ADVANCING ACTIVE DEBRIS REMOVAL: ACHIEVEMENTS AND PROSPECTS IN THE COMMERCIAL REMOVAL OF DEBRIS DEMONSTRATION

Toru Yamamoto [1], Hiroyuki Okamoto[1], Makoto Tomitaka[1], Ryo Nakamura[1], Yu Takeuchi[1]

[1] Commercial Removal of Debris Demonstration Project Team, Research and Development Directorate, Japan Aerospace Exploration Agency, 2-1-1 Sengen, Tsukuba, Ibaraki, 305-8505, Japan, Email: yamamoto.toru@jaxa.jp

ABSTRACT

The necessity and urgency of Active Debris Removal (ADR) are widely recognized, and ADR is anticipated to open new markets as a subset of on-orbit services. JAXA initiated the Commercial Removal of Debris Demonstration (CRD2) project in 2020. This project has two primary objectives:

- Demonstrate ADR technology

- Establish pathways for private companies to conduct ADR as a business

Due to the many technical challenges, the project is divided into two phases. Phase I aims to demonstrate Rendezvous and Proximity Operations (RPO) and inspection capabilities for large space debris that has been in orbit for years, showcasing a full-range non-cooperative RPO technologies. In Phase II, the project plans to demonstrate technologies for capturing the target and towing it to a lower disposal orbit. After careful consideration of multiple factors, the upper stage of a Japanese H-IIA rocket used to launch the GOSAT satellite in 2009 was selected as the target debris. Through JAXA's standard company selection process, Astroscale Japan Inc. was selected as the partner company.

For the Phase I demonstration, Astroscale's ADRAS-J satellite was successfully launched in February 2024 and, as of fall 2024, has achieved proximity operations up to 15 meters, successfully demonstrating full-range RPO capabilities with non-cooperative targets.

In fall 2024, JAXA also launched the Phase II project. This project has been carefully defined to provide a meaningful demonstration of future operational ADR activities and other on-orbit services by private enterprises, considering potential future operational scenarios.

This paper discusses the status of the CRD2 project, the outcomes achieved in the Phase I demonstration, the mission definition and approach for Phase II, and provides an outlook for the future of these ongoing projects.

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 increase in 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]. Although a PMD success rate of more than 90% is desirable, it is difficult to achieve it promptly. Somma [5,6] 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 [7] 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.

Several indicators have been proposed to quantify the extent to which orbital objects contribute to the future increase in space debris [8-10]. Based on these and other indicators, a study was conducted by several organisations to develop a ranked list of the top 50 space debris targets [11]. This list can be used as a reference when considering which targets are most suitable for ADR. According to this list, the most important groups to be removed are the massive rocket upper stages of

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between one and nine tonnes. These are clustered at specific altitudes and orbital inclinations. Considering the environmental impact, these upper rocket stages should first be removed by ADR.

Kawamoto [12] studied the effects of changing the number and timing of removals and showed that the top 50 rankings change over time if a limited number of objects are removed each year. The environment changes dramatically, e.g. due to collisions, and this changes the rankings significantly. Therefore, ADR targets should be reevaluated frequently and it is not beneficial to stick to a current particular ranking. ADR should start early and remove more objects to be effective, as delaying it results in a higher stabilized number of space debris.

Reflecting the recent global developments in space exploration, where reusable transport systems to space have finally become operational, there is growing attention on achieving reusable architectures for spacecraft through on-orbit services. These services include a variety of operations such as refueling, life extension, transportation, equipment replacement, and repair, with ADR being one of them. ADR and on-orbit services share many technical similarities, such as rendezvous and proximity operations (RPO) with the target, mechanical capture, and stable operation in a docked state to perform some service. Therefore, ADR can be considered a practical exercise for on-orbit services. ADR is expected to create a new market as a type of various on-orbit services, but for this to continue to be realized in an economically sustainable manner, private on-orbit service companies are desirable to implement ADR as part of their business portfolio.

ADR should also be carried out with clear transparency and a defined framework based on international agreements, as it is not possible to touch an orbital object of another country without the permission of the owner. However, concrete and serious discussions on resolving such obstacles cannot take place if the technology to implement ADR remains immature; establishing the technical feasibility of ADR is essential for discussions to proceed in practice.

Based on the above, JAXA has launched the Commercial Removal of Debris Demonstration (CRD2) program to establish ADR as a new business and develop a new market in which the private sector can play an active role. The program has two objectives: to demonstrate ADR technology 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, and JAXA has selected Astroscale Japan (hereafter referred to as Astroscale) as the commercial partner for both phases. This paper provides an overview of the CRD2 program, the scope and results of Phase I, and the progress of activities for the realisation of Phase II.

