Active Debris Removal Research in JAXA

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   a. What will happen if we do nothing or do something to remediate the space debris environment?
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   d. Which is the best ADR concept of those proposed so far?

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3. JAXA’s Roadmap for Debris Removal
1. General Discussion on Active Debris Removal

- Liou & Johnson’s pioneering work using LEGEND/NASA, 2011,
- IAA Cosmic Study “Space Debris Environment Remediation” (in press)
- IADC Study Report “Stability of the Future LEO Environment” (released on the HP of IADC), AI 27.1,
- Based on the study results mentioned above, IADC has organized “IADC Statement on Space Debris Removal”, concluding with necessity of ADR operation and encouragement of related research activity in technical, economical, legal and safety aspects.

**IADC definition of Space Environment Remediation**

Space debris environment remediation consists of efforts to manage the existing space debris population through active debris removal with emphasis on densely populated orbital regions.

Discussion here is mainly based on the outcome of above mentioned investigations and discussions.
1. General Discussion on Active Debris Removal

- List of evolutorial models available
  - ASI/Space Debris Mitigation long-term analysis program (SDM)
  - ESA/Debris Environment Long-Term Analysis Software (DELTA)
  - ISRO/Long-term debris environment projection model (KSCPROP)
  - JAXA-Kyushu Univ./LEO Long-Term Debris Environment Evolution (LEODEEM)
  - NASA/LEO-to-GEO Environment Debris Model (LEGEND)
  - UKSA-Univ. of Southampton/Debris Analysis and Monitoring Architecture the Geosynchronous Environment (DAMAGE)
1. General Discussion on Active Debris Removal

a. What will happen if we do nothing or do something to remediate the space debris environment?

- **If we do nothing**-----Business as usual----no mitigation measures applied!

1. General Discussion on Active Debris Removal

a. What will happen if we do nothing or do something to remediate the space debris environment?

- Regular Launch + 90% Post-Mission Disposal

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Figure 5. Effective number of objects 10 cm and larger in LEO.
1. General Discussion on Active Debris Removal

a. What will happen if we do nothing or do something to remediate the space debris environment?

• All models show almost the same conclusion.
• Modest increase of debris population in 200 years, about 30%

Is it acceptable or unacceptable?
Figure 9. JAXA’s projection of the future LEO population.
Evolution of smaller size debris

Nazarenko, 29th IADC 2011
1. General Discussion on Active Debris Removal

a. What will happen if we do nothing or do something to remediate the space debris environment?

Findings

- New Fragments by on-orbit collision will increase steadily.
- Spatial density of space debris around 900 km in altitude will be more than doubled.
- Smaller but still dangerous debris will increase faster than this.

Again, is it acceptable or unacceptable?
1. General Discussion on Active Debris Removal
   a. What will happen if we do nothing or do something to remediate the space debris environment?

   • We have to do more!
   • What is the ultimate mitigation measure?
   
   no future launch

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IAA Cosmic Study, in press
1. General Discussion on Active Debris Removal
   a. What will happen if we do nothing or do something to remediate the space debris environment?

   • Regular Launches + 90% PMD + ADR2020/02,05

   ![LEO Environment Projection](image)
1. General Discussion on Active Debris Removal

b. How long can we wait for the ADR implementation?
Figure 2.5-5: Evolution of the LEO population of 10cm and larger for active removal in the orbit region 1000km/82° at a rate of 5 objects/year, starting in 2006, 2020, 2040 or 2080.
My Personal Understanding

• Though it is not so long, we still seem to have a little bit of time to make our discussion deeper, investigate and develop affordable enabling technologies.

• It is most urgent to start and make deeper worldwide discussion on ADR from various viewpoints, such as technological, economical and legal aspects and to establish consensus on necessity of ADR operation.
1. General Discussion on Active Debris Removal

c. Which one should we remove first?
1. General Discussion on Active Debris Removal
   c. Which one should we remove first?
   
   • Possible metrics for ADR target selection.
     
