Trans. JSASS Space Tech. Japan
Vol. 7, No. ists26, pp. Pr_2_7-Pr_2_12, 2009

Strategy for Active Debris Removal Using Electrodynamic Tether*

By Satomi KAWAMOTO[1)], Yasushi OHKAWA[1)], Shoji KITAMURA[1)] and Shin-ichiro NISHIDA[1)]

[1)] *Aerospace Research and Development Directorate, Japan Aerospace Exploration Agency, Tokyo, Japan*

(Received April 25th, 2008)

In this study, the active removal of space debris is studied from the point of view of technological feasibility. First, the actual debris distribution is analyzed to determine which debris objects should be removed considering the effectiveness in preventing collisional cascading and feasibility such as the delta-V required for rendezvous with the objects. Target regions such as sun-synchronous orbit and a 1,000km altitude, 83 degree inclination orbit are then selected and rendezvous with debris object in these regions are studied. Electrodynamic tether is promising as a highly-efficient propulsion system required for debris de-orbit in these regions. A small piggyback-launched satellite to dispose of one debris object, and a dedicated debris removal satellite which removes several debris objects from crowded regions are proposed. Precise numerical simulations of EDT are performed to evaluate the de-orbit time.

Key Words: Space Debris, Electrodynamic tether, Active Debris Removal

1. Introduction

Debris mitigation measures are needed in order that space activities can be continued to the next generation. International space debris mitigation guidelines have recently been established and mitigation measures such as the prevention of on-orbit break-ups and mission-related debris release are being applied. However, if the rate of increase in debris generated by on-orbit collisions overcomes the rate of debris reduction through re-entry due to atmospheric drag, the amount of debris will increase exponentially as the result of mutual collisions, regardless of any mitigation measures. NASA's evolutionary model predicts that such collisional cascading has already started in some crowded regions such as in the 900–1000km altitude band, and the effect of mutual collisions will be apparent within a few decades even if no new objects are launched[1)]. Some evolutionary models indicate that the space environment can be maintained by total break-up prevention and end-of-mission de-orbiting. However, severe break-ups continue to occur, including due to some events such as anti-satellite experiments and rocket failures, even after the establishment of international mitigation guidelines, so it is impossible to assure that no break-ups will happen in the future. Furthermore, debris population prediction has much uncertainty because measuring the actual debris environment is difficult, and the possibility of collisional cascading cannot be denied. Active removal of existing debris is a sure method to solve the debris problem, and should be started as early as possible. Collisional cascading starts with an increase in the amount of small debris objects that are difficult to observe from the ground[2)], so it will be too late to delay debris removal until we observe many collisions of trackable debris objects. Three on-orbit collisions involving trackable debris have already occurred, and it is also estimated that collisions involving items of debris larger than 1cm occur more than once each year[3)]. It is difficult to remove small-sized debris, and so the countless small debris objects may become a great threat to space activities, especially manned spaceflight. At high altitudes, where atmospheric drag is too small to decrease the debris population, removal is the only solution. Debris removal started at an early stage can make the space environment cleaner than it is today, so it will not only just maintain the level of today's environment, but will lower future costs for debris countermeasures such as debris protection bumpers and debris collision avoidance maneuvers, not to mention the risk of losing whole spacecraft. Japan Aerospace Exploration Agency (JAXA) has therefore been studying a system for debris removal[4)5)6)].

This paper describes our strategy for active debris removal, such as which items should be removed and how, by considering the technologies required for debris removal and actual debris distributions. Direct capture by a debris removal satellite and other methods such as laser radiation from the ground have been proposed for removal. However, the feasibility of the latter is not so clear at present, and so the former is considered in this paper. The risk of collisional cascading in Low Earth Orbit (LEO) is higher than that in Geo-stationary orbit (GEO), so the removal of debris in LEO is studied. In the debris mitigation guidelines, altitudes under 2000 km are defined as a protected region. However, transferring debris in that region to higher than 2000 km is not recommended since it does not really solve the debris problem, it merely transfers it somewhere where it is less likely to affect operational spacecraft. To solve the debris problem, debris in higher orbits must be removed. Thus, we aim to lower the orbit of debris objects so that they will reenter the atmosphere. Last but not least, legal issues and cost are also very important and need to be studied in addition to technological issues to realize debris removal. Some propose that an international organization should collect a worldwide funding to realize debris removal[7)].

