PAVE THE WAY FOR ACTIVE DEBRIS REMOVAL REALIZATION: JAXA COMMERCIAL REMOVAL OF DEBRIS DEMONSTRATION (CRD2)

Toru Yamamoto(1), Jun Matsumoto(1), Hiroyuki Okamoto(1), Ryota Yoshida(1), Chiharu Hoshino(1), Koji Yamanaka(1)

(1) Japan Aerospace Exploration Agency, 2-1-1 Sengen, Tsukuba, Ibraki, Japan, Email: yamamoto.toru@jaxa.jp

ABSTRACT

The need for Active Debris Removal (ADR) and its urgency are widely recognized. There is also a sense of expectation for ADR to develop new markets in on-orbit services. On the other hand, it is essential to establish the technical feasibility of ADR as a precondition for the international discussion on the sustainable implementation of ADR activities.

In accordance with the Japanese government's Basic Plan on Space Policy, JAXA has started the Commercial Removal of Debris Demonstration (CRD2) program with the aim of establishing ADR as a new business field and developing a new market where the private sector can play an active role. This program is unique in that it aims to achieve both technology demonstration and commercialization.

CRD2 consists of two phases, Phase-I and Phase-II. JAXA selected the Astroscale company as a commercial partner for Phase I, and the project was kicked off in March 2020. The preliminary design is currently in progress. In parallel with the progress of the Phase-I project, JAXA is also actively researching the technologies required for Phase-II.

This paper presents an overview of the CRD2 program, the details and current status of Phase-I, and the progress of the research activities for Phase-II.

1 INTRODUCTION

The Inter-Agency Debris Coordination Committee (IADC) predicts that the number of space debris will continue to increase due to collisions between space debris [1]. And the increase in the number of small debris (1 mm to 10 cm), which cannot be avoided or defended against, may greatly limit human space activities in the future.

Liou [2] showed that removing large and massive debris from crowded orbits can effectively reduce the number of collisions, the primary cause of the proliferation of space debris. According to the results of calculations based on certain assumptions, Active Debris Removal (ADR) of five large pieces of important debris per year, along with appropriate implementation of commonly adopted mitigation measures, can stabilize the increase.

In addition, other studies have shown that compliance with the Post Mission Disposal (PMD) guidelines is necessary to control the increase of space debris [3][4]. Currently, the success rate of PMD is about 20% for payloads and about 60% for rocket upper stages, but the implementation of PMD is not sufficiently widespread [5]. Although a PMD success rate of more than 90% is desirable, it is difficult to achieve it promptly. Somma [6][7] states that increasing the success rate of PMD alone is likely not enough and that the implementation of ADR in addition to PMD is effective in controlling the accumulation of space debris.

Kawamoto [8] investigated the simulations of the increase in debris in Low Earth Orbit (LEO) by altitude. According to the analysis, even if the PMD success rate of 90% is achieved, the amount of debris in the altitude range of 900-1000 km will continue to increase. This trend can be controlled by performing ADR to remove the critical large debris in the crowded orbits in this altitude range.

There are two types of large space debris targeted by ADR: inactive payloads and rocket bodies. The effective target of ADR is massive debris with a high probability of colliding with other debris. According to a study by Somma et al. [7], removing rocket bodies can achieve twice the benefits for the long-term space debris population as compared with the removal of inactive payloads. And because rocket bodies are similar in shape and have few large protrusions, it is also relatively easy for ADR spacecraft to approach and capture them. Conversely, each inactive payload has a unique shape, often with large protrusions such as solar panels. The authors believe that it would be advantageous for ADR to focus first on the removal of the rocket bodies because of the technical ease and efficient environmental remediation.

Several metrics have been proposed to quantify the extent to which objects in orbit contribute to future increases in space debris [9-11]. Based on these and other metrics, a study was conducted by several organizations to create a ranked list of space debris [12]. This list can be used as a reference when considering which targets are most suitable for ADR removal.

Proc. 8th European Conference on Space Debris (virtual), Darmstadt, Germany, 20–23 April 2021, published by the ESA Space Debris Office
Ed. T. Flohrer, S. Lemmens & F. Schmitz, (http://conference.sdo.esoc.esa.int, May 2021)

According to this list, the most important group to remove is massive upper rocket stages in the range of 1-9 tons. These are clustered at certain altitudes and orbital inclinations. Considering the environmental impact, it is desirable to remove these upper rocket stages by ADR first.