     – Mass/Cross Section*Collision Probability
     – Mass/Cross Section*Collision Probability *Orbit life time
LEO Environment Projection (averages of 100 LEGEND MC runs)

- Reg Launches + 90% PMD
- Reg Launches + 90% PMD + ADR2020/05 (limited alt/inc)
- Reg Launches + 90% PMD + ADR2020/05

Effective Number of Objects (>10 cm)

Year

Figure 2.5-2: Number of catastrophic collisions vs. altitude vs. inclination of the targets after 200 years in the no-further-release scenario.
Current LEO R/Bs and S/Cs (masses >50 kg)

- 1000km, 82°
- 800km, 99°
- 850km, 71°
**Figure 2.5-3:** Evolution of the LEO population larger than 10 cm for a “no further release” scenario, with active removal from individual orbit regions at 1000km/82°, 800km/99°, 850km/71°, for a multi-region removal strategy (switch to a different orbit region after every mission), and for a removal strategy ranked by mass or by area in any LEO region.
Figure 6.1-2: Distribution of the cumulated, normalized collision rate index for LEO catalog objects (larger than 10cm) in a grid of Δi × ΔH = 2° × 50km. The collision rate index is the bin-wise sum of the object-wise product of [object flux for d>10cm] × [mean target cross-section].
Figure 6.2-1: Distribution of the cumulated short-term environment risk index for LEO catalog objects (larger than 10cm) in a grid of $\Delta i \times \Delta H = 2^\circ \times 50$km. The short-term risk index is the bin-wise sum of the short-term environmental degradation potential based on the object-wise product of [catastrophic collision probability] $\times$ [object mass].
Figure 6.3-1: Distribution of the cumulated long-term environment risk index for LEO catalog objects (larger than 10cm) in a grid of $\Delta i \times \Delta H = 2^\circ \times 50\text{km}$. The long-term risk index is the bin-wise sum of the long-term environmental degradation potential based on the object-wise product of [catastrophic collision probability] $\times$ [orbit lifetime] $\times$ [object mass].
Current LEO R/Bs and S/Cs (masses >50 kg)

- Apogee
- Perigee

- 780 km, 86.5°
- 825 km, 71°
1. General Discussion on Active Debris Removal
   c. Which one should we remove first?

• Target selection is very critical on the effect of ADR activity.
  – Mass/Cross Section*Collision Probability
  – Mass/Cross Section*Collision Probability *Orbit lifetime

  seem to be most reasonable metrics but in making an actual ADR mission plan, some other factors will have to be considered,
  – Vehicle type/class
  – RAAN distribution
  – Possibility of multiple removal in one mission
1. General Discussion on Active Debris Removal

d. Which is the best ADR concept of those proposed so far?

• High Dependency on the Target
  – Target orbit
    Re-orbit or De-orbit?
  – Target property size/mass,
    Controlled or Uncontrolled reentry?
  – Target type/class
    Same rocket upper stages or satellites?
  – Target distribution
    Densely populating in the specific orbit region?
  – Target angular motion
    Stationary, spinning or tumbling?
• Answer is,

There is no best concept for all targets!!!

Followings are the key issues to consider,
• Target selection,
• Technology Readiness,
• Development and operation cost.
Japan’s Space Basic Policy

Space Basic Policy was issued on 28\textsuperscript{th} May, 2008

- Chapter 1  General Rules
- Chapter 2  Basic Policies

(Space Environment Preservation)

- Article 20
  Government should take necessary measures to promote the space development /utilization activity in harmony with the space environment preservation,

- Article 20-2
  Government should pursue the space environment preservation through international Cooperation,
Japan’s Basic Plan for Space Policy(1)

Japan’s Basic Plan for Space Policy was issued on 2\textsuperscript{nd} May, 2009.

- Chapter 3; Measures that the Government should take comprehensively and systematically for the use and R&D of space
  - 1. Nine systems and Programs for the use and R&D of space
  - 2. Promotion of specific measures in each area
    - (6) Preservation of the environment
    - (c) Removal of debris
Japan’s Basic Plan for Space Policy(2)

IADC and other groups have pointed out that increase of collision rate among debris would invite the chain reaction of mutual collision among debris. For this issue, it is required not only to reduce the generation of debris but also to remove existing debris positively. In Japan, the technology to capture and remove the orbital objects is still in the research phase.