2 CRD2 PROGRAM

2.1 Inspirations and Ideas Behind the Program

Since the 2000s, NASA's Commercial Crew and Cargo Program Office (C3PO) has initiated a paradigm shift in the previously government-led space program by launching the COTS/CRS program, which involves private sector companies in the development and operation of transportation systems to the ISS, and has achieved significant success [13]. From the perspective of maintaining international competitiveness, we felt it was necessary to introduce this trend into Japan's space development activities. We considered ADR to be an ideal starting point for JAXA to undertake such new initiatives for the following reasons:

- Several private sector companies in Japan were eager to commercialise ADR.
- Although there was no market for ADR yet, there was an expectation that a market would be created in the near future, and private investment in companies aiming to commercialise ADR was active.
- Although ADR was technically unproven, it was considered to have a level of technical difficulty that could be overcome by private sector companies with the support of JAXA.
- The ADR technology demonstration mission had a wide range of potential applications, making it easier for private sector companies to expand their business from ADR to on-orbit services using this demonstration mission as a stepping stone.
- Although there were several examples of ADR technology demonstration missions being considered in the world, few had been executed. If JAXA started at this time, it had a high potential to be a pioneering effort worldwide.

Therefore, inspired by NASA's COTS program, we began the initial study of this program as an attempt to establish a project that incorporates technical development aspects while smoothly promoting the growth of private sector, using ADR as a showcase to design a specific institutional framework. The study was initiated in 2018 by members of the JAXA's cross-departmental study team named Readiness-team for Remove Debris Demonstration.

2.2 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. The 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 one to nine tons in the crowded orbits. Removing such massive debris from its original orbit is a technically challenging and will need the followings:

- RPO for non-cooperative targets
- Capture of non-cooperative targets, and establishment of attitude control in stacked configuration
- 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.

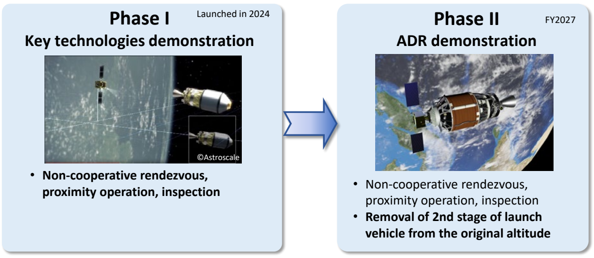

Figure 1. CRD2 program structure

Phase I will demonstrate techniques for approaching and inspecting large space debris that has actually been in orbit for years. This includes everything from launching the rocket to align it with the target orbit, to adjusting the relative phase and orbital plane to perform RPO on the non-cooperative target. In other words, it demonstrates the full-range of RPO technology for non-cooperative targets. The acquisition of detailed images of the target in Phase I will also provide an understanding of the state of the target debris in orbit over many years, significantly reducing the risk in the subsequent Phase II.

In addition to the mission scope of Phase I, Phase II will demonstrate techniques for target capture, establishment of stacked state operations, towing of the target and significant descent of orbital altitude. The images obtained in Phase I will be used to reduce risks, particularly in the capture mechanism and operations.

2.3 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 partner.

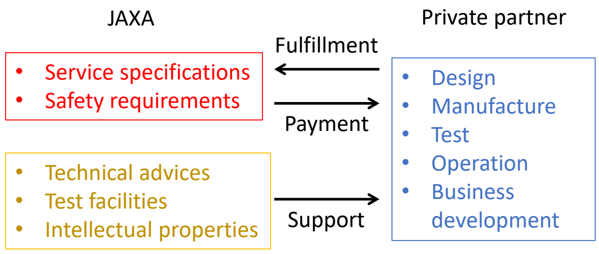

Figure 2. New partnership-type contract

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 partner 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 partner designs, manufactures, and tests a satellite that meets the service specifications and safety requirements. The satellite is then owned and operated by the private partner. In addition to providing services to JAXA, the private partner 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 partner 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 in a mandatory manner, it may be difficult for the private partner 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 partner 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 partner from aspects which enables JAXA to procure services and R&D results and the private partner to realize its own mission, both JAXA and the private partner provide funding for this project.

JAXA also provides strong support to the partner by utilizing its R&D assets. In addition to technical advice 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 partner to implement this novel program.

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

2.4 Target Space Debris Selection

The objective of ADR is to remove two principal categories of large space debris: inactive satellites and rocket upper stages. Effective ADR targets are large debris with a high collision probability. Rocket upper stages, though varied, are generally cylindrical with few large protrusions, making them relatively easy for ADR spacecraft to approach, capture, and tow. In contrast, inactive satellites pose more challenges due to their unique shapes and large protrusions like solar panels. The authors suggest that a practical approach to the technically demanding task of ADR is to build a track record of technological demonstrations and implementations, starting with simpler targets. Therefore, initiating ADR technical demonstrations with the easier-to-capture rocket upper stages is considered advantageous.