2. Technologies required for debris active removal

First of all, a debris removal satellite needs to rendezvous with a target debris object and attach an orbital transfer system. The orbits of debris objects are observed by the ground radars and optical telescopes of North American Aerospace Defense Command (NORAD), and their orbital elements are published as Two Line Elements (TLE) or Satellite Situation Report (SSR) formats. These data contain observation and propagation errors, thus a removal satellite must approach the target debris while sensing it 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 that does not possess any reflectors for a rendezvous radar. Thus optical sensors or passive radar will be required. At the same time, the fuel budget must also be reasonable.

After approaching a target debris object, its attitude must be measured. The attitude of the target is no longer controlled and so it may exhibit complex motion such as tumbling, so the attitude motion of the target needs to be measured as well as its position. The optical environment is severe for vision sensors because the intense sun light may induce halation from specular reflections of multi layer insulation on the target's surface. Capturing the target by a robot arm or some other device is also difficult because the usual debris does not possess grasp handles for capturing in contrast with cooperative targets.

One of the most important technologies for debris removal is orbital transfer. It is necessary to transfer debris to orbits where the orbital lifetime is at least less than 25 years, since most international debris mitigation guidelines require spacecraft in LEO to reenter within 25 years. Although the orbital lifetime of an object depends on its Area-to-Mass (A/M) ratio, a 630 km altitude circular orbit is the standard disposal orbit altitude assuming objects with an average A/M of 0.01 [m^2/kg]. To transfer to the orbit with orbital lifetime less than 25 years, if a conventional propulsion system with an Isp of 200 sec is used a spacecraft in a 800 km altitude orbit will require about 4% of its mass in propellant, and one in a 1400 km altitude orbit will require about 13% of its mass. Thus it will be unfeasible for removal spacecraft to remove more than one debris object from LEO with conventional propulsion because it requires too much fuel. We, therefore, propose the electrodynamic tether (EDT), which uses the interference of the geomagnetic field to generate a drag force, as a highly efficient propulsion system for lowering orbits. EDT is promising also because its thrust is so small that it does not require to be rigidly attached to the debris, reducing the technical difficulty of the attachment operation. We propose that a small, lightweight EDT package be developed and applied in the following ways.

1. As a post-mission de-orbit device to be installed on new satellites.
2. "Micro Remover", a piggyback satellite launched with a new satellite that rendezvous with debris in the near regions for disposal. This small robotic satellite would have a robot arm for capturing debris, and a single EDT package for de-orbit. This micro-remover itself will become an end-mass of the tether, and will re-enter with the debris (Fig. 1).
3. A dedicated debris removal satellite to remove several debris objects from crowded regions by international cooperation. This satellite carries several EDT packages and attaches a package to each debris object (Fig. 2).

Next, we should decide which debris objects should be removed. These should be determined considering the actual debris distribution, and feasibility in that the fuel required for rendezvous needs to be reasonable.

3. Target regions for debris removal

3.1. Debris Distribution

In this section, the actual debris distribution is analyzed to determine which debris should be disposed of by examining the orbital elements contained in the March 2008 TLE and SSR data, which contains both operational satellites and fragments. Some objects are classified and their orbital elements are not published, so a total of 11,525 out of the 12,880 catalogued objects were plotted. Studies using the evolutionary model have shown that large sized objects should be removed, since large sized debris are the source of countless small debris objects once a break-up occurs[2]. Hereafter, objects with a radar cross section (RCS) of greater than 0.5 m^2 are considered as the candidates for debris removal.

