C13

持続可能なデブリ除去運用コンセプトと 商業デブリ除去実証フェーズⅡの技術実証シナリオの検討

Study of Technology Demonstration Scenarios of CRD2 Phase2 Aiming Sustainable Debris Removal

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JAXA の商業デブリ除去実証（CRD2）は，日本由来の大型デブリの除去を，民間企業と協力して実施することで，スペースデブリの積極的除去（Active Debris Removal: ADR）に係る国際的議論の具体的な進展と，日本企業の軌道上サービス市場における国際的競争力向上の実現を目指している．これら 2 つの目的を達するためには，CRD2 で実証するデブリ除去技術は，ビジネスとして持続可能である，つまり低コストであることが 1 つの要件となる．そこで具体的なターゲットを想定したうえで，将来の ADR 事業のアーキテクチャ及び運用コンセプトについてデブリ 1 個当たりの除去コストの観点で検討を行い，その結果に基づき CRD2 フェーズⅡの技術実証シナリオを検討した．

JAXA’s Commercial Debris Removal Demonstration (CRD2) aims to improve the international competitiveness of Japanese companies in new markets such as the on-orbit service market and to lead concrete progress in international discussions on space debris removal (ADR) by removing large debris of Japanese origin in cooperation with the private sector. To achieve these two objectives, one of the requirements of the debris removal technology to be demonstrated in CRD2 is that it must be sustainable as a business, meaning that the practical use of the technology makes the debris removal feasible at low cost. This paper studies operational concept of the future ADR project with specific debris in terms of removal cost per piece of debris, and based on those studies, proposes technology demonstration scenarios of CRD2 phase2.

JAXA CRD2 Phase Ⅱ

Study of Technology Demonstration Scenarios of CRD2 Phase2 Aiming Sustainable Debris Removal

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(JAXA)

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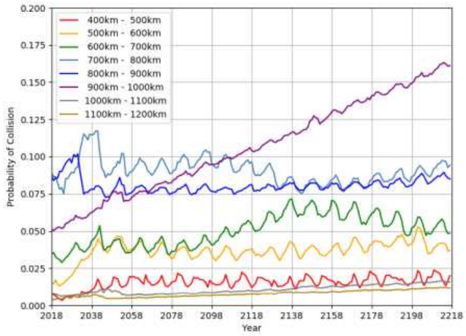
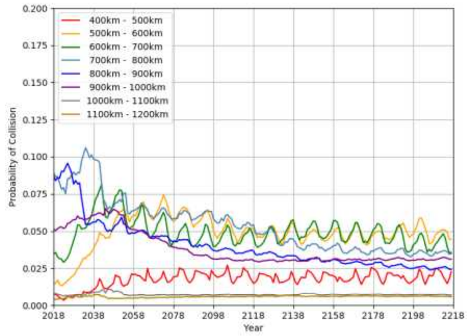
Background

- Space debris has been increasing year by year and in the future is expected to interfere with human space activities.
- Removal of massive space debris in crowded orbit (800-1000km) is effective.



Collision probability of each altitude band with 90% PMD, and no ADR



ADR of five debris objects per year

Kawamoto, Satomi, et al. "Impact on collision probability by post mission disposal and active debris removal." Journal of Space Safety Engineering 7.3 (2020): 178-191.

Commercial Removal of Debris Demonstration (CRD2)

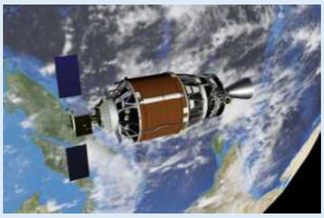
Aiming at the world's first Active Debris Removal in partnership with private sectors
Demonstration of the removal of large space debris left in orbit in two phases

- **To improve the international competitiveness of Japanese companies in new markets such as the on-orbit service market**
- **To lead concrete progress in international discussions on space debris removal (ADR)**

Phase-I Planned for launch in FY2022
Key technologies demonstration

- **Non-cooperative rendezvous, proximity operation, inspection**

Phase-II FY2025~
ADR demonstration



- Non-cooperative rendezvous, proximity operation, inspection
- **Removal of 2nd stage of launch vehicle**

CRD2 New partnership-type contract and ofjective of this study

New partnership-type contract

JAXA

- Service specifications
- Safety requirements

- Technical advices
- Test facilities
- Intellectual properties

Fulfillment

Payment

Support

Private sectors

- Design
- Manufacture
- Test
- Operation
- Business development

Objective of this study

- To achieve two objectives of CRD2, one of the requirements of the debris removal technology to be demonstrated in CRD2 is that it must be sustainable as a business, meaning that the practical use of the technology makes the debris removal feasible at low cost.
- The objective of this study is to study operational concept of the future ADR project with specific debris in terms of removal cost per piece of debris, and based on those studies, proposes technology demonstration scenarios of CRD2 phase2.