- The target space debris for CRD2 was selected based on several key considerations. Essential requirements included:
- It must be a rocket upper stage.
- The debris should be of sufficient size and mass to effectively demonstrate ADR technology.
- The debris must already be in orbit and capable of demonstrating full-range RPO capabilities (the upper stage of the launcher that deployed the ADR demonstration satellite was not considered significant enough, as it would only demonstrate proximity operations, not full-range RPO technology).
- The debris should originate from a Japanese mission (approaching or contacting debris of other countries without permission is undesirable).
- The orbital altitude should be around 600 km (even if debris is generated by contact with the target during RPO, it will not remain in orbit for a long period due to atmospheric drag, thus minimizing the impact on the space environment. This consideration ensures a safer technology demonstration. Additionally, this altitude ensures the target debris remains in orbit by the expected time of Phase II execution).

In addition to these essential requirements, other factors were also considered: the preferred size of the Payload Attach Fitting (PAF) to be captured in Phase II, the availability of images of the final launch configuration, and the suitability of the attitude motion estimated from ground observations. After a comprehensive evaluation, the upper stage of the H-IIA rocket (H-2A R/B, SSC 33500), which launched GOSAT in 2009, was selected. This debris is approximately 11 meters long, 4 meters in diameter, and weighs about 3 tonnes.

3 CRD2 PHASE I PROJECT

Following an open collaborative research, request for information and request for proposal process, Astroscale was selected as the Phase I partner company and the project was initiated in March 2020.

3.1 Service Specifications and Astroscale Missions

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 [14]. The technical scope of the CRD2 Phase I project is the demonstration of non-cooperative RPO technology. As shown in Fig. 3, the missions are divided into "Services for JAXA" and "Astroscale missions" planned and implemented by Astroscale.

Figure 3. CRD2 Phase I mission definition

JAXA's service specifications were established considering the feasibility of the services based on JAXA's technical expertise and the ability to acquire high-quality images and sufficient data to confirm the attitude motion, damage, and surface degradation of long-orbiting debris. More importantly, the service specifications were designed to ensure that the private partner would acquire valuable technologies applicable to a wide range of on-orbit service missions, including ADR. Therefore, a service specification that could demonstrate only proximity operations was intentionally avoided, using the upper stage of the launch vehicle from which the service satellite separated as the target space debris. The target space debris was carefully selected and the service specifications were carefully set so that the demonstration could be a “full-range non-cooperative RPO technology demonstration” that could demonstrate all the technologies required for non-cooperative RPO, including targeted precise launch towards orbital debris, far-field rendezvous capability, and proximity operations capability as shown in Fig. 4.

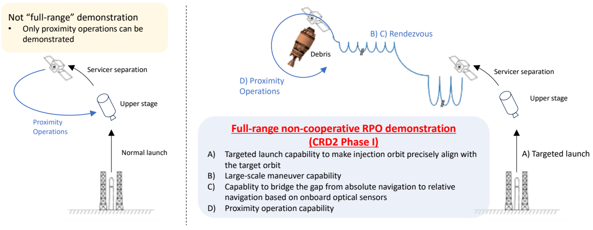

Figure 4 Full-range non-cooperative RPO demonstration concept

The service specifications describe the requirements for four specific services to be provided, as shown in Fig. 5.

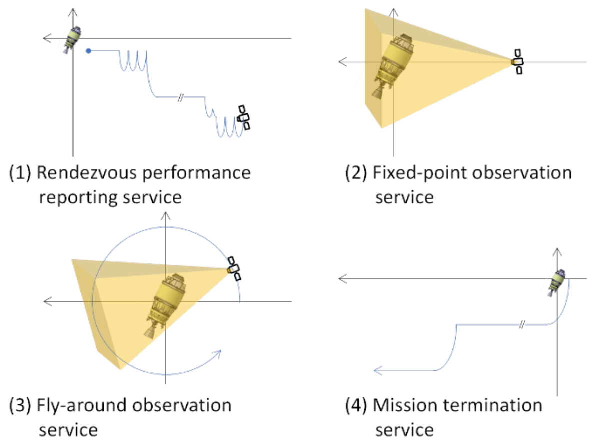

Figure 5. CRD2 Phase I Services for JAXA

The specifications include the following services:

1. Rendezvous performance reporting service: This service provides performance data such as relative orbits, maneuvers, and acquired images during RPO. The aim is to acquire the full-range of non-cooperative RPO technology, from the precise adjustment of the launch parameters with the target to the arrival in proximity of the target.
2. Fixed-point observation service: This service observes the target debris from a fixed point in the orbital coordinate system (LVLH) of the target debris, providing continuous imaging of specified quality and data volume. The aim is to acquire the technology to maintain the relative position to non-cooperative targets, which is essential for the proximity operations of the on-orbit services.
3. Fly-around observation service: This is a service that performs a relative fly-around operation with the target debris as the center and continuously takes images. The aim is to acquire the ability to photograph the entire target to understand its condition and to fly-around it to access specific parts of the target, which is essential for proximity operations in on-orbit services.
4. Mission termination service: This is a service where the demonstration satellite transitions to an orbit that does not collide with the target and has a predicted orbital lifetime of less than 25 years, providing evidence data of this transition.