Figure 3 shows the number of all cataloged objects and objects with an RCS > 0.5 m^2 in each 50 km altitude bin. This shows that the altitudes around 1000 km, 800 km and 1500 km are the most densely populated regions. These are

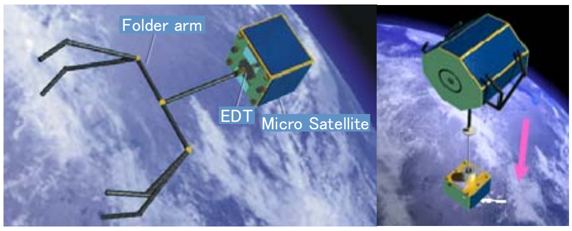

Fig. 1 "Micro Remover", a piggyback satellite to dispose of one debris object.

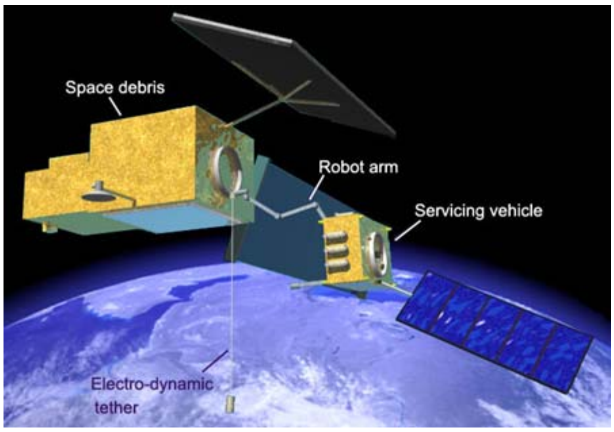

Fig. 2 A dedicated debris removal satellite, which carries several EDT packages and rendezvous with debris in crowded regions to attach an EDT package for de-orbit

the regions where the debris population has already exceeded the critical density, that is, collisional cascading is occurring, and removal from these regions will be effective to suppress further collisional cascading[8)]. Next, the inclination angles of the objects with an RCS > 0.5 m^2 at altitudes 700–1500 km are plotted in Fig. 4, and some sharp peaks are found. In order to decide the suitable regions for debris removal, the inclination distributions of some narrow altitude regions were also plotted. One example is shown in Fig. 5, which shows the number of objects with RCS > 0.5 m^2 at altitudes of 900-1000 km in each 1 deg inclination bin. A sharp peak in the inclination between 82 and 83 degrees is found. Next, the right accessions of ascending node (RAAN) of these objects are plotted in Fig. 6. This shows that several objects are found in a very narrow orbital plane.

From this analysis, the following regions are selected as candidates for removal.

- Sun-synchronous orbit (SSO), altitude 700–1000 km and inclination 98–100 degree.
- 900–1000 km altitude, and 83 degree inclination.
- 1400–1500 km altitude, 74 degree, 83 degree and 52 degree inclinations.

A sensitivity study using the evolutionary model[9)] also shows that removal of objects in these regions will be effective in lowering collision probability. The debris population around 1000 km altitude is about 25 % higher than the critical density[8)]. Thus, 25 % out of about 400 debris objects in

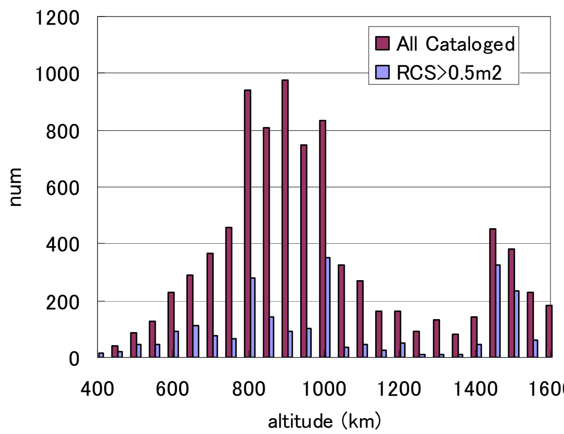

Fig. 3. The number of objects in each 50km altitude bin.