Concerning derelict objects

Table 4
The composite top 50 SMC are summarized below.

Ranking	Score	SATNO	Number of Lists	SATNAME	APOGEE, km	PERIGEE, km	INCL., deg	MASS, kg	COUNTRY	LAUNCH
1	4048	22,566	11	SL-16 R/B	848	837	71.0	9000	CIS	3/26/1993
2	3710	22,220	10	SL-16 R/B	848	827	71.0	9000	CIS	11/17/1992
3	3500	31,793	10	SL-16 R/B	846	843	71.0	9000	CIS	6/29/2007
4	3470	26,070	9	SL-16 R/B	854	827	71.0	9000	CIS	March 2, 2000
5	3330	16,182	10	SL-16 R/B	844	833	71.0	9000	CIS	10/22/1985
6	3300	20,625	10	SL-16 R/B	853	834	71.0	9000	CIS	5/22/1990
7	2880	27,006	8	SL-16 R/B	1006	986	99.5	9000	CIS	October 12, 2001
8	2862	23,705	9	SL-16 R/B	852	831	71.0	9000	CIS	10/31/1995
9	2826	25,407	9	SL-16 R/B	844	835	71.0	9000	CIS	7/28/1998
10	2800	23,405	10	SL-16 R/B	845	838	71.0	9000	CIS	11/24/1994
11	2547	17,974	9	SL-16 R/B	846	823	71.0	9000	CIS	5/13/1987
12	2412	23,088	8	SL-16 R/B	845	841	71.0	9000	CIS	4/23/1994
13	2296	22285	8	SL-16 R/B	844	840	71.0	9000	CIS	12/25/1992
14	2240	22,803	8	SL-16 R/B	850	823	71.0	9000	CIS	9/16/1993
15	1813	19,650	7	SL-16 R/B	848	831	71	9000	CIS	11/23/1988
16	1771	24,298	8	SL-16 R/B	863	839	70.8	9000	CIS	April 9, 1996
17	1650	28,353	7	SL-16 R/B	848	842	71.0	9000	CIS	October 6, 2004
18	1617	17,590	8	SL-16 R/B	841	831	71.0	9000	CIS	3/18/1987
19	1547	19,120	7	SL-16 R/B	842	814	71.0	9000	CIS	5/15/1988
20	1477	25,400	7	SL-16 R/B	813	801	98.6	9000	CIS	October 7, 1998
21	1320	27,386	5	ENVISAT	766	764	98.1	7800	ESA	January 3, 2002
22	1182	27,001	6	METEOR 3 M	1013	994	99.6	2500	CIS	October 12, 2001
23	805	24,277	4	ADEOS	794	793	98.9	3560	JPN	8/17/1996
24	600	27,601	4	H-2A R/B	836	734	98.2	3000	JPN	12/14/2002
25	564	15,334	4	SL-12 R/B(2)	847	838	71.0	2440	CIS	9/28/1984
26	512	37,932	4	CZ-2D R/B	846	791	98.7	4000	PRC	11/20/2011
27	468	10,732	4	SL-8 R/B	995	966	82.9	1435	CIS	3/15/1978
28	416	24,279	5	H-2 R/B	1306	860	98.7	2700	JPN	8/17/1996
29	384	23,704	3	COSMOS 2322	854	842	71.0	3250	CIS	10/31/1995
30	324	21,090	3	SL-8 R/B	992	961	82.9	1435	CIS	May 2, 1991
31	316	28,352	3	COSMOS 2406	863	844	71.0	3250	CIS	October 6, 2004
32	309	23,087	2	COSMOS 2278	852	841	71.1	3250	CIS	4/23/1994
33	270	19,119	2	COSMOS 1943	851	833	71.0	3250	CIS	5/15/1988
34	261	27,597	2	ADEOS 2	801	800	98.5	3680	JPN	12/14/2002
35	240	25,861	4	SL-16 R/B	645	622	98.2	9000	CIS	7/17/1999
36	240	15,772	3	SL-12 R/B(2)	848	794	71.1	2440	CIS	5/30/1985
37	228	10,693	3	SL-8 R/B	989	957	83.0	1435	CIS	2/28/1978
38	228	17,973	2	COSMOS 1844	866	824	71.0	3250	CIS	5/13/1987
39	225	27,387	3	ARIANE 5 R/B	796	748	98.6	2575	FR	January 3, 2002
40	207	7594	3	SL-8 R/B	981	955	82.9	1435	CIS	12/26/1974
41	207	23,180	3	SL-8 R/B	992	950	82.9	1435	CIS	7/14/1994
42	204	10,138	3	SL-8 R/B	1001	970	82.9	1435	CIS	August 7, 1977
43	204	13,917	3	SL-8 R/B	996	954	82.9	1435	CIS	3/24/1983
44	198	13,719	3	SL-3 R/B	896	791	81.3	1100	CIS	12/14/1982
45	194	14,625	2	SL-8 R/B	999	969	82.9	1435	CIS	November 1, 1984
46	183	20,624	2	COSMOS 2082	856	833	71.0	3250	CIS	5/22/1990
47	164	12,092	2	SL-8 R/B	996	953	82.9	1435	CIS	October 12, 1980
48	153	9044	3	SL-8 R/B	988	966	83.0	1435	CIS	7/21/1976
49	146	12,504	2	COSMOS 1275	1014	954	83.0	800	CIS	April 6, 1981
50	144	16,292	3	SL-8 R/B	996	953	82.9	1435	CIS	11/28/1985