3.2 Safety Requirements

In the CRD2 program, the document JERG-2-026 Safety Standard for On-orbit Servicing Missions [15] clarifies the safety requirements for the private partner 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. 6. 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 closer approaches, the demonstration satellite comes into the designated approach path without crossing over the path boarder.

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 shall be based on the system safety engineering practices. The private partner should conduct hazard analysis based on their design and operation.

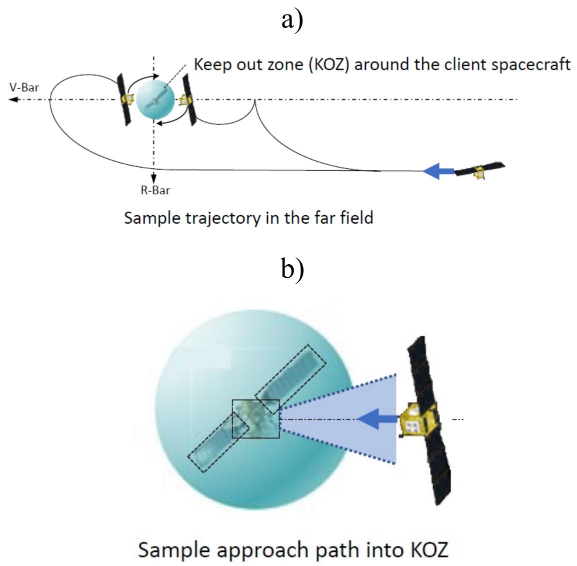

Figure 6. Basic concept of safe rendezvous trajectory

design in JERG-2-026 [15]
(a) far-range rendezvous, b) close-range rendezvous)

3.3 Technical Support from JAXA

Prior to the start of this project, an open collaborative research was carried out with multiple private sector companies as front-loading. In this process, the results of JAXA's non-cooperative RPO technical research at that time [16] were provided and used by the companies as a starting point for the research.

After initiation of the CRD2 project, JAXA has provided technical support to the private partner in three ways: by offering test facilities, by providing intellectual property of research results, and by providing technical advice. An overview is shown in Fig. 7.

When approaching non-cooperative targets, a wide range of information is required, such as their shape, mass properties, surface optical reflection characteristics, and temperature. While it is desirable to collect this information in orbit during operations in the future, for this initial on-orbit demonstration project, this information was collected in advance and used by Astroscale in the design of the satellite. Mitsubishi Heavy Industries, the owner and manufacturer of the H-IIA rocket’s upper stage, cooperated by providing JAXA with this information, along with surface material samples. JAXA subjected these surface material samples to accelerated tests equivalent to 14 years in orbit using the ultraviolet irradiation facility at the Tsukuba Space Center, performed optical measurements, and provided Astroscale with the resulting information on the expected optical reflection characteristics of the target orbital debris.

In order for developers to confidently deploy a highly experimental guidance, navigation and control system into space, it is essential to conduct verification tests that ensure the sensors, onboard computers, and software operate in a highly coordinated manner, faithfully replicating actual orbital conditions. To achieve this verification test within this project, JAXA developed and provided a large-scale motion simulator facility called SATDyn [17] capable of performing closed-loop system verification tests.

In addition, JAXA provided the following useful research output intellectual properties for achieving RPO on non-cooperative targets: an infrared camera image simulator, LiDAR simulated data, an image-based motion estimation and prediction tool, and a database of the forces and torques exerted on target debris by plumes from dedicated chemical thrusters [18,19].

Furthermore, JAXA provided more than 200 technical advice on a wide range of satellite development, mainly based on JAXA's knowledge in the RPO field. For example, JAXA conducted extensive research on angles-only navigation (AON) as a key technology to bridge the gap between absolute navigation and relative navigation with onboard optical sensors, which is a major issue for non-cooperative RPO where relative GPS navigation is not available. The results were provided to the private partner and contributed to ensuring the technical feasibility of this mission [16,20].