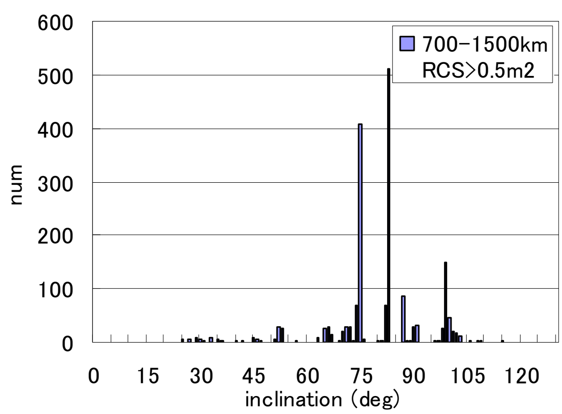

Fig. 4. The number of objects in altitude of 700-1500 km with RCS > 0.5 m^2 in each 1 deg inclination bin.

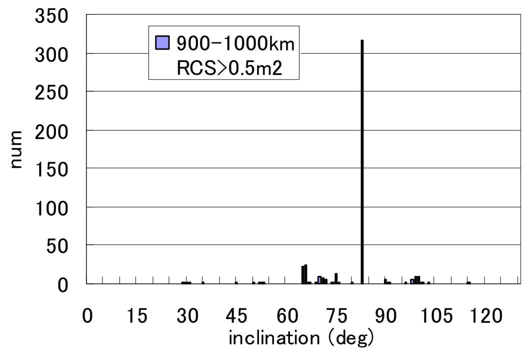

Fig. 5. The number of objects in altitude of 900-1000 km with RCS > 0.5 m^2 in each 1 deg inclination bin.

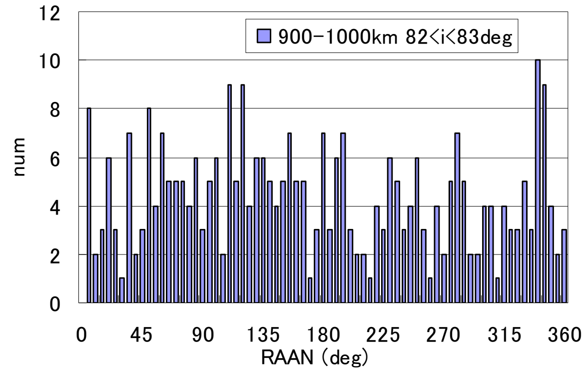

Fig. 6. The number of objects in altitude of 900-1000 km and inclination 82-83 degree with RCS > 0.5 m^2 in each 5 deg RAAN bin.

around 1000 km altitude, that is, about 100 debris removal is expected to reduce the risk of collisional cascading in this region significantly.

3.2. ΔV for orbital transfer between debris

The reason why the regions identified above are densely populated at present is because of their desirable orbits characteristics. Therefore, there is high probability that successor satellites or similar satellites will be launched into these orbits. If a piggyback satellite launched together with each new satellite could dispose of debris in the near regions, debris removal could be realized at low cost. As is shown in Fig. 6, the debris is expected in a narrow orbital plane in the target regions. Usually, it requires much fuel to change orbital plane, but in these regions, several debris can be found within the inclination difference less than 1 degree and the RAAN difference less than a few degrees. RAAN can be coincided using smaller ΔV utilizing the nodal regression of the J2 effect by changing altitude and waiting for a while. Figure 7 shows the time required to change RAAN by 1 degree and the ΔV required to change the altitude of the perigee. For example, a ΔV of 129 m/s is required to change orbital plane directly, but a total of 50 m/s would be sufficient utilizing the J2 effect: firstly, the perigee altitude of the removal satellite is lowered by about 100 km by a ΔV of 25 m/s, and the satellite remains in that lower orbit for about 40 days, after which it returns to the original orbit with ΔV of 25 m/s. After the orbital plane is coincided, the semi-major-axis needs to be coincided, and then phasing is needed. In order to rendezvous with a non-cooperative target, the light of the Sun reflected from the target debris is usable, and the position of the target can be estimated using the consequent target data direction measured by a star tracker. This star tracker navigation is promising for cost-effective rendezvous. After the debris removal satellite comes close to the target, the final approach and motion estimation and the capture operation will be conducted by a vision sensor and if possible by a ranging and ranging rate (R&RR) sensor. The total ΔV required for these operations is estimated to be about 35 m/s, as listed in Table 1. As an example, rendezvous with ADEOS2 (a Japanese Earth observation satellite which was launched in SSO and terminated in 2003) as of 2010 from ALOS (another Japanese Earth observation satellite launched in 2006) orbit requires an inclination change of 0.3 deg, a RAAN change of 4.9 deg, and an altitude change of 105 km. These can be achieved with a total ΔV 128 m/s. Rendezvous with objects in the above mentioned crowded regions can be achieved with about 150 m/s, which requires about 8% of the mass in fuel if a cost-effective mono-propellant thruster is used. Debris capture by an extendable arm or robotic arm, and motion passivation are also being studied. Details can be found in Refs. 5 and 6.

