CURRENT STATUS OF RESEARCH AND DEVELOPMENT ON ACTIVE DEBRIS REMOVAL AT JAXA

Satomi Kawamoto[(1)], Yasushi Ohkawa[(1)], Hiroyuki Okamoto[(1)], Kentaroh Iki[(1)], Teppei Okumura[(1)], Yasuhiro Katayama[(1)], Masato Hayashi[(1)], Yuta Horikawa[(2)], Hiroki Kato[(2)], Naomi Murakami[(2)], Toru Yamamoto[(2)], Koichi Inoue[(2)]

[(1)] JAXA, 7-44-1, Jindajji-Higashi-Machi, Chofu, Tokyo, Japan, kawamoto.satomi@jaxa.jp
[(2)] JAXA, 2-1-1, Sengen, Tsukuba, Ibaraki, Japan.

ABSTRACT

The Japan Aerospace Exploration Agency (JAXA) is investigating a cost-effective active debris removal (ADR) system to remove large debris objects such as rocket bodies in crowded orbits. A small satellite to rendezvous, capture and deorbit debris using an electrodynamic tether (EDT) has been studied. As the first step toward realizing a debris removal system, a flight experiment on using EDT as a key technology for cost-effective ADR was conducted in 2017, followed by a study on removal of the upper stage of a Japanese rocket by a small satellite as the next step. This paper describes the required technologies, scenario and roadmap for realizing ADR, such as non-cooperative rendezvous and motion estimation using optical cameras, and the attachment of the end of the tether using an extensible boom mechanism to the payload attachment fitting of the rocket's upper stage, and deorbiting using EDT. It also introduces the current status of research and development regarding these key technologies and system studies, such as the results of numerical simulations and on-ground experiments.

1 INTRODUCTION

Space debris is becoming a critical problem for sustainable space development and utilization activity. The Research Team for Space Debris Comprehensive Measures of the Japan Aerospace Exploration Agency (JAXA) is holistically conducting research and development regarding space debris. There are various sizes of debris ranging from small (less than 1 mm) to large intact debris (larger than a few meters), such as defunct rocket bodies or spacecraft, and countermeasures for each form can be considered, such as collision avoidance maneuvers (CAM), protection by shielding, mitigation, and remediation. Of these countermeasures, the most effective means should be taken, such as CAM for debris that can be tracked from the ground, protection against small-size debris, but there is also critical size debris that cannot be efficiently avoided or protected against, ranging from millimeters to a few centimeters. Such critical debris can cause critical damage to spacecraft upon impact, and require too much cost in trying to track it from the ground or in providing shielding protection. Thus, preventing the generation of critical size debris to an acceptable level is a more efficient way to suppress the total cost against space debris, including launching replacement spacecraft in case of damage by critical size debris, operation for CAM, building more ground facilities to achieve CAM for smaller debris, and protective design against larger debris. These costs are increasing annually. Post mission disposal (PMD) of spacecraft entails a temporary cost, but is accepted worldwide as a necessary means of preventing further degradation of the space environment. The mutual collisions between debris that have already exist in orbit are predicted and the quantity of debris will continue to increase even with the good compliance of commonly adopted mitigation measures, and remediation measures, such as active debris removal (ADR), should be considered to stabilize the future LEO environment[1,2]. The removal of small debris is inefficient given its widespread dispersal in the vast space, and the removal of large debris—the source of numerous small debris in case of fragmentation—is important for preventing future cost increases. An evolutionary debris model showed that five to ten debris objects should be removed every year in order to stabilize the environment. If the cost for ADR is too high, it is less expensive to launch replacement spacecraft in case of damage, and ADR will not be realized. Should ADR be deemed necessary in the future, however, it would be too late or too expensive to start ADR. Thus, cost-effective ADR is necessary to start ADR soon. Reference [3] estimated the debris-related cost and showed that ADR is inappropriate if the average ADR cost is 140 M Euro, as the ADR cost continues to be more expensive than the damage cost in the future. If the ADR cost is less expensive the break-even point between the ADR cost and damage cost in the future comes earlier, making ADR acceptable just like PMD. We should note that cost estimation is very difficult because we cannot predict the future expansion of space development, such as the recently proposed mega-constellation system. The prediction is uncertain and it would be too late should ADR be deemed necessary not only because it takes a long time to develop ADR technologies and related space