As a next step of this approach, Government will promote the research to demonstrate the technology to capture debris and remove it from its orbit using small satellite, with coordinating international community.
2. JAXA’s ADR System Concept
   a. ADR Operation

Scenarios for debris removal in final operation

- **Launch of a removal satellite**
- **Start rendezvous**
- **Approach to debris (non-cooperative rendezvous)**
- **Motion estimation**
- **Proximity operations**
- **Attachment of tether end**
- **Debris de-orbit with EDT**
- **Reenter with EDT**

Debris objects in a crowded region

To the next debris object
2. JAXA’s ADR System Concept
   b. Rendezvous and approach to the non-cooperative target

- **Difficulties in Rendezvous and approach to the non-cooperative target.**
  - No communication link,
  - No image marker/laser reflector,
  - Uncertainty of the orbit information,
  - Change of optical property of the surface,
  - Drastic change of lighting condition,
  - No attitude and orbit control.

- **Rendezvous and approach to the non-cooperative target would be a big technological challenge!**
2. JAXA’s ADR System Concept

b. Rendezvous and approach to the non-cooperative target

Baseline rendezvous and approach scenario to a non-cooperative target
2. JAXA’s ADR System Concept

b. Rendezvous and approach to the non-cooperative target

**Variation of navigation sensors**
2. JAXA’s ADR System Concept

b. Rendezvous and approach to the non-cooperative target

**Simulation model**

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>VISCAM(^{10})</td>
<td>Noise: 0.1 deg random ((1\sigma)) (f=75, F=1, 640\times480) CCD camera</td>
</tr>
<tr>
<td>IRCAM(^{6})</td>
<td>Noise: 0.1 deg random ((1\sigma)) (f=75, F=1, 640\times480) IR camera</td>
</tr>
<tr>
<td>LIDAR(^{10})</td>
<td>Noise: 6m random ((1\sigma)) Peak power=1MW Receiver diameter=10cm, Sensitivity=0.4A/W</td>
</tr>
<tr>
<td>Debris optical property</td>
<td>Modified Phong model (k_d = 0.2, k_s=0.5, n=28)</td>
</tr>
<tr>
<td>Navigation</td>
<td>EKF to estimate relative elements Initial error: (\text{ada} = 100) (\text{adex, adey, adix, adiy} = 500) (\text{adu} = 5000)</td>
</tr>
<tr>
<td>Guidance</td>
<td>Relative orbit feedback</td>
</tr>
<tr>
<td>Maneuver</td>
<td>Impulsive maneuver</td>
</tr>
</tbody>
</table>
2. JAXA’s ADR System Concept

b. Rendezvous and approach to the non-cooperative target

Approach Simulation using only VISCAM
Upper: Dual-Co-elliptic Rendezvous, Lower: Stable-Orbit Rendezvous
2. JAXA’s ADR System Concept

b. Rendezvous and approach to the non-cooperative target

Range of Valid Measurement
- Upper: VISCAM
- Middle: IRCAM
- Lower: LIDAR

3σ Deviation of Range Estimation
- Upper: VISCAM
- Middle: IRCAM
- Lower: LIDAR
2. JAXA’s ADR System Concept

b. Rendezvous and approach to the non-cooperative target

Findings

- Double Co-elliptic Rendezvous (DCR) --- Stable Orbit
  Rendezvous (SOR) --- Forced Motion Circular orbit would be acceptable,
- Approach only using visual camera is possible,
- Co-utilization of IR camera and LIDAR is very helpful to enhance reliability of measurement.

Conclusion

If resource is ample, combination of three types of sensors would be better (Multi-removal operation?). If not, visible camera system would be the most prospective candidate (Single-removal operation?). Image-based measurement and motion estimation technology is focused area to be investigated.
Image-based perceptions on each phase

Approach Phase

• Finding target and determining its orientation
  From dozens of kilometers to the target, the target, which is projected as being one or a few pixels in size in a telescopic camera, is detected for estimating its orientation from the viewpoint of the removal satellite.

• Course range finding to the target and its shape
  Within about 10 kilometers, the target is projected to 10 pixels more on the image. Using a small projected target, the distance to the target and its shape are approximately estimated.

Observation Phase

• Precise 3D reconstruction of the target and motion estimation
  At around 50 meters from the target, its shape and the distance from the viewpoint are precisely measured through image-based perception, i.e., stereo-vision.
  The target motion, such as nutation/tumbling, is estimated by using sequential images.
  For the final approach in the next phase, all perception information of the target should be estimated in this phase.