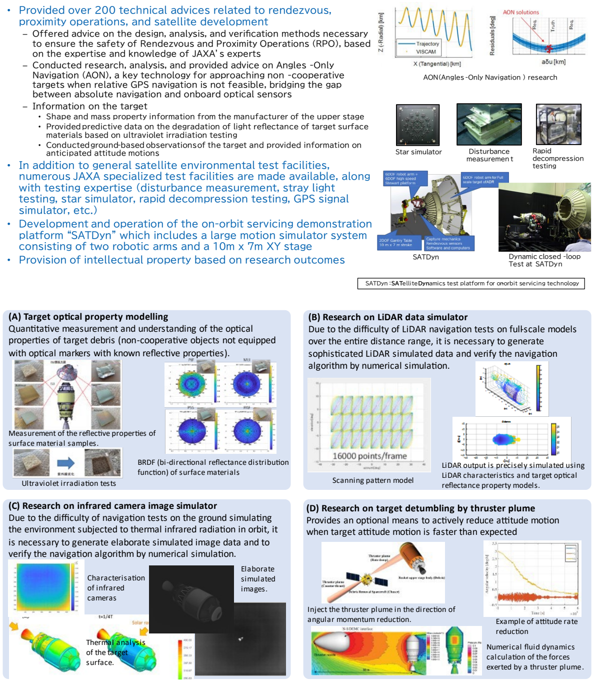

Figure 7. Overview of technical support provided by JAXA

3.4 Legal Aspects of Private Sector Implementation of On-orbit Services

This project was envisaged as the first opportunity for private sector companies to provide on-orbit services in Japan. Therefore, the Cabinet Office of the Japanese Government took this opportunity to issue the "Guidelines on a License to Operate a Spacecraft Performing On-orbit Servicing" [21]. This enabled a legal mechanism to be established whereby the Japanese Government would issue a licence to operate a mission on the basis of an application from a private sector company based on the guidelines. This practice served as a regulatory-process demonstration and promoted experiences both regulator and the industry in terms of national implementation of treaty obligations.

4 OPERATIONAL RESULTS OF THE CRD2 PHASE I

The CRD2 Phase I demonstration satellite, ADRAS-J, was developed, launched, and operated by Astroscale. In this chapter, we report an overview of these activities. [22,23]

4.1 Launch

ADRAS-J, the CRD2 Phase I demonstration satellite shown in Fig. 8, developed and operated by Astroscale, was successfully launched on 18 February 2024 by RocketLab's Electron rocket from a launch pad on New Zealand's Mahia Peninsula. The injection orbit accuracy was excellent, contributing significantly to the saving of the on-board propellant.

Figure 8. ADRAS-J, CRD2 Phase I demonstration satellite developed and operated by Astroscale

4.2 Rendezvous Performance Reporting Service

After the initial checkouts, the ADRAS-J operated by Astroscale started its approach to the debris, and by early April had succeeded in coarsely aligning its orbital altitude and plane with the target. From a distance of several hundred kilometres, relative navigation using the AON was tested, and performance was confirmed to be higher than predicted in the preliminary analysis. In view of the technical novelty of this operation, the Astroscale and JAXA cooperated in a parallel analysis of the same observation data to intercompare the AON results. As a result, the AON was successfully used to bridge the “gap” between absolute navigation and relative navigation using onboard optical sensors, reaching a distance of several hundred metres to the target and successfully acquiring non-cooperative full-range RPO technology from launch to the proximity.

4.3 Fixed-point Observation Service

After that, ADRAS-J made a further approach by relative navigation using the onboard optical sensors, and on 23 May 2024, ADRAS-J reached the HP (Home Position) at 50 m above the V-bar, and successfully performed a fixed-point observation service, that is, it continuously took images for one orbit while maintaining a relative position [24,25]. This confirmed the acquisition of a technique for maintaining relative position in the proximity of the non-cooperative target.

Figure 9. Image of fixed-point observation service, taken on 23 May 2024 [24,25]

The images obtained (shown in Fig. 9) provided valuable information on the attitude movement of the space debris and the condition of the surface material 15 years after launch.

4.4 Fly-around Observation Service

In on-orbit service, the spacecraft need to fly-around safely to access a specific part of the target and perform some work on it. To achieve this for non-cooperative targets, it is necessary to overcome the technical problems of relative navigation, such as shape and surface optical reflectance errors for which prior information is not reliable, the occasional changes in the apparent visible shape of the target as it performs fly-around, and the influence of earth-reflected light that is a disturbance to the navigation sensors (the so-called earth background problem of optical navigation), while also achieving highly accurate relative 6-DOF control needs to be achieved.

On 15 and 16 July 2024, ADRAS-J successfully conducted fly-around observations (Fig. 10) [26,27], in which it circled while keeping its camera pointed in the direction of the target and took continuous images and acquired the technology to understand the overall situation of the non-cooperative target and the ability to perform fly-around to access a specific part of the target.