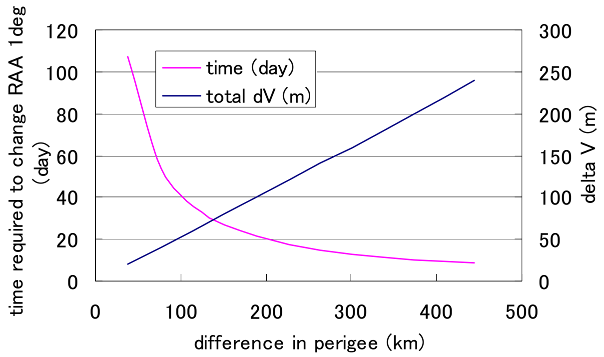

Fig. 7. Time required to change RAAN by 1 deg and ΔV required to change perigee altitude.

4. Efficient Orbital Transfer

4.1. Electrodynamic Tether (EDT)

One of the key technologies for realizing a debris removal system is orbital transfer. From trade-off studies between different propulsion systems, the electrodynamic tether (EDT) is considered to be most promising (Table 2). The principle of EDT thrust is as follows (Fig. 8). An electromotive force is set up within a conductive tether deployed from a space system as it moves through the geomagnetic field in its orbit round the Earth. If a pair of plasma contactors at either end of the tether emits and collects electrons, an electric current flows through the tether by closing the circuit via the ambient plasma. The tether then generates a Lorentz force via interaction between the current and the geomagnetic field which acts opposite to the direction of flight. Therefore, an EDT can provide deceleration without the need for propellant or high electrical power, and shows promise as a high efficiency propulsion system for debris de-orbit. An EDT is also suitable because its thrust is so small that it does not have to be as firmly fixed to the target as with a conventional propulsion system, so attaching the EDT to the debris by a robot arm will be less

Table 1 Rendezvous operation and required ΔV

phase	orbit and operation	ΔV (m/s)
phasing #1 (GPS absolute navi.)	perigee lower than the target by 40 km. Waiting max. 119 rev toward 50 km bihind the target	10.4
phasing #2 (star tracker navi.)	perigee lower than the target by 1 km. Waiting 10 rev toward 5km bihind the target debris	10.1
rendezvous using vision sensor (and R&RR sensor)	perigee lower than 100m-5m. Toward 100m behind the target debris	4
final approach	linealy approach from 100m	3.4
capture	motion estimation and capturing by robot arm	7.1
	total	35

challenging.

The main components of an EDT are the tether (Fig. 9), an electron collector and an emitter, a reel and a deployment mechanism. For the electron emitter, an electron gun, a hollow cathode, and filed emitter cathodes (FEC) are proposed, while a sphere electron collector, a hollow cathode and a bare tether are proposed for the electron collector. A combination of FEC and bare tether could realize the smallest and lightest EDT system. In our study, a carbon nanotube (CNT) FEC (Fig. 10) is adopted because it is simple and durable in the low vacuum environment[10]. A bare tether (a conductive wire without insulation) can collect electrons directly from the ambient plasma when the tether has a positive electrical potential by the electromotive force.

Table 2 Trade-off between propulsion systems for debris removal.

