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導電性テザーシステムの実用化に向けた研究

Toward the Application of Electrodynamic Tether Systems to Orbital Debris Deorbit

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軌道上デブリ低減に寄与する継続的なデブリ除去を実現するためには、なるべく低コストな除去システムを構築する必要がある。導電性テザー推進には、推進剤不要・デブリへの取付容易・推力方向制御不要、などの長所があるため、上記の要求に応えるデオービット推進系として有力な候補となる。本発表では、導電性テザー推進の長所と短所や、実用化に向けた技術ステップ、解決すべき技術課題等について述べる。

Low cost development of active debris removal (ADR) systems is required to realize the sustainable debris remediation strategy. An electrodynamic tether (EDT) is a promising candidate for the deorbit propulsion device of the ADR systems because of its advantages such as the absence of consumables, the absence of thrust vectoring, and the easy attachment to debris. In this presentation, the pros and cons of the EDT, its development scenario and technological issues for the ADR application are to be described.

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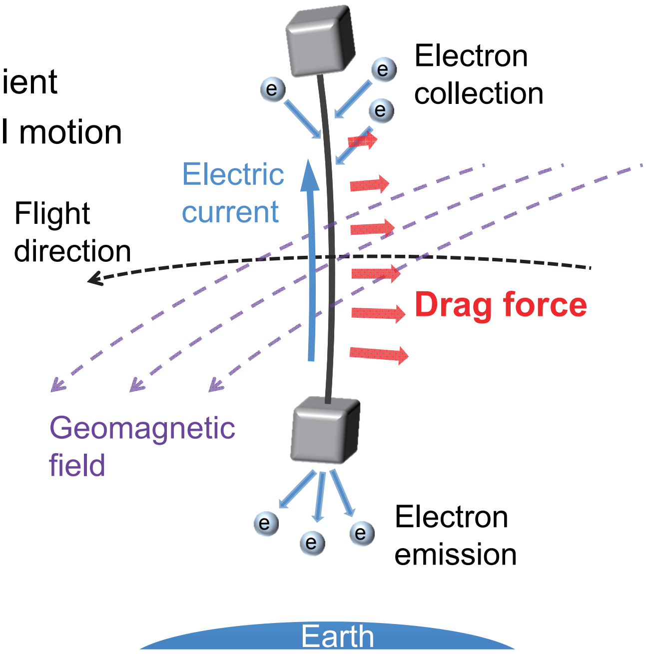
Outline

- *Electrodynamic Tether (EDT)*
- *Pros and Cons of EDT*
- *Deorbit Capability of EDT*
- *R&D Steps of EDT for Active Debris Removal (ADR)*
- *EDT Experiment on HTV-6 (KITE)*
- *EDT Specification Comparison (KITE vs ADR)*
- *What should be Improved - From KITE to ADR -*
- *Enhancement of EDT Capabilities*
- *Conclusion*

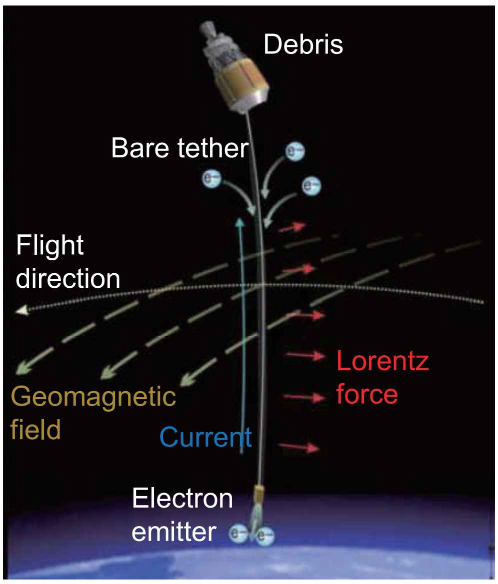
Electrodynamic Tether (EDT)

- EDT is "Propellant-free propulsion"
- Fundamentals
  - Attitude stabilization by gravity gradient
  - Electromotive force (EMF) by orbital motion
    - $V_{emf} = (v \times B) L$
  - Electron emission and collection
  - Electric current through tether
  - Lorentz force
    - $F = (J \times B) L$



EDT for Debris Deorbit - Pros -

- One of the key technologies for active debris removal (ADR) is a propulsion system for deorbit
- Pros of EDT;
  - Propellant-free
  - Less electrical power required
  - No thrust vectoring required
  - No center-of-mass consideration required on attaching
  - No strong force required on attaching
- ADR system can be simpler and cheaper using EDT for deorbit