Removal operation Phase

• Image-based perception for robotic operations
  Until contacting with the target, visual perception or target tracking is continually executed for a robotic operation, i.e., attaching a removal device on the body of debris.
  After attaching the device, the performance of the device is monitored in the middle distance.
Our activities in image-based perception for debris removal

Usually, the research and development of image-based perception requires much experimental evaluation of the proposed methods with the actual images. In the debris removal operation, it is not easy to obtain the actual images of the debris in an earth orbit; therefore, we have to use other means to obtain more realistic images. The following are our activities in this regard.

- **Synthesis of images through computer graphics**
  - for the performance of the proposed algorithm, tests in many cases

- **A miniature scaled model of the debris**
  - for actual tests of the cameras, lens, and real material, i.e., refraction on MLI (multi-layer insulation)

- **Images of the (actual) HII-A upper rocket in a facility**
  - for actual scale tests of the camera, lens, and actual surface materials

- **Actual similar images obtained from the ISS, HTV, and HII-A**
  - for actual lighting environments

- **Through a demonstration experiment on the orbit, actual images are obtained**
  - this is a perfect experiment and a unique opportunity.
Rendezvous & motion measurement sensor

On-orbit Visual Environment Simulator

Motion estimation of debris attitude using a vision sensor
2. JAXA’s ADR System Concept

c. Angular momentum reduction

ADEOS is tumbling in rotating rate around 0.3deg/sec
Impact Thruster
Stabilizing and capturing debris by a robot arm

- Extensible boom to capture with light mass
- “Brush-contactor” for slowing tumbling motion
- Joint virtual depth control and joint mechanism with torque sensor to buffer and brake residual motions of space debris
2. JAXA’s ADR System Concept

d. Principle of the thruster

- EDT is “Propellant-free propulsion”
- Fundamentals,
  - Attitude stabilization by gravity gradient,
  - Electromotive force (EMF) by orbit motion,
    - \( V_{EMF} = (v \times B) L \)
  - Electron emission and collection from ambient plasma,
  - Electric current generated through tether,
  - Lorentz force,
    - \( F = (J \times B) L \)
- EDT is suitable for ADR because of high efficiency and simplicity.
Results of numerical simulation

- Debris will reenter within one year using a 10 km EDT
- De-orbit time is short enough for survival of multi-strand tether severed by debris impacts
  - Slack of the one cord of the net tether realizes larger electron collection and long survivability against small-size debris impacts

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

Change in altitude of debris in orbit altitude 1000 km, inclination 83 deg (1400kg) with EDT of 10 km.
## Ejection test on an air table

### Net Tether

A net tether is shown in the image.

### Methods

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

**Edt**
Tether collision with small debris

- Hyper-velocity impact tests using two-stage light gas gun were performed
  - Projectiles: tens of 100/200/300 μm Al/SUS spheres for each shot
  - Velocity: 5-6km/s
  - Shots: total 10 shots
- \( d_C \) (minimum fatal debris diameter) and \( D_{TC} \) (critical distance) were investigated
  - Tether cord with diameter of 400μm was not severed by 200μm particles
  - Tether is severed less easily than expected (\( d_C/D_T > 0.5 \), \( D_{TC} < 0 \))

Components of hyper velocity impact test

Results of hyper-velocity impacts
Carbon Nanotube Cathode - Introduction -

- Simple and low-power electron emission device is needed in electrodynamic tether system

- Carbon Nanotube Cathode
  - Electrons are extracted just by applying a strong electric field
  - Neither consumables nor heater power is required
  - Nano-scale tube enhances electron emission

![Diagram of Carbon Nanotube Cathode](image)
Carbon Nanotube Cathode - Device -

- A carbon nanotube cathode with 3-mA-emission capability is being developed in JAXA
  - Multi-wall-nanotube by arc discharge method is used
  - High extraction efficiency (90%) is obtained by mask electrode

![3-mA Cathode](image1.png)
![Schematic](image2.png)
Carbon Nanotube Cathode - for KITE -

- Eight 3-mA Cathodes are being integrated for Konotori Integrated Tether Experiment “KITE” which will be launched in 2015 on Japanese HTV-6

Carbon Nanotube Cathode Assembly for KITE

Conceptual image of KITE
3. JAXA’s Roadmap for debris removal

**Space Environment Preservation**

**Satisfy 25-year-rule**
- De-orbit Device for New S/C

**Prevent Collisional Cascading**
- Removal of multiple debris (by international Cooperation)

**Removal of One Debris**
- EDT for Small Sat.
- EDT for Large S/C
- Non-cooperative rendezvous
- On-orbit servicing
- Micro Remover to remove one debris