ADR is expected to open new markets in on-orbit services [13][14]. For this to be realized, the whole ecosystem of ADR which makes this business commercially practicable should be taken in. In addition, orbital objects of other countries should not be touched without the permission of the owner. ADR should be done with clear transparency after establishing such a framework based on an international agreement. However, if the technology to realize ADR remains immature, we cannot develop or seriously discuss this. Establishing the technical feasibility of ADR is essential to any real progress in the discussion.

Based on the above, JAXA has started the Commercial Removal of Debris Demonstration (CRD2) program to establish ADR as a new business and to develop a new market where the private sector can play an active role. The purpose of this program is twofold: to demonstrate the ADR technologies and to pave the way for the private sector to implement ADR as a business.

CRD2 consists of two phases, Phase-I and Phase-II. JAXA selected the Astroscale company as a commercial partner for Phase-I, and the project was kicked off in March 2020. Its preliminary design is in progress. In parallel with the progress of the Phase-I project, JAXA is also actively researching the technologies required for the next Phase-II.

This paper provides an overview of the CRD2 program, the details and current status of the Phase-I project, and the progress of the research activities toward the Phase-II.

2 CRD2 OBJECTIVE AND PROGRAM STRUCTURE

The purpose of this CRD2 program is to establish ADR as a business and develop new markets where the private sector can play an active role.

This program has two goals:

- To demonstrate ADR technologies
- To pave the way for the private sector to implement ADR as a business

A unique feature of this program is that it aims at both technology demonstration and commercialization.

As mentioned earlier, the debris with the highest-ranking effect on improving the space environment is the massive debris of about 1-9 tons in the crowded orbits. Removing such massive debris from its original orbit is a technically challenging and will need the following:

- Rendezvous and Proximity Operations (RPO) for non-cooperative targets
- Capture of non-cooperative targets and attitude control in combined state
- Large descent of heavy targets to lower orbits

These require novel technology elements that are not yet proven, including rendezvous docking with cooperative targets. We thought it would be too risky to demonstrate this challenging mission at one try. Therefore, we decided to structure CRD2 as a two-stage program, as shown in Fig. 1.

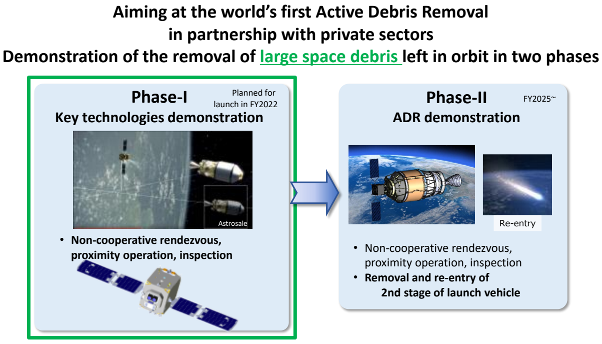


Figure 1. CRD2 program structure

In Phase-I, we demonstrate technologies for approaching and inspecting a large space debris that has actually been in orbit for many years. This will include everything from purchasing and launching a rocket to align with the target's orbit and adjusting the relative phase and orbital plane for performing RPO on the non-cooperative target. In other words, it is a demonstration of a full range of RPO technology for non-cooperative targets. In addition, by obtaining detailed images of the target in Phase-I, we will be able to understand the status of the debris that has been in orbit for many years, which will significantly reduce the risk in the subsequent Phase-II. The Phase-I project has already begun, and the demonstration satellite is under design for a future launch which enables to implement the Japan Basic Plan on Space Policy.

In addition to the scope of the Phase-I mission, Phase-II will demonstrate the technology to capture the target, lower it from its original orbit, and safely re-enter the Earth for disposal. The images obtained in Phase-I will be used to reduce risks, especially in the capture mechanism and operations. Phase-II is currently in the preparatory phase of the project.

3 CRD2 NEW PARTNERSHIP-TYPE CONTRACT

We thought that the CRD2 program would only achieve half of its objectives if the national space agency were to implement it on its own initiative. This method of implementation might achieve the goal of demonstrating ADR technology, but it would not pave the way for the private sector to implement ADR as a business. Therefore, we decided to adopt a new partnership-type contract as shown in Fig.2, in order to challenge the division of roles between JAXA, the national space agency, and the private sector.