Methods	merits	demerits
Chemical thruster	- established technology	- low Isp - difficult to fix to debris object
Ion thruster	- high Isp	- high electrical power
Solid rocket motor	- established technology - compact	- generate numerous slag/dust debris - difficult to fix to debris object
Air bag	- simple - no electrical power	- huge size required for heavy debris - debris impact risk
EDT	- high Isp - easy to attach to debris object	- debris impact risk (sustainable by net tether)

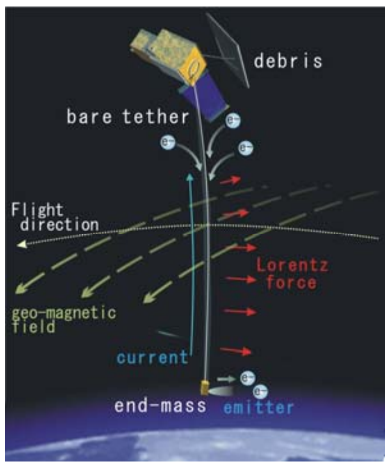

Fig. 8. The principle of EDT

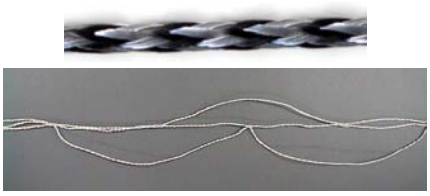

Fig. 9. Bare tethers. Braided tether (top) and net tether with different lengths of cord (bottom).

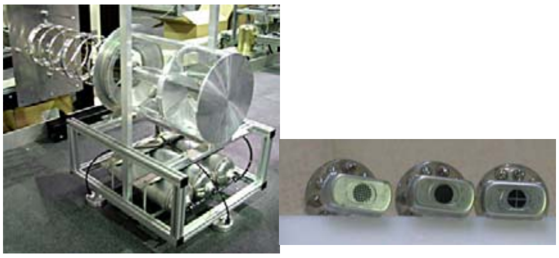

Fig. 10. Reel and deployment mechanism (left) and FEC (right)

A single line tether would be susceptible to being severed by collisions with even very small debris objects and micrometeoroids, and could be severed within a short period of time in crowded orbits[11], so a braided tether and a net tether are proposed. A net tether is expected to have a longer lifetime because the space between the cords that results when one cord of the net is longer than the others plays important role in surviving debris impacts. A multi-line bare tether has a greater electron collection capability. A simple spool-type reel for tether deployment and a deployment mechanism which utilizes double helical spring for stable deployment are also being studied. These key components have been manufactured and are now being evaluated[6) 12) 13)] and their characteristics are used in the numerical simulations mentioned in the following section.

4.2. Numerical simulation of EDT

Precise numerical simulations are conducted for some aspects of mission analysis, such as for calculating orbital changes and tether stability[12]. A tether is modeled as a lumped mass to take into account its flexibility by dividing the tether into point masses connected by segments consisting of a spring and viscous damper. To model electron collection by the bare tether, the two-dimensional Orbital Motion Limit (OML) theory was used. The following models are used: IGRF 2000 (International Geomagnetic Reference Field) (10 *10) for the geomagnetic field, IRI2001 (International Reference Ionosphere) for the plasma density, NRLMSISE-00 (NRL Mass Spectrometer, Incoherent Scatter Radar Extended Model) for atmospheric density, and EGM96 (Earth Gravitational Model) (10 *10) for the Earth's geo-potential field. Orbital perturbations caused by the Lorentz force, atmospheric drag and geo-potential are taken into account using Gauss's variational equations of motion. Thermal calculations are carried out by considering the direct solar flux, albedo, the Earth's infrared emission, Joule' heat, electron collection heat, and aerodynamic heat. The tether is assumed to be the braided tether described in the above section with the following characteristics: diameter 1.98 mm, line density 1.98 g/m, electrical resistance 0.0485 Ω/m, and tensile modulus $1.4x10^{10}$ N/mm^2.