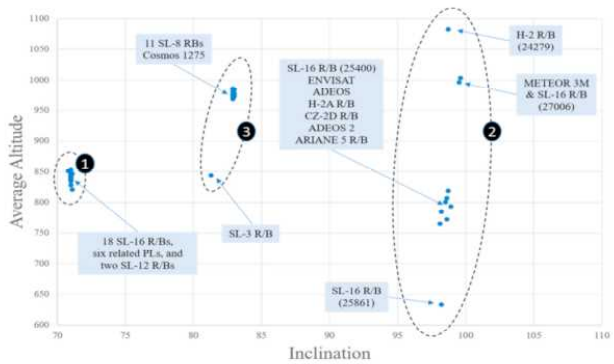
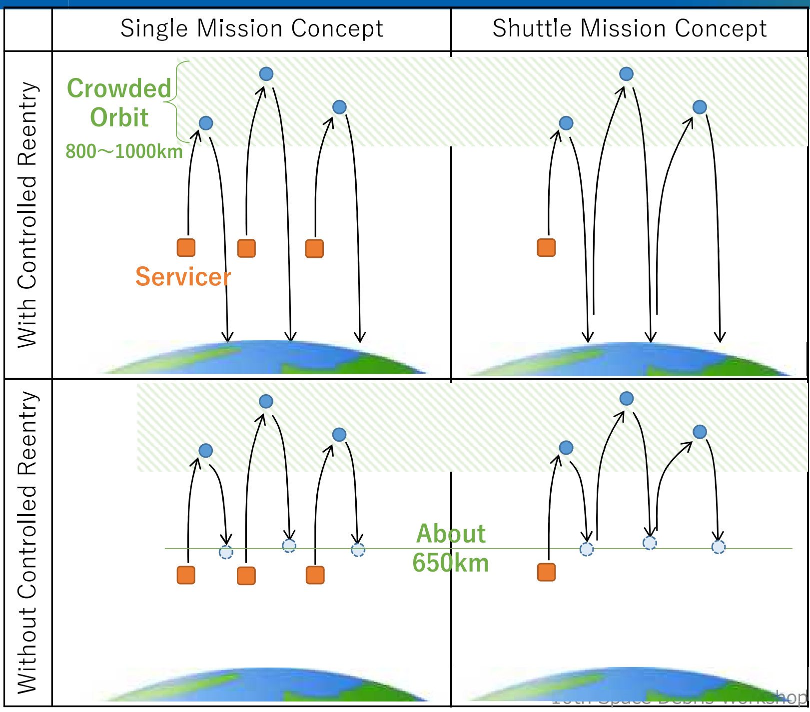


Fig. 6. Top 50 SMC objects are located in clumps that might aid in the efficient removal of them from orbit.