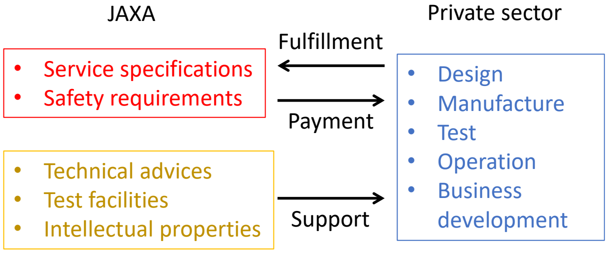


Figure 2. New partnership-type contract

In a traditional JAXA satellite project contract, JAXA sets the detailed satellite’s technical specifications, and requirements for reliability, quality assurance, and safety requirements. And the private sector delivers a satellite to JAXA that meets the specifications and requirements. JAXA owns and operates the satellite.

In contrast, under the CRD2 partnership-type contract, JAXA does not procure a satellite but instead procures services and R&D results while setting service specifications and safety requirements. The private sector designs, manufactures, and tests a satellite that meets the service specifications and safety requirements. The satellite is then owned and operated by the private sector. In addition to providing services to JAXA, the private sector can use the satellite for their own missions.

In a typical JAXA satellite project, JAXA applies strict reliability and quality assurance requirements. This is to ensure the successful execution of government missions. On the other hand, the private sector may prefer to set different reliability and quality assurance requirements to be more cost-competitive in their business. Therefore, if JAXA's reliability and quality assurance standards are applied to this program, it may be difficult for the private sector to make a smooth transition into the business.

For this reason, the CRD2 program does not apply JAXA's reliability and quality assurance standards but allows the private sector to propose and apply their own standards. To ensure safety and prevent collisions with targets, a critical issue in RPO, only safety requirements for that purpose is applied for the CRD2 program.

This contract is a firm-fixed price contract. There are several milestones set from the start to the completion of the project. Each milestone will be reviewed, and, if approved, a predetermined amount which is some portions of the agreed fixed price will be paid. Since this CRD2 framework is beneficial for both JAXA and the private sector from aspects which enables JAXA to procure services and R&D results and the private sector to realize its own mission, both JAXA and the private sector provide funding for this project.

JAXA also provides strong support to the partner by utilizing its R&D assets. In addition to technical advices from JAXA experts in various fields, JAXA provides dedicated test facilities for spacecraft RPO, as well as intellectual properties resulting from its R&D activities, thereby helping to reduce the risk for the private sector to implement this novel program.

Through this program, the private sector will have the opportunity to build an integrated system needed to provide services. In parallel, the private sector will promote market creation and business development. This partnership-type contract is intended to strongly support the steps for the private sector in starting the business through this program.

4 CRD2 PHASE-I PROJECT

CRD2 Phase-I was kicked off in 2020. This section describes the Phase-I project in more detail.

4.1 Service specifications

As mentioned above, in CRD2 Phase-I, JAXA will procure services and R&D results. The requirements for the services to be provided to JAXA are specified in the service specifications [15]. There are several candidate space debris to be targeted, which are described in the document. An image of the target is shown in Fig. 3.

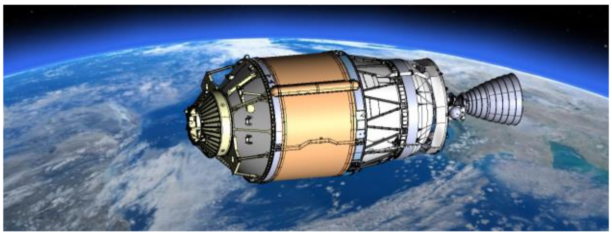
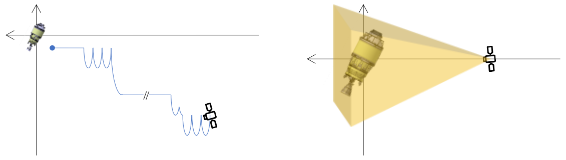


Figure 3. Illustration of CRD2 target debris

They are all real rocket upper stages that have existed in LEO for many years. They are Japanese rocket upper stages that launched JAXA satellites in the past and have a mass of about three tons.

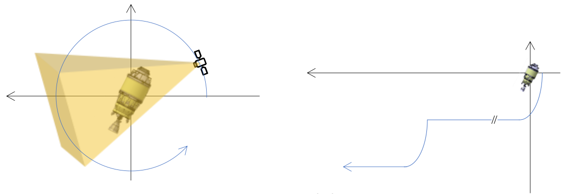
The most effective removal target for improving the space environment is the massive debris at an orbital altitude of 900-1000 km, but the candidates for CRD2 are debris at an orbital altitude of about 600 km. The reason for this is that even if debris is generated by contact with the target during RPO, it will not stay in orbit for a long period of time due to the existence of atmospheric drag, and will have less impact on the space environment. In other words, this is a consideration for a safer technology demonstration. The specific target will be selected from among these candidates after a technical review, referring to information obtained from ground-based telescope observations.