Figure 10. Images of fly-around observation service, taken on 16 July 2024 [26,27]

4.5 Astroscale Mission

The “Astroscale mission” was an ambitious goal independently designed and operated by Astroscale, in addition to the baseline services for JAXA. The objective was to demonstrate highly precise and complex close-range RPO capabilities by advancing to the Capture Initiation Point (CIP), where future debris removal missions start robotic capture operations.

When ADRAS-J was 50 meters behind the upper stage the spacecraft reduced the gap in a straight-line approach then maneuvered to approximately 15 meters below the Payload Attach Fitting (PAF) - the planned capture point for the follow-on CRD2 Phase-II ADRAS-J2 mission - aligning the spacecraft’s relative speed, distance, and attitude. ADRAS-J successfully maintained this position until an autonomous abort was triggered by the onboard collision avoidance system due to an unexpected relative attitude anomaly with the upper stage. The spacecraft safely maneuvered away from the debris as designed before reaching the CIP. While ADRAS-J did not reach its intended final distance, the mission demonstrated the robustness of its safety measures during simulated capture operations. [28,29]

4.6 Mission Termination Service

After the Astroscale mission was executed, ADRAS-J transitioned to an orbit that does not collide with the target and has a predicted orbital lifetime of less than 25 years, providing evidence data of the transition.

As a result, all four services for JAXA were completed, and the success of all missions planned for the CRD2 Phase I project was confirmed.

4.7 World-first Achievements in ADRAS-J Operations to Date

Several demonstration missions of non-cooperative RPO technology have been carried out in the world in the past, but these were mostly military missions of individual countries, and detailed implementation results have not been made public. Therefore, it is not easy to confirm what can be called a world first. Based on information in the press, it is highly likely that China's demonstration satellites have experience in non-cooperative RPO, capture and towing, etc., but the specific details of their implementation are not known. Based on the extent to which the content of the implementation can be confirmed through the investigation of public information, the authors assess that ADRAS-J's operational achievements to date have elements that can be regarded as world firsts in the following aspects [30 - 34]:

- Realisation of full-range non-cooperative RPO (XSS-10 is an RPO for the upper stage of the launch vehicle that launched itself; XSS-11 has announced plans for a full-range non-cooperative RPO, but the public results of the operations are limited to successful observation and photography of the upper stage of the launch vehicle that launched itself; no public information on the results of full-range non-cooperative RPOs.)
- Realisation of a complete, full orbital revolution fly-around with non-cooperative targets (XSS-10 has performed partial arc-around operations, but

not full-around operations; XSS-11 has no publicly available operational record).

- Achieving a proximity of up to 15 meters to orbital debris and capturing images of it (The confirmed achieved distance of XSS-11 is approximately 100 meters, XSS-11 has publicly reported a proximity achievement of 1500 feet (457 meters)).

Although not from a technical point of view, the acquisition of full-range non-cooperative RPO technology by a private partner, rather than by a space agency or the military, is unprecedented and can be regarded as a remarkable feature of the project results.

5 CRD2 PHASE II PROJECT

5.1 Project Overview

An important requirement for the debris removal technologies to be demonstrated in the CRD2 program is their economic viability, in particular their ability to remove debris at low cost to ensure financial sustainability. In this context, an analysis of future architectures and operational concepts for ADR has been carried out, considering the aspect of removal cost per piece of debris [35]. The results confirm the superiority of the shuttle mission concept of multiple debris removal by a single ADR satellite without controlled re-entry, both in terms of cost effectiveness and feasibility for a specific target scenario.

As shown in the results of Kawamoto's study [12], it is advantageous to start ADR as early as possible to improve the orbital environment; setting the ADR hurdle too high would be counterproductive as it would delay the start of ADR. In this ADR concept, the on-orbit environment is improved before and after the ADR execution, while the risk to the ground remains unchanged. Therefore, we consider this concept to be a reasonable choice as an initial target ADR mission scenario. This has led to the establishment of the CRD2 Phase II technical demonstration scenario, which focuses on rendezvous, close proximity operations, capture, towing and release without controlled re-entry, as the basis for defining the Phase II service requirements.

Phase II is the mission scope for the total on-orbit demonstration of the ADR technology by capturing and towing debris in addition to the implementation of Phase I. In the capture phase, the technology required for on-orbit services will be acquired to capture and rigidly mate with non-cooperative targets, and to establish stable operations in the stacked configuration in terms of attitude, power, heat, etc. In the towing phase, technology will be acquired for the ability to transport large objects to their destinations through large orbital transfer. These acquired technologies can be used for a wide range of on-orbit servicing missions and space logistics operations. The service specifications describe the requirements for the specific services to be provided, as shown in Fig. 12.

