”, “transfer”, “de-orbit”, and “ascent (SHUTTLE architecture only)”

5. ADR spacecraft model computaion





LARGE : ISS cargo suply ship class spacecraft

SMALL : Small spacecraft

MICRO : Micro spacecraft

	MICRO	SMALL	LARGE		
Bus dry mass	80	250	2700	kg	micro: 80kg <-- WET質量100kg台の衛星のBUS質量 small: 250kg <-- NEC NEXTarバスカタログ large: 2700kg <-- HTV-Xサービスモジュール想定値
Bus power	100	300	1000	W	micro: 100W <-- SDSシリーズを参考に設定 small: 300W <-- NEC NEXTarバス（NECデブリ除去衛星、FFAST） large: 1000W <-- HTV電気モジュールを参考に設定
RCS thrust	3.5	12.9	381	N	...
RCS ISP	200	200	250	s	...
HALL thrust	7.80 e-3	7.25 e-2	7.25 e-1	N	micro: BUSEK BHT-200 13mN @ 200W を 120Wで運転と想定 small: BUSEK BHT-1000 58mN @ 1000W を 1250Wで運転と想定 large: smallを電力10倍にスケールアップ
HALL ISP	1390	1750	1750	s	
HALL efficiency	0.44	0.5	0.5		
EDT power	60	60	60	W	...
EDT mass	45	45	45	kg	...
…	…	…	…		…

Using left parameters and required ΔV as inputs, ADR spacecraft parameters are computed using models in the textbook “Space Mission Analysis and Design (SMAD)”.

- Mass of RCS fuel
- Mass of Xe fuel
- Mass of each subsystem
- Power
- Duration of Electric propulsion operation
- Etc...

```
Nthruster: 12
Mfuel_rcs: 9.1905
      Pep: 1.2434e+03
      Mep: 159.8424
      Tep: 4.3645e+04
 Mfuel_ep: 664.2168
     Mkit: 0
    n_kit: 0
     Mbus: 410.7615
     Mdry: 571.5230
     Mwet: 1.2449e+03
     Mgnc: 30
     Mcom: 10
     Mcdh: 10
   Mtherm: 12.5000
Mpower_bus: 62.5000
     Mstr: 100
     Mrcs: 25
     Pbus: 300
     Vbus: 1.7300
  Isp_trs: 1750
  Isp_prx: 200
  Isp_des: 1750
```

6. ADR spacecraft cost computation

```
Nthruster: 12
Mfuel_rcs: 9.1905
      Pep: 1.2434e+03
      Mep: 159.8424
      Tep: 4.3645e+04
 Mfuel_ep: 664.2168
     Mkit: 0
    n_kit: 0
     Mbus: 410.7615
     Mdry: 571.5230
     Mwet: 1.2449e+03
     Mgnc: 30
     Mcom: 10
     Mcdh: 10
   Mtherm: 12.5000
Mpower_bus: 62.5000
     Mstr: 100
     Mrcs: 25
     Pbus: 300
     Vbus: 1.7300
  Isp_trs: 1750
  Isp_prx: 200
  Isp_des: 1750
```

Using ADR spacecraft parameters as inputs, ADR spacecraft costs are computed using models in the textbook “Space Mission Analysis and Design (SMAD)”.

Considering infration rate from FY2000 and currency exchange rate, the cost is converted to that of FY2016 in Japanese Yen.

	R&D and first demo spacecraft	Recurrent cost	Comment
KIT	0	0	KIT in FY00 $K
STR	7176	1310	Structure in FY00 $K
THERM	2044	302	Thermal in FY00 $K
POWER	9307	2627	Power in FY00 $K
TTCDH	5327	3481	TT&C, DH in FY00 $K
AOCS	8855	4117	AOCS in FY00 $K
RCS	7721	3860	RCS in FY00 $K
EP	30530	10230	EP in FY00 $K
IAT	6576	3288	Integration, Assembly & Test in FY00 $K
PROG	10833	5417	Program Level in FY00 $K
GSE	3122	1561	Ground Support Equipment in FY00 $K
LOOS	2886	1443	Launch & Orbital Operations Support in FY00 $K
TOT_FY00D	103810	41400	Total cost in FY00 $K
TOT_CURRD	143260	57131	Total cost in current $K
TOT_CURRY	163	65	Total cost in current ¥oku-en

In this example,
R&D and first demo spacecraft = 163億円
Recurrent cost = 65億円

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All selectable options/parameters to define a scenario