The service specifications describe the requirements for four specific services to be provided, as shown in Fig. 4.



(1) Rendezvous performance reporting service

(2) Fixed-point observation service



(3) Fly-around observation service

(4) Mission termination service

Figure 4. CRD2 Phase-I Services

The first service is the rendezvous performance reporting service. This service will provide JAXA with performance data on how the actual operations went against a series of planned rendezvous with the non-cooperative target, starting immediately after launch and ending with the approach to the non-cooperative target.

The second is the fixed-point observation service. The demonstration satellite will perform precise relative position-keeping control at a certain position in the Local Vertical, Local Horizontal (LVLH) coordinate system with the target at the origin. Images of the target will be acquired over time, and the private sector will provide them to JAXA. The specifications include the duration, interval, and quality of the images. The continuously acquired image data will be used to understand the natural free attitude motion of the target, its shape, and its surface degradation.

The third is the fly-around observation service. In this service, the demonstration satellite orbits around the target and keeps its camera pointed at the target while continuously acquiring images provided to JAXA by the private sector. The acquired images will be used mainly to observe the target from various directions to better understand its shape and surface deterioration.

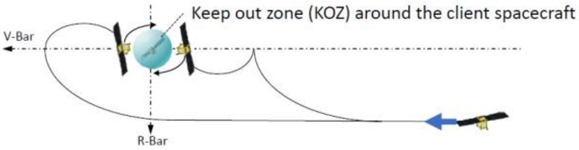
The fourth is the mission termination service. After a series of rendezvous and proximity operations are completed, the demonstration satellite is taken out of the target's vicinity and its orbit is lowered to a disposal orbit. The data indicating the success of the operation is then provided to JAXA.

4.2 Safety requirements

In the CRD2 program, the document JERG-2-026 Safety Standard for ON-ORBIT Servicing Missions [16] clarifies the safety and security requirements for the private sector to limit, manage, and avoid the risk of collisions with targets when designing, manufacturing, testing, and operating the demonstration satellite. This standard has been developed based on the mission experiences of RPO for the International Space Station.

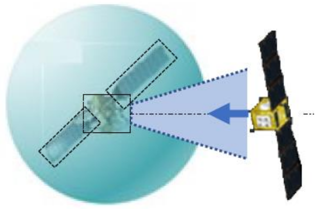
The basic concept of safe relative trajectory design is shown in Fig. 5. In the far field, the demonstration satellite must take a safe trajectory that does not interfere with the keep-out zone (KOZ), even in the passive state. In the closed approach, the demonstration satellite comes into the designated approach path without crossing over the path boarder.

a)



Sample trajectory in the far field

b)



Sample approach path into KOZ

Figure 5. Basic concept of safe rendezvous trajectory design in JERG-2-026 [16]
(a) far-range rendezvous, b) close-range rendezvous)

The total system shall be one fault tolerant (1FT) for a critical event such as a collision with the target. Thus, a single failure shall not result in a collision and shall not result in loss of essential functions for proper disposal. The analysis, evaluation and safety reviews will be based on the system safety engineering practices. The private sector will conduct hazard analysis based on their design and operation.

4.3 Selected partner company

In the fall of 2019, JAXA issued a Request for Proposal (RFP) for CRD2 Phase-I. After going through the normal vendor selection process, Astroscale was selected as the partner company for CRD2 Phase-I in March 2020 [17], and the project began.

4.4 Spacecraft: ADRAS-J

Astroscale has named the demonstration satellite of the CRD2 Phase-I project as ADRAS-J. It is a demonstration satellite designed, manufactured, tested, owned, and operated by Astroscale [18]. It is shown in Fig. 6.