EDT for ADR

EDT for Debris Deorbit - Cons and Countermeasures-

- Long mission duration
  - Several months to a year because of low thrust levels
    ⇒ Reducing operation cost by autonomous operation
- Possibility of mission failure due to tether being severed
  - Tether severed by impacts of small debris or micrometeoroids
    ⇒ Reducing risk by adopting “net-type” tether
- Collision risk with operational satellites
  - Collision may cause damage on operational satellites
    ⇒ Risk should be assessed against mission payoff in advance
    ⇒ Collision avoidance maneuver by on/off of tether current
- Difficulty of controlled reentry
  - Controlled reentry is difficult because of low thrust levels
    ⇒ Target selection considering a hazard to the ground
    ⇒ Reentry control using chemical propulsion at final stage

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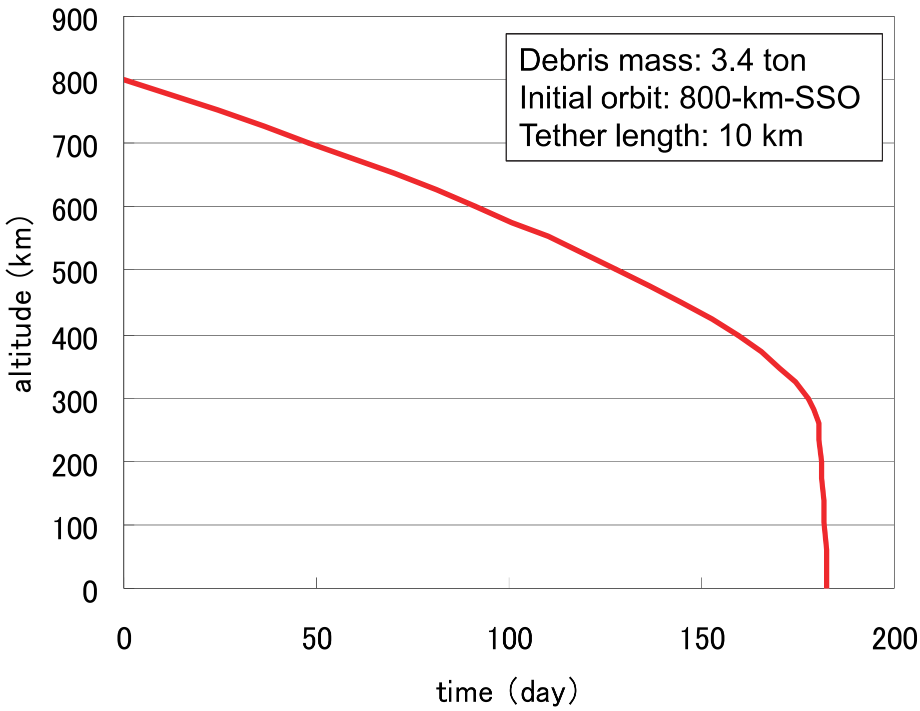
Deorbit Capability of EDT (an example)

- 10-km-EDT can deorbit 3.4-ton SSO debris from 800-km-altitude to atmosphere within a year