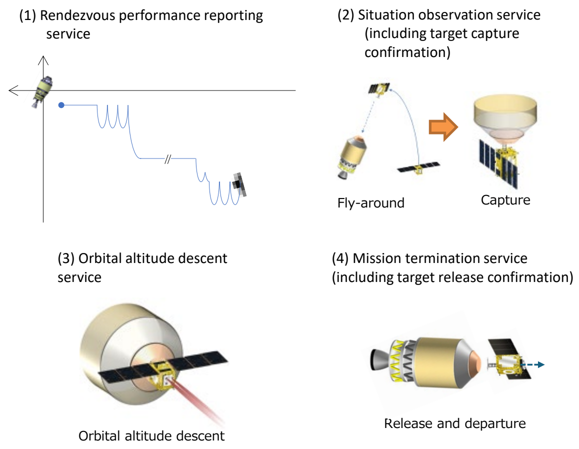

Figure 11 CRD2 Phase II Services for JAXA

5.2 Current Status and Prospects of the Project

After basic research at JAXA, a front-loading study with private sector companies, and the request for proposal process, Astroscale was selected as the partner company following Phase I, and the contract was signed in August 2024. In September of the same year, the project organisation was established within JAXA, and the project is now progressing steadily in collaboration between JAXA and Astroscale, with the aim of launching a demonstration satellite in FY2027.

The service specifications for this project are designed to provide a comprehensive technical demonstration for the “removal of large debris in crowded orbits” a process believed to enhance the space environment. Specifically, the project aims to advance the technical and business feasibility of ADR while stimulating global discussions on its implementation. This will be achieved through the actual capture and de-orbiting of large space debris by towing, in collaboration with the private company.

6 CONCLUSIONS

The CRD2 program represents a new and ambitious initiative for JAXA, with two primary objectives: first, to acquire ADR technology to address the increasingly critical issue of space debris, and second, to support the commercial activities of Japanese companies. The program is structured in two phases, with JAXA providing ongoing technical support throughout the process to ensure that it is conducted within an acceptable risk threshold.

The results obtained from Phase I of the project are of significant value, both in terms of the challenge of designing and implementing a novel framework, and in terms of the demonstration and acquisition of comprehensive full-range non-cooperative RPO technology by the private partner.

The Phase II project is already underway, with the demonstration of large space debris removal being conducted in collaboration with the private sector to realize cost-effective ADR solutions that will play a critical role in remediating the future space environment. It is anticipated that this will enhance the feasibility of ADR from both technological and business perspectives, contributing to the sustainable utilization of outer space.

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8 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. In Proc. 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. Somma, G.L. et al. (2016). Adaptive remediation of the space debris environment using feedback control. In Proc. 67th International Astronautical Congress, IAC-16-A6.IP.3, Guadalajara, Mexico.
6. Somma, G.L., Lewis, H. & Colombo, C. (2017). Increasing ADR effectiveness via an altitude-shell-dependent removal approach. In Proc. 68th International Astronautical Congress, IAC-17 A (Vol. 6).
7. 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.
8. Utzmann, J., Oswald, M., Stabroth, S., Voigt, P. & Retat, I. (2012). Ranking and characterization of heavy debris for active removal. In Proc. 63rd International Astronautical Congress, IAC-12-A6.2.8, Naples, Italy.
9. Rossi, A., Valsecchi, G.B. & Alessi, E.M. (2015). The criticality of spacecraft index. Advances in Space Research 56(3), 449-460.
10. Letizia, F., Colombo, C., Lewis, H. & Krag, H. (2017). Extending the ECOB space debris index with fragmentation risk estimation. In Proc. 7th European Conference on Space Debris, Darmstadt, Germany.
11. McKnight, D. et al. (2021). Identifying the 50 statistically-most-concerning derelict objects in LEO. Acta Astronautica 181, 282-291.
12. Kawamoto, S., Nagaoka, N., Kitagawa, Y., Harada, R. & Hanada, T. (2022). Considerations on the lists of the top 50 debris removal targets. Journal of Space Safety Engineering 9(3), 455-463.
13. NASA. (2014). Commercial Orbital Transportation Services: A New Era in Spaceflight, NASA/SP-2014-617.
14. Japan Aerospace Exploration Agency. (2019). JX-ESPC-101897 CRD2 (phase-I) service specification.
15. Japan Aerospace Exploration Agency. (2020). JERG-2-026 Safety Standard for On-orbit Servicing Missions.
16. Yamamoto, T., Murakami, N., Nakajima, Y. & Yamanaka, K. (2014). Navigation and trajectory design for Japanese active debris removal mission. In 24th International Symposium on Space Flight Dynamics (pp. 1-29), Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland, USA.
17. Okamoto, H. & Kato, H. (2022). The Development of the Hybrid Dynamics Simulation System for Rendezvous and Docking: SATDyn. In 2022 IEEE Aerospace Conference (AERO) (pp. 1-9), IEEE.
18. Okada, N., Hidaka, M., Negishi, H., Nakajima, Y., Sasaki, T. & Yamamoto, T. (2022). Infrared image generator of artificial space object for verifying relative navigation in rendezvous. In 2022 IEEE Aerospace Conference (AERO) (pp. 01-07), IEEE.
19. Nakajima, Y., Tani, H., Yamamoto, T., Murakami, N., Mitani, S. & Yamanaka, K. (2018). Contactless space debris detumbling: a database approach based on computational fluid dynamics. Journal of Guidance, Control, and Dynamics 41(9), 1906-1918.
20. Hidaka, M., Nakamura, R. & Yamamoto, T. (2022). Covariance-based Observability Analysis Method For Angles Only Rendezvous Navigation. In Proc. 2022 AAS/AIAA Astrodynamics Specialist Conference, AAS 22-558, Charlotte, North Carolina, August 7-11 2022.
21. National Space Policy Secretariat, Cabinet Office, Japan. (2021). Guidelines on a License to Operate a Spacecraft Performing On-Orbit Servicing, https://www8.cao.go.jp/space/english/activity/application.html, (accessed 16.09.2024).
22. Atarashi, E., Inoue, H., & Fujii, G., (2024). Ultra-