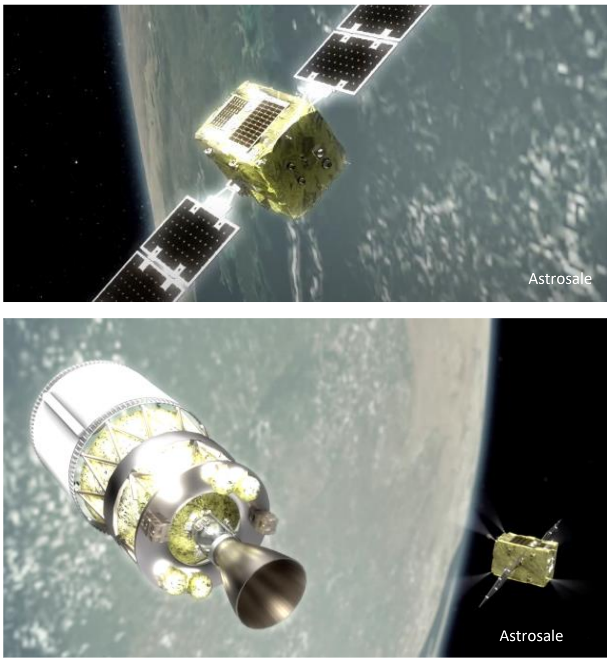


Figure 6. Illustration of ADRAS-J [18]

ADRAS-J is a small satellite with a wet mass of about 180 kg. It is a spacecraft with the capability to perform a full range of RPO for a non-cooperative target, including approach to the target orbit after launch operations, and rendezvous and proximity operations for non-cooperative targets through the process of adjusting the relative phase and orbital plane by performing multiple maneuvers.

4.5 Mission

As mentioned above, the CRD2 program allows the private sector to use the demonstration satellite not only for providing services to JAXA, but also for their own missions. The overall mission of the CRD2 Phase-I is shown in Fig. 7.

JAXA Services	Astroscale Missions
1. Rendezvous performance report service 2. Fixed-point observation service 3. Fly-around observation service 4. Mission termination service	1. Target inspection and diagnosis 2. Close approach to target 3. Extra missions

Figure 7. CRD2 Phase-I Mission definition

This can be divided into two categories. The first is providing the services described in the service specifications to JAXA. The second is carrying out the missions that Astroscale has set for itself. Astroscale defines its mission as "Target inspection and diagnosis" and "Close approach to the target". The company is also envisions additional missions.

4.6 Concept of operations

The concept of operations of CRD2 Phase-I is shown in Fig. 8.

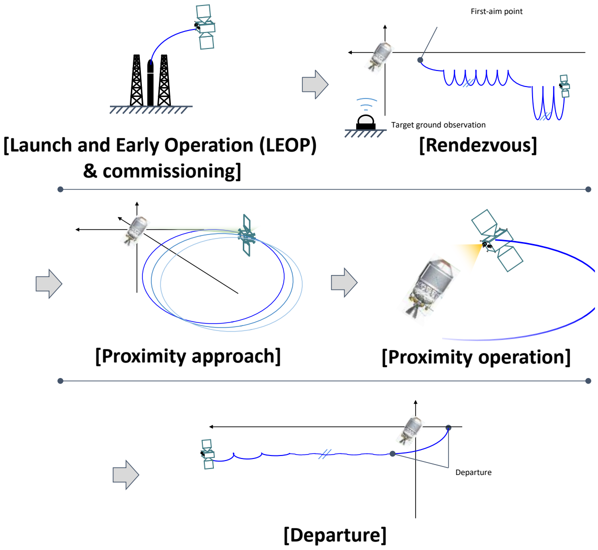


Figure 8. CRD2 Phase-I concept of operations [18]

The timeline of the concept of operation is roughly as follows:

First, the launch vehicle carrying the ADRAS-J will separate the ADRAS-J at the optimum orbital altitude, eccentricity, and orbital inclination for rendezvous with the target. The launch time is also adjusted to the optimal time for rendezvous with the target.

After that, ADRAS-J will perform a far-field rendezvous and gradually approach the target based on the absolute orbit information of the target obtained from the Commercial Space Operations Center (ComSpOC) and other sources. Then, the satellite detects the target with its onboard relative navigation sensor, performs relative navigation using the measurements, and starts proximity operations.

The satellite will then perform the services required by JAXA, such as fixed-point and fly-around observations, while maintaining stable relative navigation and control. Astroscale's original missions will also be carried out during the proximity operations.

After all proximity operations have been completed, the mission will finally be completed by taking a farewell to the target and performing maneuvers to lower its altitude and transfer to a disposal orbit.

4.7 Milestones

In CRD2 Phase-I, four milestones have been set as shown in Fig. 9. A predetermined amount of money will be paid depending on whether or not each milestone is achieved.