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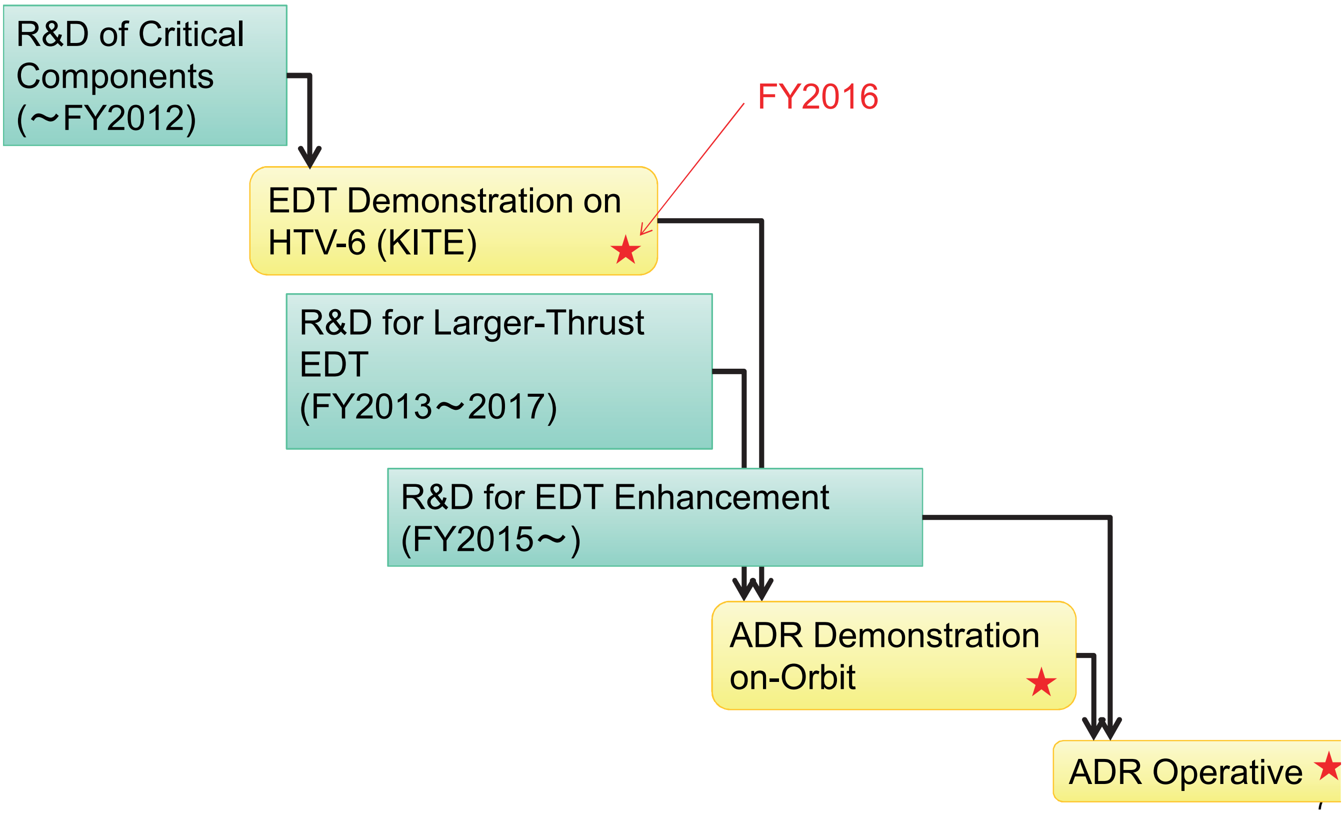
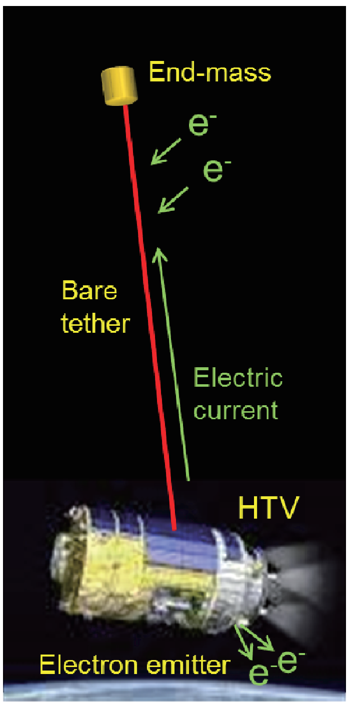
R&D Steps of EDT for ADR



KITE – On-Orbit EDT Demonstration using HTV-6



KITE Image on Orbit

Primary objective of KITE;
“To demonstrate key technologies of EDT preparing for future ADR”

KITE Specifications

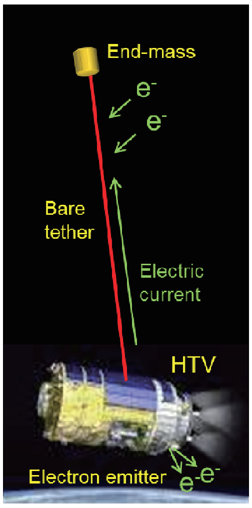
Platform	H-II Transfer Vehicle (HTV)
Mission period	7 days (planned)
Orbit	20 km (or more) below ISS orbit
Tether length	700 m (approx.)
Tether current	10 mA (approx.)
Electron collector	Bare tether
Electron emitter	Field emission cathode

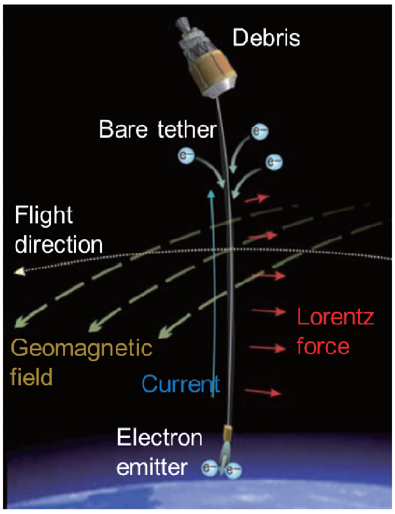
※Expected thrust: ～0.1 mN (max.)