Proc. 7th European Conference on Space Debris, Darmstadt, Germany, 18–21 April 2017, published by the ESA Space Debris Office
Ed. T. Flohrer & F. Schmitz, (http://spacedebris2017.sdo.esoc.esa.int, June 2017)

law but also because smaller debris would be difficult to remove after being generated. Furthermore, the increased reliability of PMD requires additional cost and ADR could help to alleviate the severe requirement of spacecraft reliability. Once ADR technologies become both technologically feasible and economically viable, discussions about the responsibility for debris remaining in orbit will advance; currently, no blame is assessed for leaving debris on orbit because there is no technology to remove it. Therefore, cost-effective ADR is necessary for sustainable space development.

JAXA has been studying cost-effective ADR. This paper describes the current status of related research and development.

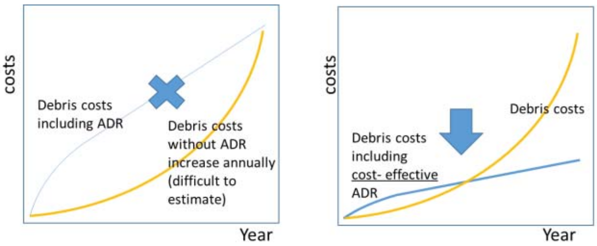

Figure 1. Debris costs increase annually. If the ADR cost is too expensive, the break-even point between the ADR cost and debris cost will be in the distant future (left). If the ADR cost is not so expensive, the break-even point will be in the near future, similar to the cost for PMD, which is widely accepted today.

2 TARGET OF REMOVAL AND REQUIRED TECHNOLOGIES

We set the target of removal as large intact objects in crowded LEO regions which have a high probability of collisions. GEO is also congested and the burdens of CAM should be alleviated by ADR, but urgent priorities are given to LEO. There are some crowded regions such as Sun-Synchronous Orbit or a specific inclination such as 74 deg. or 83 deg. These debris objects are too heavy to remove by lasers or sweepers using current technologies at acceptable cost, and thus require that a removal satellite be launched into the crowded orbit. The upper stages of rockets and satellites are types of target debris, and upper stage debris is a suitable target both technologically and non-technologically. First of all, unlike some satellites, upper stages do not possess such appendages as solar paddles that pose a collision risk in proximity operations. Their axisymmetric shape means that their attitude motions are likely to be simple with no complicated tumbling. Some studies have shown that rotational motions can be stopped due to the interaction between their metal bodies and the geomagnetic field. The attitude of a Japanese H-IIA rocket body observed by German TIRA radar in 2006 was almost stable with gravity gradient torque. The light curve observations using a ground optical telescope also showed that some rocket bodies have stable attitude motion, while some objects exhibit frequent changes in the light, indicating their rotation. In addition to these technological points, it is also suitable from a non-technological point of view: design details of the upper stages of rockets are less confidential than those of satellites.

Target objects requiring removal are studied using evolutionary debris models. Many studies have concluded that debris objects having high mass [kg] multiplied by collision probability should be targets, but sometimes debris objects at a lower altitude can be selected with this index. If the target debris object is in a lower orbit, the fragments will soon re-enter the Earth's atmosphere, even in case of collisions. Thus, the parent objects that may cause many fragments in the future are selected as targets [4].

Figure 2 shows the required technologies for removing rocket bodies in a crowded orbit (at an altitude of 800-1000 km). The targets are non-cooperative, uncontrolled objects that possess no marker or reflector for rendezvous, or a handle to capture. And deorbit requires large dV. There are various types of debris with different shapes or attitude motions, and we propose to start developing ADR technologies for less challenging targets at first, because a general-purpose capture mechanism often becomes costly. We focus on less challenging cases with almost stable attitude motion with known geometries to step out for ADR, and will expand the target range in the future to include satellite debris or rotating debris (*Figure 3*) [5]. We also propose the use of a small removal satellite, as a small size is important to lower the cost including launch, and it has less impact on the environment even in case of failure. Given the possibility of colliding with critical size debris in crowded orbital regions, another removal satellite should be inserted into orbit to try again in case of such collision. In that sense, the electrodynamic tether (EDT) is promising since it enables a small satellite to achieve ADR, as will be described in a later section.