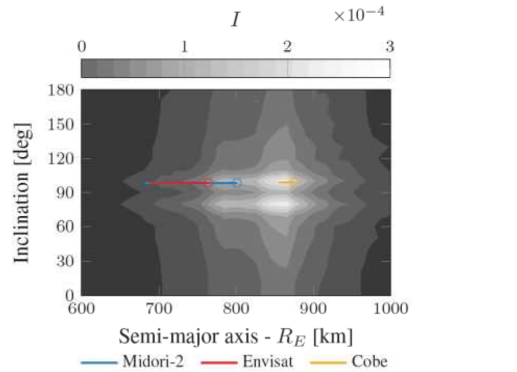
Target debris of this study are debris in near-sun-synchronous orbits at altitudes of approximately 800 km to 1000 km

McKnight, Darren, et al. "Identifying the 50 statistically-most-concerning derelict objects in LEO." Acta Astronautica 181 (2021): 282-291.

Future ADR architecture and operational concept



- Controlled reentry is performed to reduce the Expected Casualty Ec of the debris upon reentry.
- To improve the orbital environment, it is important to shift the debris that remains in the orbit for a long period of time to a short lifetime orbit.



Letizia, Francesca, et al. "Extending the ECOB space debris index with fragmentation risk estimation.", European space debris conference, 2017

Simple evaluation

- Targets are debris at an altitude of 900 km(Weight:3ton)
  - To 350km : Electric propulsion
  - To 200km : altitude decay due to atmospheric drag
  - Reentry : continuous thrusting with chemical propulsion at 40 m/s
  - If controlled reentry is not performed, the debris is released after descending to an altitude of 650 km.
- Electric propulsion is used for large orbit changes except controlled reentry, and the specific impulse is assumed to be 1600 s.
- Change in orbit altitude is assumed to be a transition from a circular to a circular orbit

$$\Delta v = \sqrt{\frac{\mu}{r_2}} - \sqrt{\frac{\mu}{r_1}}$$

- Rendezvous and nearby operations are performed by chemical propulsion. The specific impulse is assumed to be the worst-case value of 100 s, assuming pulse injection. The required ΔV is uniformly 100 m/s.

Example of Estimated Required Propellant

■ **Estimated propellant (2-debris removal Shuttle concept, with controlled re-entry)**

Operation	⊿V[m/s]		Mass[kg]		Propellant[kg]		Electric Prop. Total impulse	Note
	RCS	EP	Before	after	N2H4	Xe		
#1 rendezvous		262	**1540**	1514		26	4.0.E+05 [Ns]	500km→900km Rocket Injection Error Correction : 50m/s
#1 Prox. Operation	100		1514	1368	147			
#1 deorbit		297	4368	4199		82	1.3.E+06 [Ns]	900km→350km
#1 reentry	40		4286	4199	87			
Return to orbit	200		1199	1083	116			
#2 rendezvous		297	1083	1063		20	3.2.E+05 [Ns]	350km→900km
#2 Prox. Operation	100		1063	959	103			
#2 deorbit		297	3959	3885		74	1.2.E+06 [Ns]	900km→350km
#2 reentry	40		3885	3807	78			
Total	**480**	**1152**			**531**	**202**	**3.2.E+06 [Ns]**	
			Dry Mass		N2H4 Mass	Xe Mass		
			800kg		535kg	205kg		

Satellite mass and cost estimates for each concept

Concept	Single	Sigle	Shuttle	Shuttle	Shuttle	Note*1
Number of removal debris	1	1	2	2	3	
Controlled Reentry	w/o	W	w/o	W	w/o	
Base Mass [kg] *2	200	250	250	643	405	Dry Mass without capture mechanism, electric propulsion, and tanks
Chemical propellant[kg]	35	120	90	535	210	
Electrical propellant[kg]	35	75	70	205	120	
Chemical Prop. Tank [kg]	4	12	9	54	21	Chemical propellant*0.1
Electrical Prop. Tank[kg]	6	12	11	33	19	Electrical propellant*0.16
Electrical Propulsion[kg]	37	43	42	64	50	Electrical propulsion subsystem （31kg（approximation））＋tank
Capture Mech.[kg]	40	40	40	40	40	Set in reference to JAXA Research
Dry Mass[kg]	280	345	341	800	516	
Wet Mass[kg]	350	540	501	1540	846	
Satellite Cost[million dollar]	49	58	58	105	77	model-based estimation
Launch Cost[million dollar]	11	16	15	46	25	$30,000.／kg
Removal cost per one debris [million dollar]	**60**	**74**	**36**	**76**	**34**	No precision in absolute values due to model-based estimation, used for relative evaluation

＊1） W. J. Larson, et.al., "Space mission analysis and design, third edition". Microcosm, Inc.