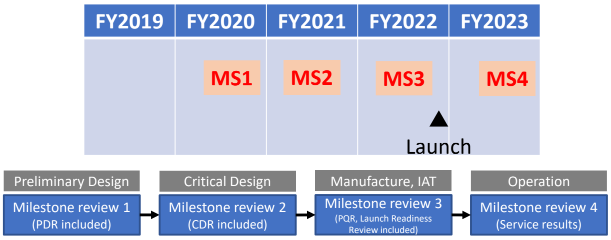


Figure 9. CRD2 Phase-I milestones

Milestone 1 is the completion of Preliminary Design Review (PDR), milestone 2 is the completion of Critical Design Review (CDR), and milestone 3 corresponds to the completion of Post Qualification Test Review (PQR) and Launch Readiness Review.

Milestone 4 is notable. The milestone 4 review is conducted after the launch and operation of ADRAS-J are completed to determine whether the services that meet the service specifications have been provided. The payment for milestone 4 is at least 25% of the total. This firm-fixed price and pay-for-success system is designed to encourage the private sector to struggle between the pressure to reduce costs and the pressure to improve reliability and quality to better ensure the success of the service delivery, and in the process gain a competitive development process as well competitiveness in its future business.

4.8 Milestone 1 status

Astroscale is currently performing the preliminary design of the demonstration system, including the demonstration satellite ADRAS-J and associated ground facilities. Specific activities include the design of concept of operations, system/subsystem requirements definition, system design, subsystem design, Bread-Board Model (BBM) testing of the Commercial-Off-The-Shelf (COTS) rendezvous sensors (shown in Fig. 10), safety design, and planning of manufacturing, integration, assembly, and testing. We are now conducting the milestone 1 review.

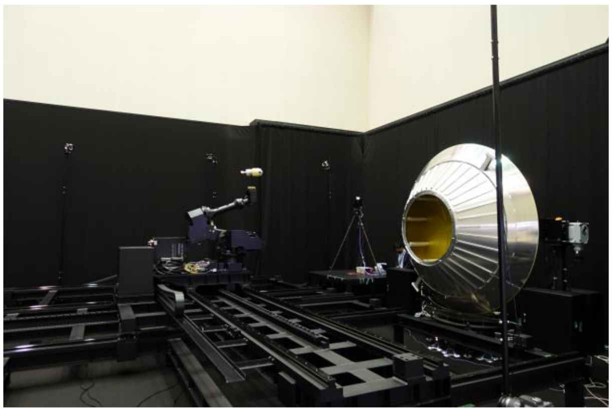


Figure 10. COTS rendezvous sensor BBM test in JAXA SATDyn [22] facility

5 CRD2 PHASE-II R&D

In parallel with implementing of the CRD2 Phase-I project, JAXA has been researching and developing key technologies necessary for Phase-II. Fig. 11 shows representative key research themes. The following is a brief description of the technical issues each research is intended to solve.

The target of the CRD2 is a massive rocket upper stage, and its length is about 10 meters. Therefore, it is difficult to conduct ground tests of the rendezvous sensors using a full-scale target model under various conditions for the position, attitude, and lighting environment. On the other hand, tests using a reduced-size scale model of the target cannot accurately simulate the ranging error of Light Detection and Ranging (LiDAR) sensors. To solve this problem, we are working on a simulator that can generate LiDAR-simulated measurements that accurately simulate the target's optical reflection characteristics and the ranging error of LiDAR [19]. The outcome of this research will enable us to generate high-fidelity simulated sensor measurements even for targets that are too large to be tested on the ground, and to verify the relative navigation algorithms even for such large targets.

In another problem, the CRD2 target is so massive that a large total impulse is required to change its orbit significantly. If we use only a chemical propulsion system, the mass of the propellant will be excessive. To solve this problem, we are studying hall thrusters with high efficiency and large total impulse [20].

In addition, the target debris, which is a non-cooperative target, is in a free attitude motion in orbit and is not stationary. To capture such a target reliably, JAXA is studying a gripper for non-cooperative targets with a wide capture envelope and does not fail to capture the target due to bouncing off the target on contact [21].