4.3. Results of numerical simulation

Results of the numerical simulations for a number of debris de-orbits are shown below. The available current varies depending on the plasma density, geomagnetic field and so on. Figure 11 shows the average Lorentz force for various orbits with different altitudes and inclinations. The Lorentz force becomes smaller at high altitudes and high inclinations, but it is still large enough to transfer debris in SSO. Figures 12 and 13 show the altitude change of debris with a 10 km EDT attached. In Fig. 12 the target is a large Earth observation satellite in SSO with a mass of 3400 kg, and in Fig. 13 the target is a 1400 kg rocket remnant in a 900–1000 km altitude, 83 degree inclination orbit. To reduce calculation time, the average thrusts are calculated for each altitude as shown in Fig. 11 and time required to reenter the atmosphere are calculated. These figures show that using a 10 km EDT the debris will reenter within one year. A

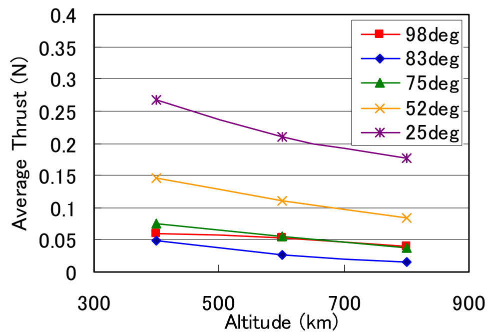

Fig. 11. The average thrust of EDT

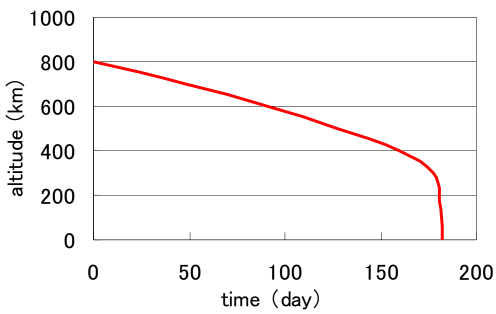

Fig. 12. Change in altitude of debris in SSO (3400kg) with EDT of 10 km.

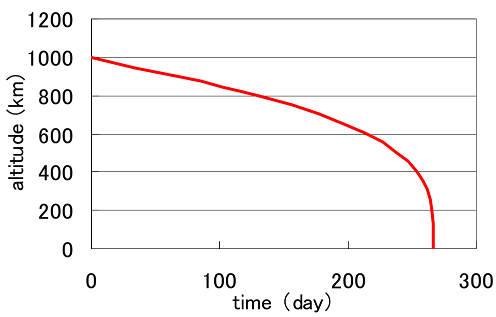

Fig. 13. Change in altitude of debris in orbit altitude 900-1000 km, inclination 83 deg (1400kg) with EDT of 10 km.

1400 kg rocket remnant in around 1400 km altitude, 74 degree inclination orbit is also expected to reenter within one year. Many of other debris objects in around 1400 km altitude will reenter within shorter time period if they are not so heavy, like Globalstar (450 kg) or small satellites (less than 100 kg). As mentioned above, the tether could be severed by small debris and meteoroids[11)] but lifetime evaluation using NASA's ORDEM 2000 (Orbital Debris Environment. Model) debris flux model estimates that the de-orbit time will be short enough for its survival. In fact, TiPS (Tether Physics and Survivability Satellite), a 4-km tether launched in 1996, orbited for about 10 years at 1000 km without being severed, although there were frequent close approaches by debris object to within a few kilometers. This demonstrated that a tether several kilometers in length can have a good chance of surviving for several years. It is also noted that the numerical simulations in this study used OML theory, which can simulate electrons collection by a single tether in a static plasma. However, Particle in Cell (PIC) simulations to calculate the motion of electrons and ions show that more current can be obtained by a multi-line tether with plasma flow[14)]. On-orbit experiments will be necessary to estimate the real EDT thrust.

5. Conclusions

In this paper, a strategy for debris active removal is described considering required technologies and debris distribution. Conclusions are the following.