＊2） The tank mass is about 10% of the Base Mass, but the lower limit of the Base Mass is 200 kg and the upper limit of the Dry Mass is 800 kg.

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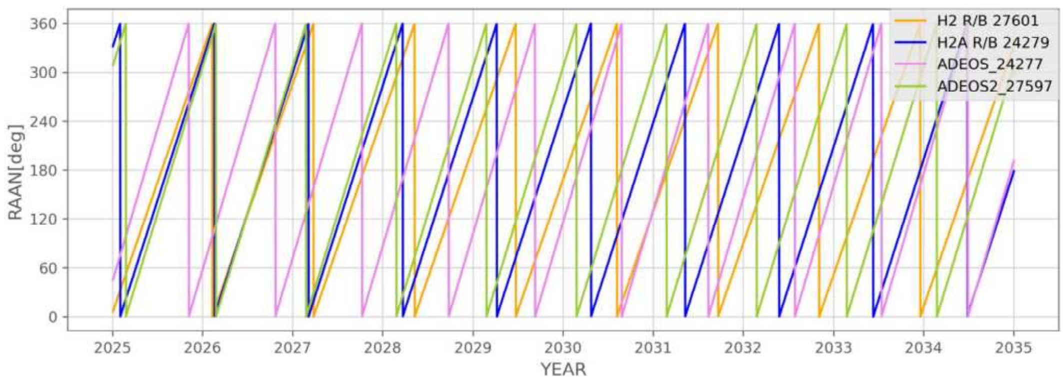
Example scenarios with specific targets

- Debris in near-sun-synchronous orbits at altitudes between 800 km and 1000 km have already lost their sun-synchronous nature.
- Example scenario of "Shuttle mission concept" with specific targets is illustrated by creating a simulated orbit with electric propulsion maneuvers taken into account.
  - Scenario 1 : Japanese debris（ADEOS, ADEOS2, Rockets that launched them）
  - Scenario 2 : ARIANE 40 R/B



Maneuver logic for electrical propulsion

- Control semi-major axis, inclination, and eccentricity vector simultaneously
- Thrust Direction $\vec{T}$ ：Linear sum of optimal thrust direction to change each orbit elements

$$\vec{T} = \sum_{COE} \left(1 - \delta_{COE_t, COE_s}\right) \frac{COE_t - COE_s}{\Delta COE_0} \vec{T}_{COE}$$