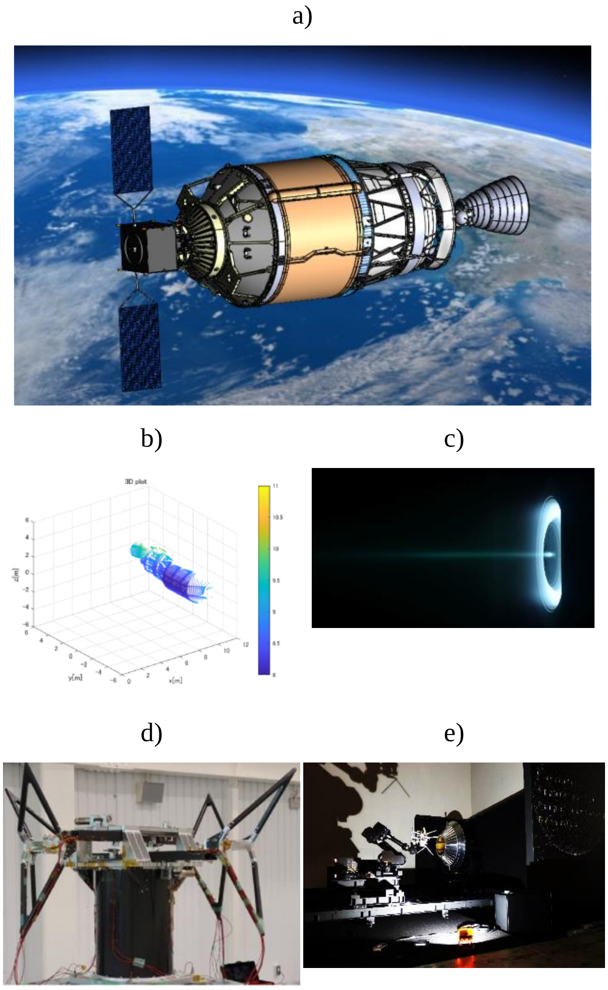


Figure 11. JAXA R&D items for CRD2 Phase-II (a) Illustration of CRD2 Phase-II mission, b) LiDAR measurement simulator [19], c) High-total impulse hall-effect thruster [20], d) Debris griper [21], e) Capture dynamics test facility SATDyn [22])

Furthermore, the proximity operation to capture the debris is an integrated operation of multiple technological elements such as relative navigation, guidance, control, onboard computers, and capture mechanisms. Therefore, it is necessary to have an environment where all these technological elements can come together to conduct hardware-in-the-loop tests of the capture operations. JAXA is researching and developing a rendezvous and capture dynamics hybrid simulator: SATDyn, for such an application [22].

Then, JAXA has put together several novel technical elements and is now working on the operational concept design and the conceptual study of the demonstration system [23-26]. Through these activities, JAXA is trying to improve the technical feasibility of the CRD2 Phase-II and to develop its service specifications so that JAXA can request the private sector to provide the services under a similar contractual approach.

6 CONCLUSIONS

JAXA launched the CRD2 program in 2020 to establish ADR as a new business field and to develop a new market where the private sector can play an active role.

This program has two goals:

- To demonstrate ADR technologies
- To pave the way for the private sector to implement ADR as a business

Because of the high level of technical challenges, this program consists of two steps, Phase-I and Phase-II. In addition, the new partnership-type contract has been designed and applied in this program, which is intended to encourage the private sector to start its business in this field.

Astroscale has been selected as the partner company for the CRD2 Phase-I. The preliminary design is now in progress for a future launch which enables to implement the Japan Basic Plan on Space Policy. By obtaining detailed images of the target in orbit during Phase-I, we will be able to learn the status of that real space debris that has been in orbit for many years; this will significantly reduce the risks of the subsequent Phase-II.

In parallel with the progress of Phase-I, JAXA has been conducting several studies to overcome the Phase-II technical issues. These studies' results will contribute to making the service specifications of the Phase-II more concrete and realistic. They will also serve to lower the threshold for the private sector to participate in Phase-II. Many of these technical issues are common not only to ADR but also to many other on-orbit servicing missions. Therefore, the outcomes of the CRD2 program are expected to contribute not only to the solution of the space debris problem but also to the promotion of on-orbit servicing.

7 REFERENCES

1. Inter-Agency Space Debris Coordination Committee (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*, 47(11), 1865-1876.

3. Liou, J. C. (2013). An update on the effectiveness of post mission disposal in LEO, *Inter-Agency Space Debris Coordination Committee,* IAC-13-A6. 4.2, Beijing, China.

4. Dolado-Perez, J. C., Revelin, B., & Di-Costanzo, R. (2015). Sensitivity analysis of the long-term evolution of the space debris population in LEO. *Journal of Space Safety Engineering*, 2(1), 12-22.

5. ESA Space Debris Office (2019). ESA's Annual Space Environment Report, GEN-DB-LOG-00271-OPS-SD.

6. Somma, G. L. et al. (2016). Adaptive remediation of the space debris environment using feedback control. *in Proceedings of the 67th International Astronautical Congress*,IAC-16-A6.IP.3, Guadalajara, Mexico.