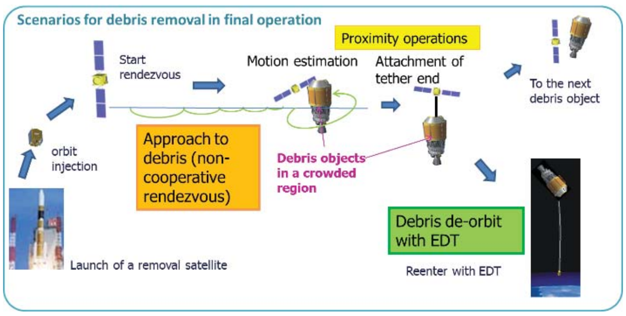

Figure 2. Scenarios for debris removal in final operation.

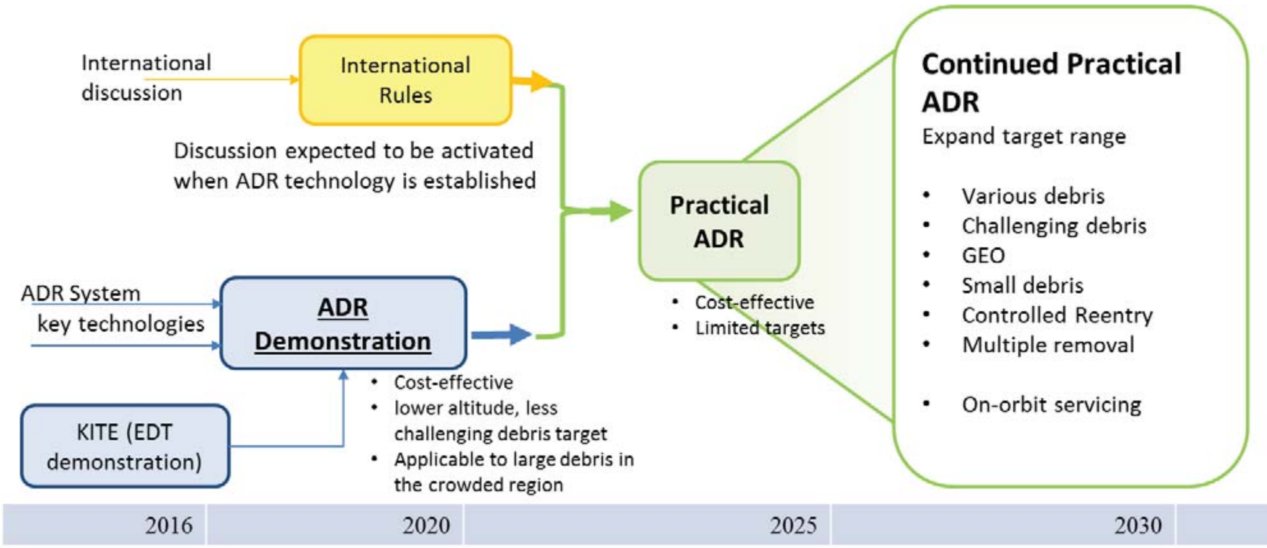

Figure 3. The roadmap of ADR (demonstration step is now being re-examined).

3 CURRENT STATUS OF EACH TECHNOLOGY

This section describes each technology for ADR and its current status at JAXA.

3.1 Non-cooperative rendezvous

A rough estimate of a debris position can be obtained from the observed orbits of debris objects published as Two Line Elements (TLE). However, these data contain observation and propagation errors, and the positional accuracy is a few km in LEO. A removal satellite must therefore use sensing within the vicinity of the target debris to avoid colliding with it. There is much experience with cooperative rendezvous docking, but rendezvousing with debris is more difficult because debris objects are non-cooperative and do not possess any navigation aids such as markers or laser reflectors. Navigation sensors applicable to non-cooperative targets are being investigated, and detectability analysis models are being developed. The optical camera and the infrared camera are selected as the nominal sensor combination, and LIDAR is considered optional. The navigation sensor usage matrix has also been designed [6].