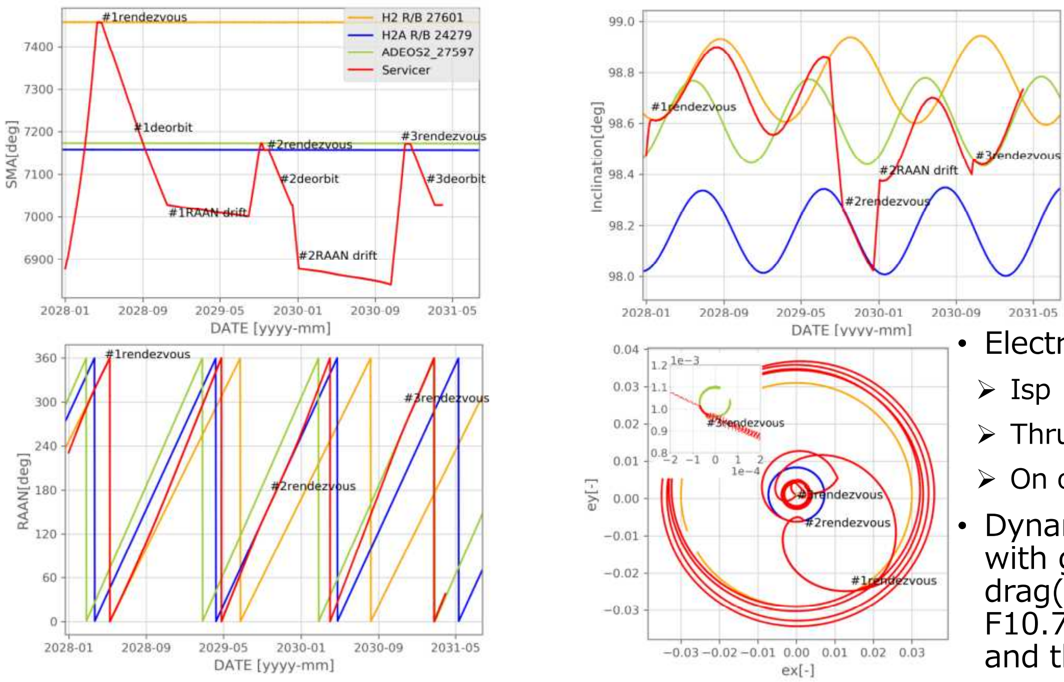
- ➢ Semi-major axis $\vec{T}_{SMA} = [\sin\alpha \quad \cos\alpha \quad 0]^T, \ \alpha = \tan^{-1}\left(\frac{e \sin\nu}{1 + e\cos\nu}\right)$
- ➢ Inclination $\vec{T}_{INC} = [0 \quad \cos\beta \quad \sin\beta]^T, \ \beta = \mathrm{sgn}(\cos(\omega + \nu))\frac{\pi}{2}$
- ➢ Eccentricity vector $\vec{T}_{EVEC} = (\vec{r} \times \vec{v}) \times \overrightarrow{\Delta_e} + (\overrightarrow{\Delta_e} \times \vec{v}) \times \vec{r}$

※$\overrightarrow{\Delta_e}$ is a vector that represents the difference between the target eccentricity vector and the current eccentricity vector considering only the orbit plane. $\|\overrightarrow{\Delta_e}\|$ is used for $COE_t - COE_s$ of eccentricity vector.

- ➢ The control of the RAAN is controlled using the difference in the orbit plane rotation speed (rate of change of the RAAN, $\Delta\dot{\Omega}$) due to perturbation, instead of orbit control by maneuvers.
  - ✓ The semi-major axis and inclination can be changed to increase the value of $\Delta\dot{\Omega}$, if necessary. But the expected $\Delta\dot{\Omega}$ is about several tens of degrees/year.
  - ✓ RAANs of debris to be targeted in the Shuttle mission concept should be close in value.

Scenario1 : Japanese debris

H2 R/B 27601→H2A R/B 24279→ADEOS2

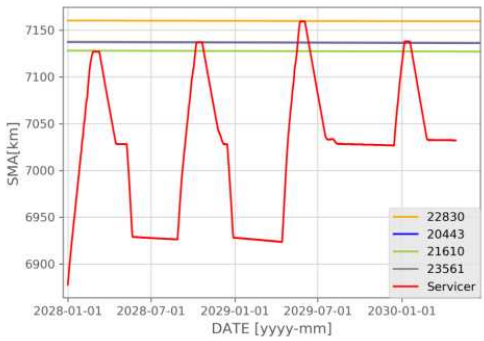


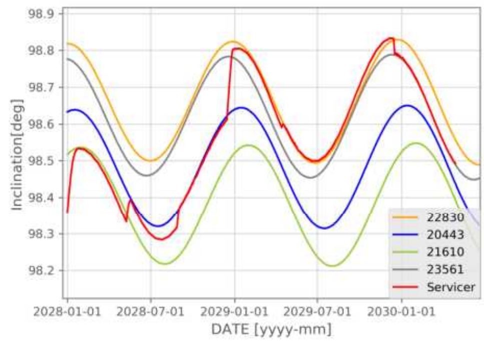
- Electric Propulsion
  - ➢ Isp：1600seconds
  - ➢ Thrust：60mN
  - ➢ On only during daytime
- Dynamic Simulation with gravity（J4）, drag(NRLMSISE00, F10.7=100, Ap =15), and thrust acceleration.