項目		選択肢		項目設定の意図
architecture	アーキテクチャ	SINGLE	singleアーキテクチャ	アーキテクチャの違いがコストに与える影響を見る。
		MOTHERSHIP	mothershipアーキテクチャ	
		SHUTTLE	shuttleアーキテクチャ	
n_debris	除去衛星1機が除去するデブリ数	1, 3, 5, 7, 9	mothership/shuttle：除去衛星1機が除去するデブリ数 shingle：1本のロケットで打ち上げる除去衛星の数	除去衛星あたりのデブリ数が変わるとコスト面でどの程度効率化されるかを見る。
Mdebris	デブリ質量[kg]	8000, 3000, 200		除去するデブリ質量がコストに与える影響を見る。
sc_size	除去衛星サイズ	MICRO	バスDRY重量80kg程度のマイクロ衛星	除去衛星のサイズがコストに与える影響を見る。一般に、小型の衛星のほうがコストは安いが、大質量デブリの除去が困難（推薬量や電気推進稼働時間の観点で）になる。
		SMALL	バスDRY重量250kg程度の小型衛星	
		LARGE	バスDRY重量2700kg程度の大型輸送船	
ep_type	衛星バス電気推進タイプ	NONE		除去衛星に電気推進系を具備することがコストに与える影響を見る。 近傍ランデブに必要なRCSは必須であり、いかなる場合にも具備する想定。
		ION	イオンエンジン	
		HALL	ホールスラスタ	
		EDT_PAY	EDT（singleアーキテクチャのみ）	
kit_type	キット推進系タイプ	NONE		デブリ除去キットのタイプがコストに与える影響を見る。
		EDT_KIT	EDT（mothership/shuttleアーキテクチャのみ）	
		SRM	固体ロケットモータ	
kit_size	キットサイズ	KIT200	200kgのデブリを落とすキット	デブリ質量に対応した選択肢。
		KIT3000	3000kgのデブリを落とすキット	
		KIT8000	8000kgのデブリを落とすキット	
flag_inj_err	ロンチウインドウ	INJ_ZERO_WINDOW	ロンチウインドウ0分	ロンチウインドウの大小は、昇交点赤経Ωの初期誤差となり、推薬量、ひいてはコストに影響を与える。
		INJ_15MIN_WINDOW	ロンチウインドウ±15分	
flag_Hdest	廃棄軌道高度	HDEST_25YRS	25年で再突入する軌道	廃棄軌道の目標高度がコストに与える影響を見る。
		HDEST_HIGH	25年で再突入する軌道よりも高い高度	
flag_rocket	打上ロケット	EPSILON	イプシロン	ロケットの積載能力と打ち上げコストがキャンペーンコストに与える影響を見る。また、将来輸送系コストが劇的に下がった場合にどうなるかを見る。

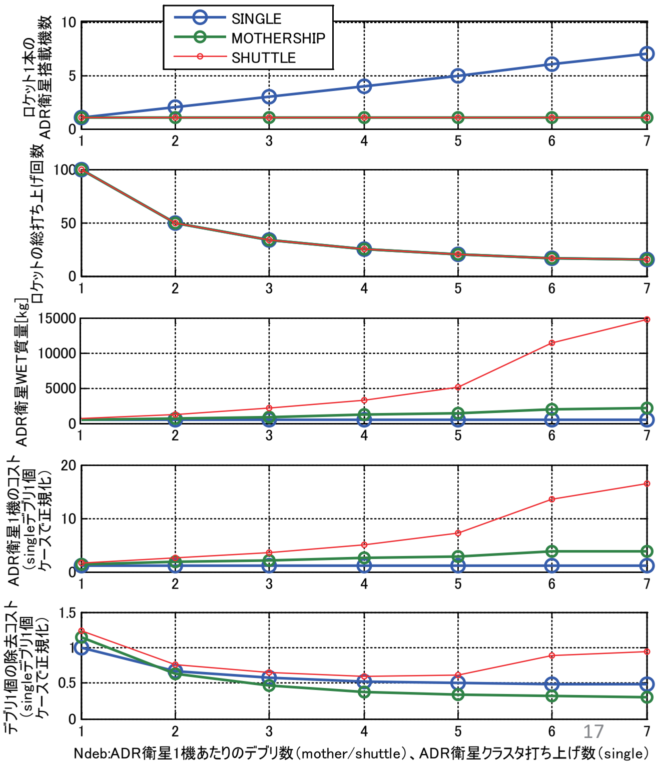
AN EXAMPLE OF PARAMETRIC STUDY

As a trial, select some parameters and do a parametric study

Parameter	Choices
architecture	SINGLE or MOTHERSHIP or SHUTTLE
n_debris	1〜13
Mdebris	1.5ton(COSMOS-3M) or 8ton(ZENIT)
sc_size	MICRO or SMALL or LARGE
ep_type	HALL or EDT_PAY
kit_type	NONE or EDT_KIT or SRM
flag_inj_err	INJ_ZERO_WINDOW
flag_Hdest	HDEST_25YRS
flag_rocket	HIIA or FALACON9