The target object located within tens of km is expected to be observed by using cameras, but it is observed as a point in the distance. Thus a navigation using only the direction information is studied. This is called Angles-Only Navigation (AON). When the removal spacecraft comes within a few kilometers of the target object, the target object can be observed at a multi-pixel resolution, and the primary navigation method is switched to Model Matching Navigation (MMN), a model based tracking algorithm to provide relative position information. The navigation filter design is studied and rendezvous simulations are carried out to examine the navigation and trajectory design (*Figure 4*). Linear Covariance Analysis (LCA) were performed for various simulation and it is shown that investigating of the trajectory dispersions from LCA would clarify the requirements for relative navigation sensors/system. Passive abort safety for avoiding collisions with debris in case of failure, is also being considered (*Figure 5*) [7].

3.2 Proximity operations

After the removal satellite comes to close to the debris, it must apply to thrust to the debris object for deorbiting. It can push, pull through a tether, or irradiate an ion-beam or laser, and the requirement for capture depends on how to apply thrust. If the debris object is pulled, connecting points are not limited, but torque and the center of mass

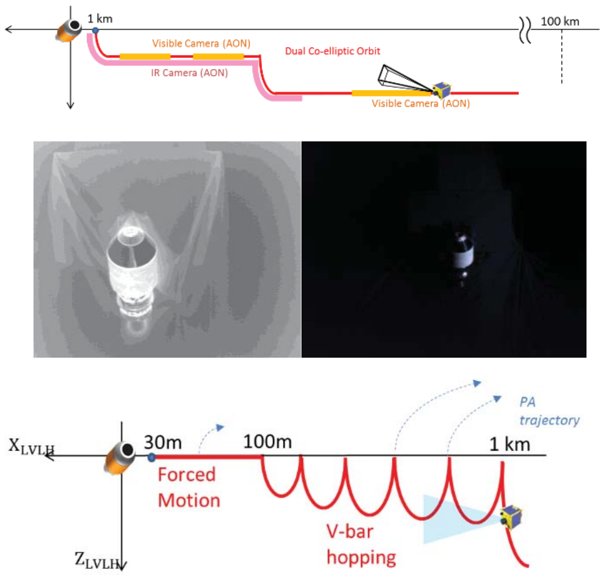

Figure 4. Rendezvous sequence.

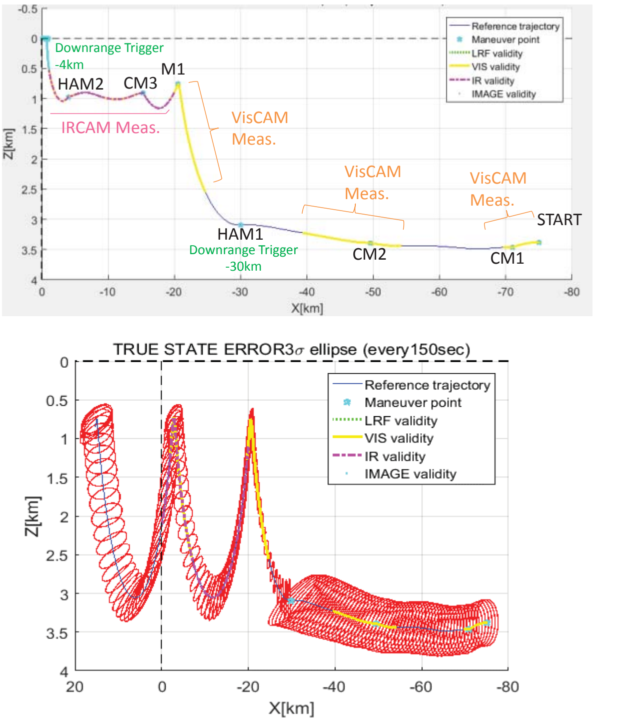

Figure 5. Reference trajectory (top) and the investigation of passive abort safety (bottom).

should be controlled in case of pushing it. It also requires a rigid and firm connection. We studied the application of thrust using a tether at first because it is less challenging, as well as estimating motion for attaching the end of the tether end.