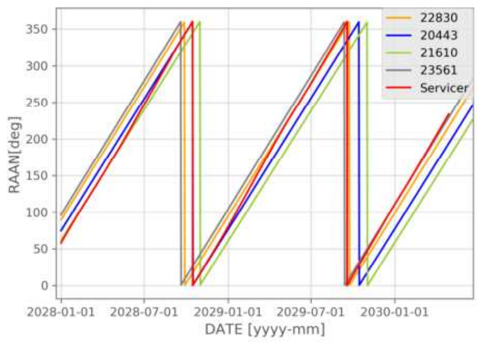
Scenario1 : Japanese debris

Operation	⊿V[m/s]		System Mass[kg]		Propellant[kg]		Electric Prop. Total impulse	Note
	RCS	EP	Before	after	N2H4	Xe		
#1 rendezvous		469.3	**800.0**	776.4		23.59	3.70.E+05 [Ns]	Rocket injection(500km)→ H-2_RB_24279
#1 Prox. Operation	100		776.4	701.1	75.3			
#1 deorbit		220.9	3701.1	3649.3		51.78	8.12.E+05 [Ns]	Descent to 650km
#1 RAAN drift			649.3					Wait at 650km
#2 rendezvous		362.5	649.3	634.5		14.84	2.33.E+05 [Ns]	Rendezvous to H-2A_RB_27601
#2 Prox. Operation	100		634.5	572.9	61.5			
#2 deorbit		68.4	3572.9	3557.4		15.56	2.44.E+05 [Ns]	Descent to 650km
#2 RAAN drift		118.7	557.4	553.2		4.20	6.59.E+04 [Ns]	Descent to 500km for RAAN drift, inclination change close to inclination of the ADEOS2
#3 rendezvous		279.9	553.2	543.4		9.79	1.53.E+05 [Ns]	Rendezvous to ADEOS2
#3 Prox. Operation	100		543.4	490.7	52.7			
#3 deorbit		75.8	3490.7	3473.8		16.84	2.64.E+05 [Ns]	Descent to 650km
Total	300	1595.5			**189.6**	**136.60**	2.14[MNs]	**Dry Mass : 473.8kg**