**Removal of multiple debris**
- Debris Removal System to remove multiple debris

**Current Situation**
- Mitigation guidelines were enacted
  - Reentry within 25 years is required
- Collisional cascading started
  - Removal of existing debris is needed

**International Cooperation**
- with IADC, IAA, etc.

<table>
<thead>
<tr>
<th>Proximity Operations</th>
<th>Enlargement of EDT</th>
<th>Non-cooperative rendezvous</th>
<th>Flight Experiment of EDT</th>
</tr>
</thead>
</table>

**Timeline**
- 2008
- 2013
- 2018

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**Debris Removal System**

- EDT Demo

**Cooperation**

- Attachment of EDT
- 5-10km EDT
- Demonstration of <1km EDT
# KITE: EDT Demonstration experiment(1)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch Date</td>
<td>TBA in 2015</td>
</tr>
<tr>
<td>Orbit</td>
<td>Circular 350~ 400 km altitude</td>
</tr>
<tr>
<td>Mission Period</td>
<td>about 7 days</td>
</tr>
<tr>
<td>Tether length</td>
<td>700m</td>
</tr>
<tr>
<td>Tether current</td>
<td>Max 10mA</td>
</tr>
<tr>
<td>Mission equipment mass</td>
<td>45kg (Endmass 20kg, On board mass 25kg)</td>
</tr>
<tr>
<td>Required power</td>
<td>182.5W</td>
</tr>
</tbody>
</table>
1.1 HTV Configuration Overview

**HTV Characteristics**

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Dimensions</th>
<th>Total mass full loaded</th>
<th>Launch Vehicle</th>
<th>Target orbit</th>
<th>Cargo capability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Length: 9.2 m</td>
<td>16.5 ton</td>
<td>H-IIB launch Vehicle</td>
<td>Altitude: 350km~460km</td>
<td>6 ton in total</td>
</tr>
<tr>
<td></td>
<td>Diameter: 4.4 m</td>
<td></td>
<td></td>
<td>Inclination: 51.6deg</td>
<td>Press. Up to 5.2 ton</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>Un-press. Up to 1.5 ton</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Propulsion system</td>
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</tbody>
</table>
By prioritizing the HTV mission objective i.e. transport of cargo/supplies to the ISS, EDT Exp should be performed from the end of integrated operation until reentry.
A solar array panel on the back of ULC could be removed based on power resource experience on HTV1 through HTV3. Then the end-mass could be deployed from there. And, the backside on HTV is covered by the rendezvous sensor (RVS) which is used in approaching ISS. The RVS could monitor the end-mass motion. Therefore, GPS for monitoring the end-mass position and transponder for transmitting the information would be unnecessary. As a result of that, EDT system could be much simpler.
# 3.4 Study of EDT Exp Sequence

<table>
<thead>
<tr>
<th>Phase</th>
<th>Deployment</th>
<th>Stable Libration</th>
<th>Electron Emitter Ops</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phenomena</td>
<td>Eject &amp; Deploy</td>
<td>Libration</td>
<td>Emission</td>
</tr>
<tr>
<td></td>
<td>700m deployment</td>
<td></td>
<td>Collecting</td>
</tr>
<tr>
<td></td>
<td>Config</td>
<td></td>
<td>Lorenz Force</td>
</tr>
<tr>
<td>Outcome</td>
<td>Acquire the characteristics</td>
<td>Acquire the</td>
<td>Confirm driving current</td>
</tr>
<tr>
<td></td>
<td>- tether deployment</td>
<td>characteristics</td>
<td>by emitting and collecting electron</td>
</tr>
<tr>
<td></td>
<td>- libration during</td>
<td>of libration</td>
<td>Confirm Lorenz force</td>
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<tr>
<td></td>
<td>deployment</td>
<td>after deployment</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Acquire the characteristics</td>
<td>Confirm Mutual</td>
<td></td>
</tr>
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<td></td>
<td>of libration</td>
<td>characteristics</td>
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<td></td>
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<td>between orbital</td>
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<td></td>
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<td>motion and</td>
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<td></td>
<td></td>
<td>generated voltage</td>
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- Current (10mA max)