Since the attitude of debris objects is not controlled, the relative attitude and relative position of the debris object should be measured in order to attach a propulsion system to deorbit it. Since the target is assumed to be a non-cooperative target without markers or reflectors, it is proposed that such quantities be measured or estimated by using passive imaging. However, the on-orbit visual environment has two characteristics that make image processing difficult: collimated, intense sunlight, and no diffuse light source other than the albedo of Earth. This results in very high image contrast. At JAXA, small model rocket bodies are set in an optical simulator in order to simulate the images taken by optical cameras in the orbital environment (*Figure 6*) In the optical simulator, a light to simulate solar light and a screen to simulate Earth in the background are set in a dark room, in order to evaluate the measurement accuracy of the relative motion of a non-cooperative target when the direction of light changes momentarily. An algorithm for estimating the motion (relative attitude and relative position) of an object has been studied.

There are many ideas for capture such as a robot arm, net, harpoon, and others. We are studying the capture for the less challenging target, and a simple boom mechanism for the upper stages of rockets is being studied [8]. Many

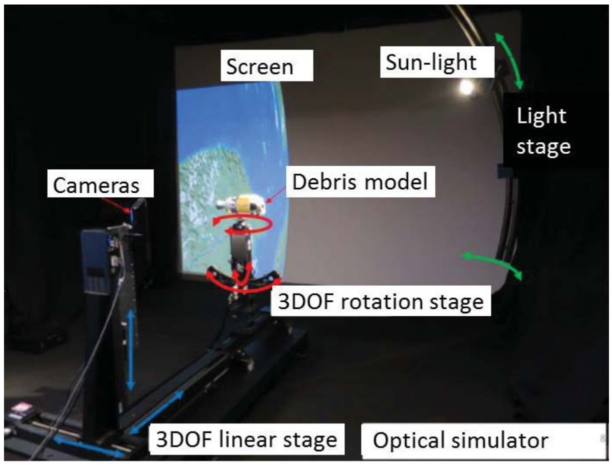

Figure 6. Optical simulator to simulate optical condition on orbit.

upper stages have a payload attachment fitting (PAF) to mount payload. An extensible boom will be inserted into the large hall of PAF, and spread inside for hooking (*Figure 7*). This method requires less accurate relative position and attitude. PAF-Tracking Navigation (PTN) is used to estimate relative position and relative attitude with respect to the surface of the PAF.

Another candidate is a "puncher" (similar to a harpoon) that drives the tip of a harpoon through the wall of the debris object. The harpoon will be ejected from a distance, while the puncher will be ejected by touching the wall, so as to decrease its reaction force and attitude accuracy requirement [9]. We are also studying a stretching gripper to capture both PAF and the nozzle of a rocket's upper stage [10, 11]. The stretching gripper has the V-shaped tips, which enables to grasp the target robustly even in the presence of position error. The impedance control for a free-flying robot to adapt the gripper position was proposed and verified experimentally using an air-floating system with a realistic robot and a target (*Figure 8*).

3.3 Deorbit

For cost-effective ADR, deorbit using EDT is being studied. When a tether is deployed in orbit, it is vertically stabilized by gravity gradient force. Electromotive force

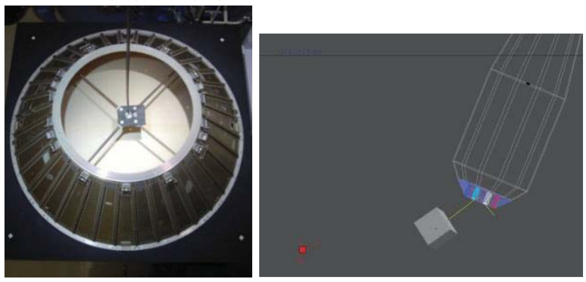

Figure 7. Extensible boom capturing the PAF of rocket upper stage.