- To remove debris effectively, debris in crowded regions such as SSO, 900–1000 km altitude and 83 degree inclination, 1400–1500 km altitude and 74 degree, 83degree, or 52 degree inclination, can be the targets of removal.
- About 100 large sized items of debris (satellite or rocket remnants) in these crowded regions should be removed.
- As a first step towards debris removal, a Micro Remover piggyback satellite launched with each new satellite into the above orbits could be cost-effective. Large satellites dedicated to debris removal could be realized later by international cooperation.
- Fuel or ΔV for rendezvous within the above regions can be attained by a cost-effective mono-propellant thruster.
- Rendezvous with debris objects is not easy because the objects are not cooperative, but star tracker and visual imaging sensors can be used as low-cost sensors.
- EDT is promising for debris de-orbit because it can generate thrust without requiring much propellant or high electrical power. Attachment of an EDT to debris is expected to be easier than attaching a conventional thruster because the EDT's thrust is small.
- The debris with an EDT attached will gradually lose altitude due to the EDT thrust. Precise numerical simulations were performed, and it is considered that an EDT with a length of 5–10 km can de-orbit a large debris object from a crowded orbit within one year.
- A net tether is expected to survive the impact of small size debris until the debris reenters the atmosphere
- Other technologies required for debris removal, such as the capturing by a robot arm and motion estimation, are also being studied by JAXA.

We plan a test flight experiment using a small satellite to establish and demonstrate EDT technology within a few years. Then, enlargement of EDT will be studied to develop a large EDT system for de-orbiting a rocket upper stage or a large satellite. And then, a Micro Remover to demonstrate debris removal will be developed. At the same time, an international framework should be discussed to move toward the final goal of debris removal to maintain the space environment for the next generation.

References

1) Liou, J.-C and Johnson, N.: Risks in Space from Orbiting Debris *Science,* **311**(2006), pp.340-341.

2) Eichler, P.: Analysis of the necessity and the effectiveness of countermeasures to prevent a chain reaction of collisions, *Acta Astronautica,* **26**(1992), No.7, pp.487-495.

3) Johnson, N.: Environmentally-induced Debris Sources, *COSPAR,* PEDAS1-B1.4-0020-02, 2002.

4) Kibe, S., Kawamoto, S., Ohkawa, Y., Terui, F., Nishida, S. and Gilardi, G.: R&D of the Active Removal System for Post-mission Space System, *IAC*-03-IAA.5.4.07, 2003.

5) Nishida, S., Kawamoto, S., Ohkawa, Y., Yoshimura, S., Terui, F. Nakajima, A. and Kitamura, S.: Development Status of an Active Space Debris Removal System, *IAC*-05-B6.3.03, 2005.

6) Nishida, S., Kawamoto, S., S., Ohkawa, Y., Terui, F. and Kitamura, S.: Space debris removal system using a small satellite, *IAC*-06-B6.4.02, 2006.

7) Mine. M.: Business model for the space environment maintenance and demonstration plan for the debris removal system, *3rd space debris work shop*, JAXA, 2008.

8) Kessler, D.: Collisional cascading: The limits of population growth in low Earth orbit, *Advances in Space Research* **11**(1991), No. 12, pp. 63-66,.

9) Liou, J.-C and Johnson, N.: A sensitivity study of the effectiveness of active debris removal in LEO, *IAC*-07-A6.3.05, 2007.

10) Ohkawa, Y., Kitamura, S., Kawamoto, S., Iseki, Y., Hashimoto, K. and Noda, E.: An Experimental Study of Carbon Nanotube Field Emission Cathodes for Electrodynamic Tethers, *IEPC*-2005-104, 2005.

11) Pardini, C., Hanada, T. and Krisko, P.: Benefits and risks of using electrodynamic tethers to de-orbit spacecraft, *IAC*-06-B6.2.10, 2006.

12) Kawamoto, S., Makida, T., Sasaki, F., Ohkawa, Y. and Nishida, S.: Precise Numerical Simulations of Electrodynamic Tethers for an Active Debris Removal System, *Acta Astronautica* **59** (2006) pp.139-148.

13) Kashihara, K., Qu, D., Muranaka, T., Cho, M. and Kawamoto, S.: Laboratory Experiment and Simulation of Bare tether Current Collection in Plasma Environment, 25th ISTS, 2006.

14) Ikeda, T., Nakamura, Y., Ohtsu, H., Yamagiwa, Y., Kawamoto, S. Ohkawa, Y. and Nakajima, A.: Multiple Bare Tethers for Electrodynamic Tether Propulsion, *IEPC*-2007-280, 2007.