EDT Specification Comparison - KITE vs ADR -

	Tether length	Tether current	Thrust level
EDT for ***KITE***	～ 0.7 km	～ 10 mA	～ 0.1 mN
EDT for ***ADR***	5 ～ 10 km	～ 1000 mA	～ 50 mN

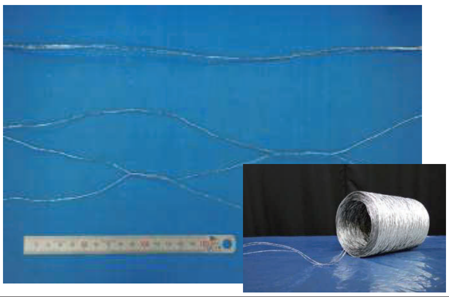
0.7 km



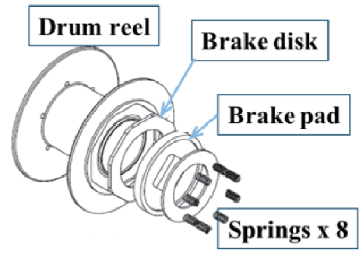


5 – 10 km

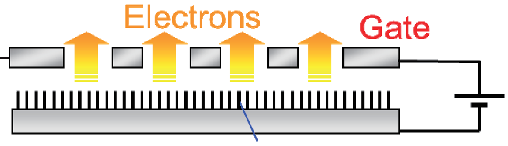
What should be improved for ADR - Tether -

Tether for ***KITE***	Length: 0.7 km, Current: 10 mA  Material: Al + SUS Tension (max.): 50 N Simple winding equipment with full human support
Tether for ***ADR***	Length: 5 ～ 10 km, Current: 1000 mA  Material: Al + SUS + Aramid Tension (max.): 160 N Semi-automatic winding equipment with less human support

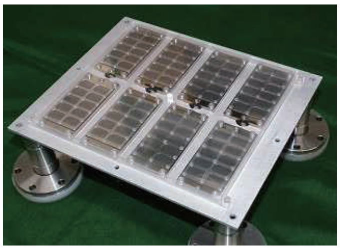
What should be improved for ADR - Deployment and Braking -

Tether Braking for ***KITE***	Length: 10 m of 0.7 km  Simple braking mechanism at the end of deployment
Tether Braking for ***ADR***	Length: several km of 5 ～ 10 km To be developed Gradual braking during the deployment

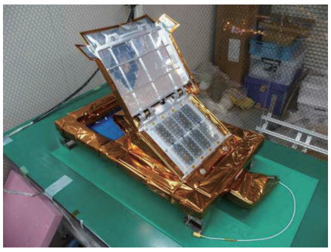
What should be improved for ADR - Electron Emitter 1 -



Field Emission Cathode

Electron Emitter for ***KITE***	Emission current: ～ 10 mA Extraction voltage: ～ 900 V  Area: 0.05 m^2 Sparse area for emission
Electron Emitter for ***ADR***	Electron emission current: ～ 1000 mA Extraction voltage: ～ 500 V To be developed Area (TBD): 0.5 m^2 Dense area for emission Various approach for larger current & lower voltage (geometries and material)

What should be improved for ADR - Electron Emitter 2 -

Electron Emitter for ***KITE***	Others  Simple opening mechanism for emitter surface protection Small commercial high-voltage converters
Electron Emitter for ***ADR***	Others To be developed Mass-&-area-saving opening mechanism for emitter surface protection High-efficient high-voltage converters

What should be improved for ADR - Larger EDT System -

System for ***KITE***	Tether voltage by EMF: ～ 120 V • HTV potential is (just) monitored • No special care for avoiding high-voltage discharge Tether current: ～ 10 mA • Small mechanical relays and resistances for tether current switching
System for ***ADR***	Tether voltage by EMF: ～ 500 V In order to avoid high-voltage discharge, • S/C potential should be monitored and controlled • Geometrical design needed Tether current: ～ 1000 mA • High-power relays and resistances for high-current hot switching

Enhancement of EDT Capabilities

Operation-Free

- Final goal (or conceptual ideal) of EDT propulsion is "Operation-Free" system
- This means no operation needed after tether deployment
  - No electrical power for EDT devices (electron emitters and etc.)
  - No manual controlled operation

⇒ Passive electron emitter

⇒ Power generation by EMF

Controlled Reentry

- "Uncontrolled Reentry" is one of major cons of EDT

⇒Controlled reentry by using chemical propulsion at the final stage of de-orbit

Conclusion

- Electrodynamic Tether (EDT) is a prospective candidate as de-orbit propulsion of active debris removal (ADR) systems
- Key technologies of EDT will be demonstrated in this winter on HTV-6
- R&D for enlarging EDT system is being performed toward ADR
- "Operation-Free" and "Controlled-Reentry" are advanced concepts for enhancing EDT capabilities