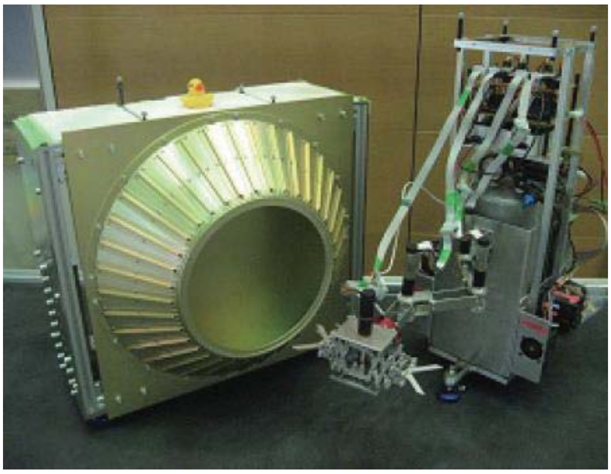

Figure 8. Air-floating target (left) and a robot with stretching gripper (right).

is set up within a conductive tether as it moves through the geomagnetic field in its orbit around Earth. If a cathode at the end of the tether (where electric potential is low) emits electrons, the electrons are collected from the ambient plasma by the other end of the tether (i.e., on the side with higher electric potential) when the tether is bare (i.e., uninsulated). The electric current flows through the tether by closing the circuit via the ambient plasma. The tether then generates a Lorentz force due to the interaction between the current and the geomagnetic field (*Figure 9*). Therefore, EDT systems can provide deceleration without the need for a propellant. Previous studies showed that debris objects that should be removed from crowded orbits can re-enter the Earth's atmosphere within one year with a 10-km EDT [12]. The Lorentz force is small enough and no thrust vector control is required throughout the deorbiting phase. Hence, the tether can be attached anywhere onto a debris object. Thus, the operation is comparatively less challenging than fixing a conventional thruster to the target, which requires it to be fixed to strong points and in the right direction. If a bare tether is used for collecting electrons directly from the plasma, and Field Emission Cathodes (FEC) are used, no propellant is required for deorbiting.

The tethered tug concept is also being studied. We can use any propulsion system other than EDT, such as electric propulsion or chemical propulsion. In case large thrust is applied through the tether, the tether should be deployed horizontally to tow the debris. However, gravity gradient torque stabilizes the tether's vertical direction, while a horizontal tether is unstable for a long time. Thus, a vertically deployed tether will be used to apply thrust at a proper timing to prevent unstable tether motion such as tumbling. A properly timed thrust can control the libration of tether for stable operation. Controlled re-entry through a tether is also being studied. However, this controlled re-entry by tethered tug requires not only a lot of fuel for re-entry but also additional intensity for the capture point; therefore, we consider that controlled re-entry will be achieved in the future [13].

4 KITE Experiment

4.1 Objectives of KITE

A demonstration of EDT using the H-II Transfer Vehicle (HTV, or "Kounotori") called the Kounotori Integrated Tether Experiment (KITE) was planned [14]. The objective of the KITE experiment is to demonstrate the EDT system, deploy a bare tether on orbit, and drive electric current by emitting electrons from FEC (*Figure 9*). An end mass where a 700-m tether is installed will be ejected from the HTV. The tether deployment dynamics are measured by a rendezvous radar onboard the HTV that is used to rendezvous with the ISS. Only reflectors on the end mass are needed for measuring its relative position; that is, no electronic devices are required. A maximum current of 10 mA flowing through the tether was planned. HTV thrusters were planned to be used to suppress the tether libration.

4.2 Results of KITE

HTV6 was launched in December 2016, and after it detached from the ISS, the KITE experiment was started. The tether should have been deployed on Jan. 2017, but the end mass could not be ejected from the HTV. The most possible cause of failure is considered that one of four actuators for fixing the end mass did not work. The investigation into the cause of the tether not deploying is ongoing, although it may not be used for the case of debris removal, as the tether will be deployed from a debris object after its end is attached to the debris. Although on-orbit tether deployment could not be achieved, the technology level of EDT was advanced by analysis and ground tests during development phases, such as manufacturing and winding of bare tether, and tether dynamics for stable operation and control.