7. Somma, G. L. et al. (2017). Increasing ADR effectiveness via an altitude-shell-dependent removal approach. *in Proceedings of the 68th International Astronautical Congress*, IAC-17.A6.IP.36x37651, Adelaide, Australia.

8. Kawamoto, S., Nagaoka, N., Sato, T., & Hanada, T. (2020). Impact on collision probability by post mission disposal and active debris removal. *Journal of Space Safety Engineering*, 7(3), 178-191.

9. Utzmann, J., Oswald, M., Stabroth, S., Voigt, P., Retat, I. (2012). Ranking and characterization of heavy debris for active removal. *in Proceedings of the 63rd International Astronautical Congress*, IAC-12-A6.2.8, Naples, Italy.

10. Rossi, A., Valsecchi, G. B., & Alessi, E. M. (2015). The criticality of spacecraft index. *Advances in Space Research*, 56(3), 449-460.

11. Letizia, F., Colombo, C., Lewis, H., Krag, H. (2017). Extending the ECOB space debris index with fragmentation risk estimation, *in Proceedings of the 7th European Conference on Space Debris*, Darmstadt, Germany.

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

13. Brettle, H., Forshaw, J., Auburn, J., Blackerby, C., Okada, N. (2019). Towards a Future Debris Removal Service: Evolution of an ADR Business Model. *in Proceedings of the 70th International Astronautical Congress*, IAC-19, A6,10-B4.10,8, x49992, Washington D.C., United States.

14. Rocca, G. L., Wright, E., Poirier, C., Bordacchini, G. (2020). *ESPI Report 76 - In-Orbit Services - Full Report*, European Space Policy Institute (ESPI), Vienna, Austria.

15. Japan Aerospace Exploration Agency (2019). *GKD-2019013 CRD2 (phase-I) service specification*.

16. Japan Aerospace Exploration Agency (2020). *JERG-2-026 Safety Standard for ON-ORBIT Servicing Missions.*

17. Japan Aerospace Exploration Agency (2020). JAXA concludes partnership-type contract for Phase I of its Commercial Removal of Debris Demonstration (CRD2), *JAXA press release*, https://global.jaxa.jp/press/2020/03/20200323-1_e.html

18. Fujita, S. (2021). ADRAS-J Project Overview - World first ADR Technology Demonstration-. *in Proceedings of the 9th Space Debris Workshop*.

19. Nakajima, Y., Sasaki, T., Okada, N., Yamamoto, T. (2021). LiDAR measurement simulator considering target surface reflection. *in Proceedings of the 8th European Conference on Space Debris*.

20. Cho, S., Watanabe, H., Matsunaga, Y., Tsukizaki, R., Ohkawa, Y., Kondo, H., Kusawake, H., Yamaomto, T. (2021). R&D status of JAXA 1-kW Hall Thruster System for Active Debris Removal. *in Proceedings of the 8th European Conference on Space Debris*.

21. Tanishima, N., Okamoto, H., Iki, K., Watanabe, K., Okumura, T. (2021). Concept and design of robustness improved caging based debris gripper. *in Proceedings of the 8th European Conference on Space Debris*.

22. Okamoto, H. (2021). The development of the rendezvous and capture dynamics hybrid simulator: SATDyn. *in Proceedings of the 8th European Conference on Space Debris*.

23. Okamoto H., Yamamoto T. (2019). A Novel Concept of Cost-Effective Active Debris Removal Spacecraft System. *in Proceedings of the 1st International Orbital Debris Conference*, Sugar Land, Texas, USA.

24. Sasaki, T., Nakajima, Y., Okamoto, H., Yamamoto, T. (2020). Adaptive Torque Equilibrium Attitude Guidance for Rapid Deorbit of Space Debris by Aerodynamic Drag Considering Model Uncertainty. *in Proceedings of the 71th International Astronautical Congress*, IAC-20, C1, 8, 2, x59770.

25. Oki, Y., Okamoto, H., Sasaki, T., Yamamoto, T., Wada, K. (2021). Satellite System Design with The Blocking Effect: Application to Active Debris Removal Mission. *in Proceedings of the AIAA SciTech 2021 Forum*, AIAA2021-1039.

26. Yamamoto T., Nakajima Y., Sasaki T., Okada N., Haruki M., Yamanaka K. (2019). GNC Strategy to Capture, Stabilize, and Remove Large Space Debris. *in Proceedings of the 1st International Orbital Debris Conference*, Sugar Land, Texas, USA.