Scenario2 : ARIANE 40 R/B





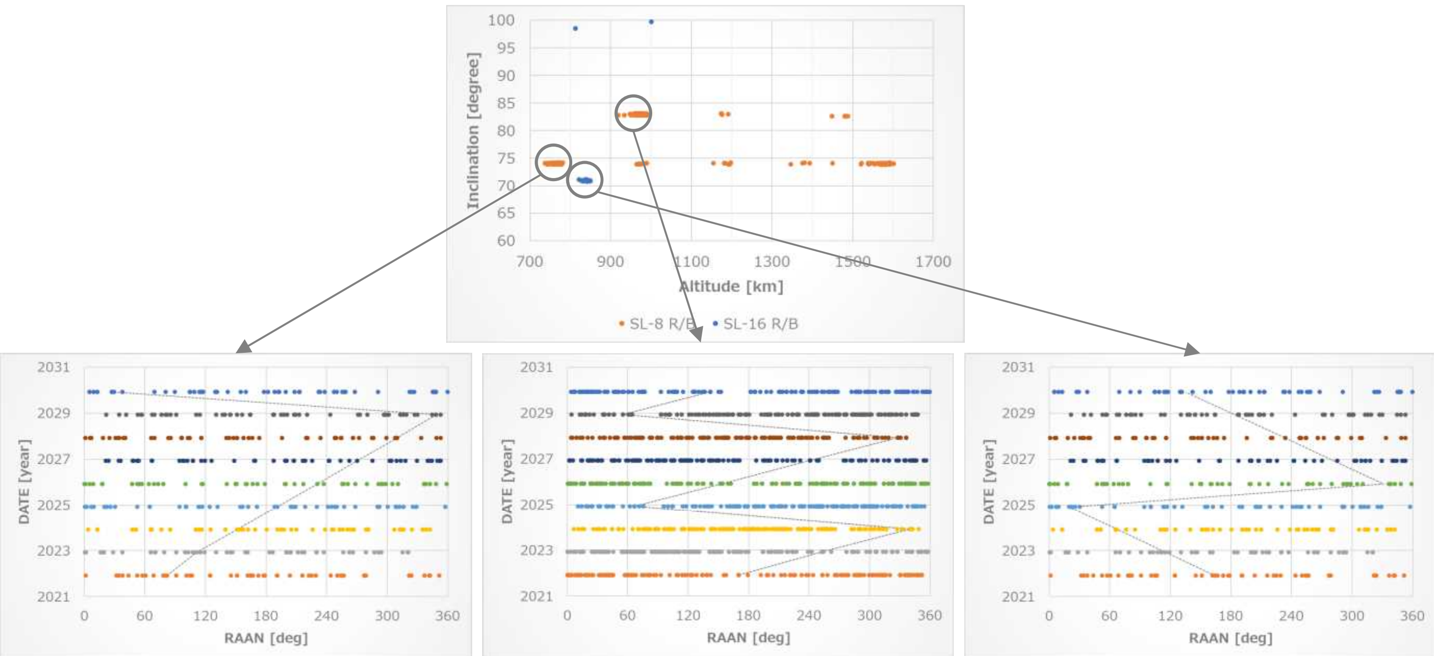


- Electric Propulsion
  - ➢ Isp : 1600seconds
  - ➢ Thrust : 60mN
  - ➢ On only during daytime
- Dynamic Simulation with gravity（J4）, drag(NRLMSISE00, F10.7=100, Ap =15), and thrust acceleration. Weight of ARIANE 40 R/B is 1780kg

Scenario2 : ARIANE 40 R/B

Operation	⊿V[m/s]		System Mass[kg]		Propellant[kg]		Electric Prop. Total impulse	Note
	RCS	EP	Before	after	N2H4	Xe		
#1 rendezvous		248.6	**800.0**	787.4		12.58	1.97.E+05 [Ns]	Rocket injection(500km)→ ARIANE_R/B_21610
#1 Prox. Operation	100		787.4	711.0	76.4			
#1 deorbit		54.7	2491.0	2482.4		8.67	1.36.E+05 [Ns]	Descent to 650km
#1 RAAN drift			702.4	699.6		2.78	4.36.E+04 [Ns]	Descent to 500km for RAAN drift, inclination change close to inclination of the 20433
#2 rendezvous		201.5	699.6	690.6		8.93	1.40.E+05 [Ns]	Rendezvous ARIANE_R/B_20443
#2 Prox. Operation	100		690.6	623.6	67.0			
#2 deorbit		68.1	2403.6	2393.2		10.42	1.63.E+05 [Ns]	Descent to 650km
#2 RAAN drift		77.2	613.2	610.2		3.01	4.72.E+04 [Ns]	Descent to 500km for RAAN drift, inclination change close to inclination of the 22830
#3 rendezvous		213.9	610.2	601.9		8.27	1.30.E+05 [Ns]	Rendezvous to ARIANE_R/B_22830
#3 Prox. Operation	100		601.9	543.6	58.4			
#3 deorbit		106.1	2323.6	2307.9		15.67	2.46.E+05 [Ns]	Descent to 650km
#3 RAAN drift		0.0	527.9	527.9		0.00	0.00.E+00 [Ns]	Wait at 650km
#4 rendezvous		145.5	527.9	523.0		4.88	7.65.E+04 [Ns]	Rendezvous to ARIANE_R/B_23561
#4 Prox. Operation	100		523.0	472.3	50.7			
#4 deorbit		59.2	2252.3	2243.8		8.49	1.33.E+05 [Ns]	Descent to 650km
Total	400	1174.9			**252.5**	**83.71**	1.31[MNs]	**Dry Mass : 464kg**

Discussion on Russian Rockets



Summary

- One important requirement for the debris removal technology to be demonstrated in CRD2 is that it must be low-cost to the extent that it is sustainable.
- The architecture and operational concept of future ADR projects were studied from the perspective of debris removal cost per piece, and the **Shuttle mission concept**, which removes multiple pieces of debris with a single service satellite without controlled re-entry, was confirmed to be advantageous.
- The feasibility of this concept was confirmed for specific targets.
- For the CRD2 Phase II technical demonstration scenario, it is appropriate to set the service requirements based on the main technical items to be demonstrated, such as **capture and grasp, descent into orbit, and release (without controlled re-entry).**

Requirements	Contents
General Requirements	Acquisition and provision of position, velocity, attitude, angular velocity, and navigation sensor data of the satellite and target debris during the service period
Observation Service	Acquisition and provision of camera images when approaching target debris
Orbit Descent Service	Orbital descent of target debris (The target altitude is still under consideration.)
Termination Service	Safe release of debris after orbit descent