FEC was conversely operated without critical trouble throughout the one-week experiment. Electron emission characteristics to the ambient space plasma was obtained

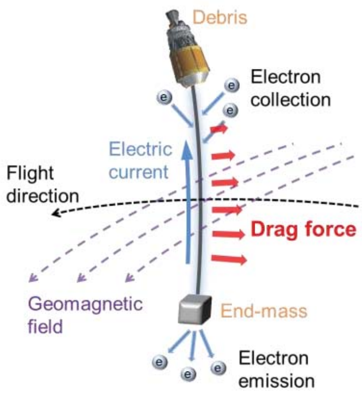

Figure 9. The principle of EDT

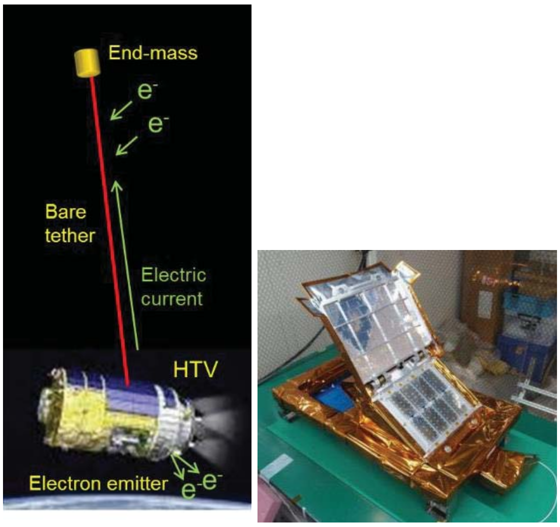

Figure 10. KITE mission (left) and FEC (right).

even though the tether was not deployed as positive parts of the HTV collected electrons from the plasma. Electron emission ability was better than expected by the ground experiment. *Figure 11* shows a comparison of electron emission characteristics between on-orbit and the ground experiment. In this figure, emission current is plotted against plasma (or anode) potential with reference to FEC potential. FEC was operated in a dense Atomic Oxygen (AO) environment compared with the environment where ADR will be performed in the future; therefore, it was operated under an accelerated test condition. It was also shown by a potential monitor [15] that the potential of the HTV can be controlled using FEC.

The next demonstration step is now being re-examined.

4.3 Small satellite system and other studies

System studies are also being conducted. We investigated the feasibility of an ADR mission using a small satellite weighing around 200 kg and about 1 m in length which could be launched as part of a dual launch, or as clusters. The demonstration using H-IIA rocket's upper stage as a target was investigated. If the satellite is launched into near orbit from the already existing H-IIA rocket's upper stage, the removal satellite can wait for several months to arrive in the orbit of the target by utilizing nodal regression of the orbit. *Figure 12* shows one of the concept of the removal satellites. The removal satellite attaches one end of the tether to the debris object, and then deploys the tether from an onboard reel with its thrusters. The removal satellite functions as the end mass of the tether and deorbits with the debris. Trade-off of various ADR options and parameters (architecture, spacecraft size, de-orbit propulsion type, etc...) in terms of cost needed to remove a massive debris are also conducted [16]. For the removal of debris objects in Geo-Synchronized Orbit (GEO), ion beam irradiation is studied [17].

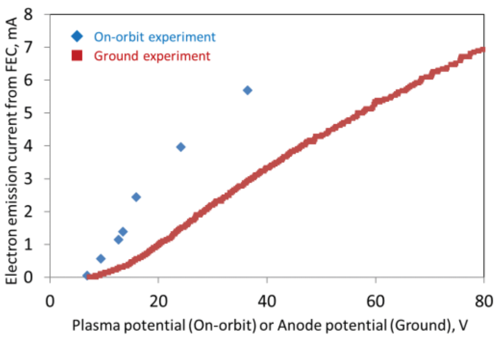

Figure 11. Electron emission characteristics of on-orbit and the ground experiment.

5 CONCLUSION

The paper introduced the current status of research and development regarding ADR at JAXA. JAXA has been studying cost-effective ADR using a small satellite and some key technologies such as non-cooperative rendezvous, motion estimation, capture, and deorbit by EDT. As the first step toward realizing a debris removal system, a flight experiment on using EDT was conducted in 2017, and FEC was operated without critical trouble, although the tether was not deployed. Electron emission ability was better than expected by the ground experiment. Removal of the upper stage of a Japanese rocket by a small satellite is being studied as the next step demonstration toward the realization of ADR.