close RPO on-orbit demonstration of ADRAS-J Program. In Proc. 75th International Astronautical Congress, IAC-24,A6,6,9,x87881, Milan, Italy.
23. Gutierrez-Ramona, R., Lidtke, A., Charls, K., Sellamuthu, H., Alder, A., Steindorf, L., Seto, Y., Chant, T., & Inoue, H., (2024). Hitting a moving target – ADRAS-J launch targeting to rendezvous with a derelict resident space object. In Proc. 75th International Astronautical Congress, IAC–24–A6,IP,106,x87269, Milan, Italy.
24. JAXA press release. (2024). CRD2 Phase I / ADRAS-J update: "fixed-point observation" images of space debris have been released, https://global.jaxa.jp/press/2024/06/20240614-2_e.html, (accessed 16.09.2024).
25. Astroscale press release. (2024). Historic Approach to Space Debris: Astroscale's ADRAS-J Closes in by 50 Meters, https://astroscale.com/historic-approach-to-space-debris-astroscales-adras-j-closes-in-by-50-meters/, (accessed 16.09.2024).
26. JAXA press release. (2024). CRD2 Phase I / ADRAS-J Update: Fly-Around Observation Images of Space Debris Released, https://global.jaxa.jp/press/2024/07/20240730-1_e.html, (accessed 16.09.2024).
27. Astroscale press release. (2024). Astroscale's ADRAS-J Continues to Make History: Successfully Demonstrates Fly-Around Observations of Space Debris, https://astroscale.com/astroscales-adras-j-continues-to-make-history-successfully-demonstrates-fly-around-observations-of-space-debris/, (accessed 16.09.2024).
28. Astroscale press release. (2024). Astroscale's ADRAS-J Achieves Historic 15-Meter Approach to Space Debris, https://astroscale.com/astroscales-adras-j-achieves-historic-15-meter-approach-to-space-debris/, (accessed 24.03.2025).
29. Commercial Removal of Debris Demonstration Phase I, ADRAS-J Mission Achievement Briefing., (2024), https://www.youtube.com/live/S8bkr_-J1Mk?si=iWg1MlzfQSPPxR4x, (Japanese, accessed 24.03.2025).
30. Arney, D. et al. (2023). In-space Servicing, Assembly, and Manufacturing (ISAM) State of Play-2023 Edition., Consortium for Space Mobility and ISAM Capabilities (COSMIC) Kickoff.
31. Davis, T. et al. (2003). XSS-10 Micro-Satellite Flight Demonstration Program., Small Satellite Conference, SSC03-IV-1.
32. Woffinden, D.C. & Geller, D.K. (2007). Navigating the road to autonomous orbital rendezvous. Journal of Spacecraft and Rockets 44(4), 898-909.
33. Weeden, B. (2023). Chinese Military and Intelligence Rendezvous and Proximity Operations., Secure World Foundation.
34. Burke, K. (2024). PLA On-Orbit Satellite Logistics., China Aerospace Studies Institute.
35. Nakamura, R., Okamoto, H. & Yamamoto, T. (2023). Study on Technology Demonstration Scenarios of CRD2 Phase2 for Sustainable Debris Removal. In Proc. Second International Orbital Debris Conference, #6129.