除去デブリ数の影響のアーキテクチャによる違いの分析例

- singleでは、Ndebの増加に伴い、同様なADR衛星を1本のロケットにたくさん積むだけのため、ADR衛星コストはほぼ変わらない一方で、デブリ1個あたりの除去コストは、ロケットをシェアする効果で低減する傾向が見える。
- mothershipでは、Ndebが増加するとキット搭載数が増加しADR衛星コストが増す一方、1回の打ち上げで軌道投入・除去できるデブリ数が増えコスト削減効果もある。この計算ではNdeb=3以上では後者の効果が勝りsingleよりもコスト的に有利。
- shuttleでは、Ndebの増加にともない、重いデブリを背負っての降下および重い燃料を背負っての上昇に要する燃料の質量増加が著しく、コスト低減降下が見られない。
- アーキテクチャごとの個性や、条件が変わった場合のコストへのインパクトを分かりやすく評価でき、ADRシナリオの検討・最適化に有効。



An example of parametric study results

CASE ID	Size	Architecture	EP type	Kit type	Debris mass	Launcher	No. of launchs	No. of ADR spacecraft	No. of debris per ADR spacecraft	Mdry [kg]	Mwet [kg]	EP operation time [hours]	ADR spacecraft Recurrent cost TFU	Launcher total cost	ADR spacecraft total cost	Cost per one debris
A	MICRO	SINGLE			1.5ton	H-IIA	15	100	1	114	284	0	1.00	1.00	1.00	1.00
B	MICRO	SINGLE		EDT	1.5ton	H-IIA	12	100	1	180	214	0	1.08	0.80	1.08	1.00
C	MICRO	SINGLE	HALL		1.5ton	H-IIA	7	100	1	103	135	14915	0.68	0.47	0.68	0.62
D	MICRO	SINGLE	HALL	EDT	1.5ton	H-IIA	13	100	1	191	216	0	1.13	0.87	1.13	1.05
E	MICRO	SINGLE	HALL	SRM	1.5ton	H-IIA	20	100	1	279	315	16042	1.68	1.33	1.68	1.58
F	MICRO	SINGLE			8.0ton	H-IIA	100	100	1	217	902	0	2.31	6.67	2.31	3.58
G	MICRO	SINGLE		EDT	8.0ton	H-IIA	12	100	1	180	214	0	1.08	0.80	1.08	1.00
H	SMALL	MOTHER SHIP	HALL	EDT	1.5ton	H-IIA	10	10	10	1704	1910	3368	5.73	0.67	0.57	0.60
I	SMALL	MOTHER SHIP	HALL	SRM	1.5ton	H-IIA	15	15	7	1788	1954	2515	5.97	1.00	0.90	0.93
J	LARGE	SHUTTLE			1.5ton	FALCON 9	33	33	3	3956	4585	3211	16.70	1.54	5.51	4.35

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Findings from this parametric study

1. When debris mass is heavy (such as 8 tons), EDT is substantially effective as a deorbit device.
2. When debris mass is relatively light (such as 1.5 tons), difference between EDT and RCS/SRM becomes small.
3. High ISP propulsions such as HALL thrusters are attractive. However, its operation life can be a bottleneck. If good balance of operation life, input power, and thrust can be found, this could be a good option.
4. MOTHERSHIP architecture using EDT kits and HALL thrusters (case H) could be a good option.

Conclusions and way forward

- A framework of a quantitative parametric study to answer "Which ADR scenario is the most low cost one?" has been constructed
- At this moment, mathematical models are yet immature. They should be improved and verified.
- Not only the russian upper stage scenario, but also other scenarios will be investigated by this framework
  - SSO debris scenario
  - Mega constellation scenario
  - GEO satellite scenario
- We expect the results of this research will be used as material to investigate strategic technology development plan for cost-effective ADR