6 REFERENCES

1. Inter-Agency Space Debris Coordination Committee (IADC) Working Group 2, (2012). Stability of the Future LEO Environment, http://www.iadc-online.org/Documents/IADC-2012-08,%20Rev%201,%20Stability%20of%20Future%20LEO%20Environment.pdf

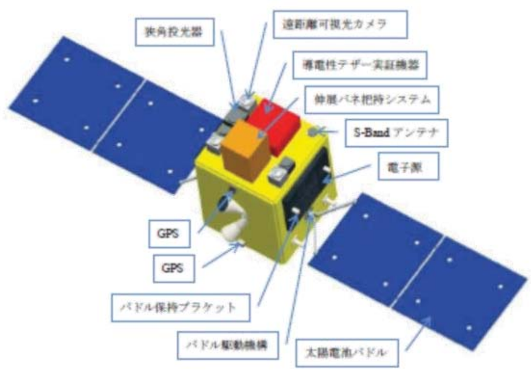

Figure 12. The concept of the removal satellite.

2. Liou, J.-C. (2011). An active debris removal parametric study for LEO environment remediation, Advances in Space Research Volume 47, Issue 11, 1, pp.1865-1876.
3. Wiedemann, C., et. al., (2015). The Cost-Effectiveness of Post-Mission Disposal Maneuvers, IAC-15.A6.8.4
4. Zemoura, M., Batra, S., Hanada, T. & Kawamoto, S. (2016). Impacts of debris removal on future near-Earth-orbit population & Selection of targets at short and long terms, 4th International Workshop on Space Debris Modelling and Remediation.
5. Kawamoto, S. (2016), Implementation schemes for continued active debris removal, 4th International Workshop on Space Debris Modelling and Remediation.
6. Yamamoto, T., Murakami, N., Nakajima, Y., & Yamanaka, K. (2014), Navigation and Trajectory Design for Japanese Active Debris Removal Mission, 24th International Symposium on Space Flight Dynamics (ISSFD).
7. Murakami, N. & Yamamoto, T. (2016). Rendezvous Strategy for the Active Debris Removal Missions, Proceedings of the 7th Space Debris Workshop, JAXA, pp.231-246.
8. Shibasaki, K., Oobayashi, W., et. al. (2016). Conceptual study of Mechanical and Sensing System for Debris Capturing for PAF, Proceedings of the 7th Space Debris Workshop, JAXA, pp.271-288.
9. Izumiyama, T., Sasagawa, C., et. al., (2016). Conceptual Study for Orbital Debris Removal System using small “Harpoon” , Proceedings of the 7th Space Debris Workshop, JAXA, pp.289-296.
10. Kato, H., (2016). Robotic Technology on Space Debris Capture and Beyond, Proceedings of the 7th Space Debris Workshop, JAXA, pp.248-259.
11. Hirano, D., Kato, H. & Tanishima, N. (2017). Caging-Based Grasp with Flexible Manipulation for Robust Capture of a Free-Floating Target, ICRA. (Accepted)
12. Kawamoto, S., Makida, T., et al. (2006). Precise Numerical Simulations of Electrodynamic Tethers for an Active Debris Removal System, Acta Astronautica 59 pp.139-148.
13. Kawamoto, S., Ohkawa, Y., et al. (2016). A Flight Experiment of Electrodynamic Tether Using HTV toward the Realization of Debris Removal, Transactions of JSASS, Aerospace Technology Japan, Vol.14, No. ists30.
14. Ohkawa, Y., Kawamoto, S., et al. (2016). Preparation for On-Orbit Demonstration of Electrodynamic Tether on HTV, Transactions of JSASS, Aerospace Technology Japan, Vol.14, No. ists30.
15. Okumura, T., Miura, Y., et al. (2016). Development of Potential Monitor and Electron Emitter Module for EDT Experiment on HTV-6, 14th Spacecraft Charging Technology Conference.
16. Yamamoto, T. (2016), A Parametric Study on Active Debris Removal Scenario, Proceedings of the 7th Space Debris Workshop, JAXA, pp.179-190.
17. Kitamura, S., Hayakawa, Y. & Kawamoto, S. (2014). A reorbiter for large GEO debris objects using ion beam irradiation, Acta Astronautica, 94, 2, pp.725-735.