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導電性テザー実証実験（KITE）にて得られた成果

Results from In-Orbit Electrodynamic Tether Experiment (KITE)

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デブリデオービットへのエレクトロダイナミックテザー（EDT）技術の応用を目指して、HTV6 号機を利用した、約 1 週間の軌道上実証実験（KITE、Kounotori Integrated Tether Experiment）を2017年初頭に実施した。約700mのテザーを伸展し 10mA 級のテザー電流を流すことを計画していたが、エンドマス保持・放出機構の不具合により、残念ながらテザーを伸ばすことは出来なかった。一方、カーボンナノチューブ電界放出型電子源（FEC）やプローブ機能付き宇宙機帯電モニタ（LP-POM）などの他の KITE 機器はミッション期間を通じて良好に動作し、貴重な軌道上データを取得した。本発表では、その代表例として、低軌道環境での FEC の耐久性や、電離層プラズマ中での HTV 帯電挙動などの評価結果を示すとともに、KITE の成果を活かした今後の展開を紹介する。

To demonstrate electrodynamic tether technologies for space debris removal, JAXA planned and conducted an in-orbit tether experiment called “KITE” on the H-II Transfer Vehicle 6 (HTV-6) in early 2017. Although the tether could not be deployed due to a mechanical malfunction of the end-mass releasing mechanism, other KITE devices such as a carbon-nanotube-based field-emission-cathode (FEC) and an electric potential monitor (LP-POM) operated well without any critical trouble. In the workshop, some examples of in-orbit data on the FEC and LP-POM and the current and future activities based on KITE technologies are to be presented.

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Results from In-Orbit Electrodynamic Tether Experiment (KITE)

by
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Presentation Outline

- Electrodynamic Tether for Debris Deorbit, Pros and Cons
- KITE Objective and Mission Outline
- Results of KITE
- Current Activities

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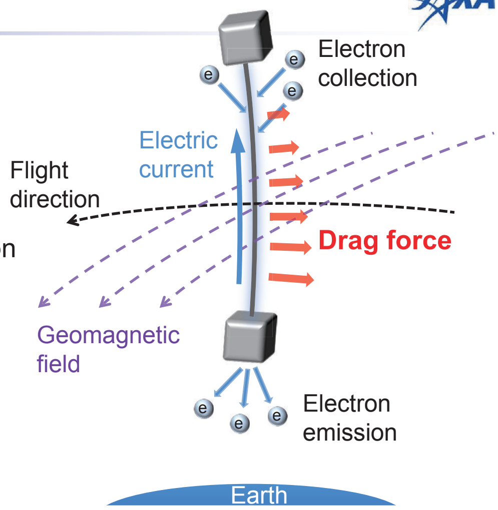
Electrodynamic Tether (EDT)

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



EDT for Debris Deorbit - Pros -

- Deorbit propulsion is important for ADR
- 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

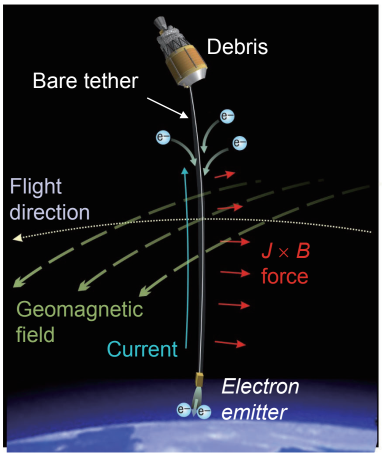


Image of EDT for debris removal

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EDT for Debris Deorbit - Cons and Countermeasures-

- 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 thruster or on/off of tether current
    - ⇒ "Converging" tether
- 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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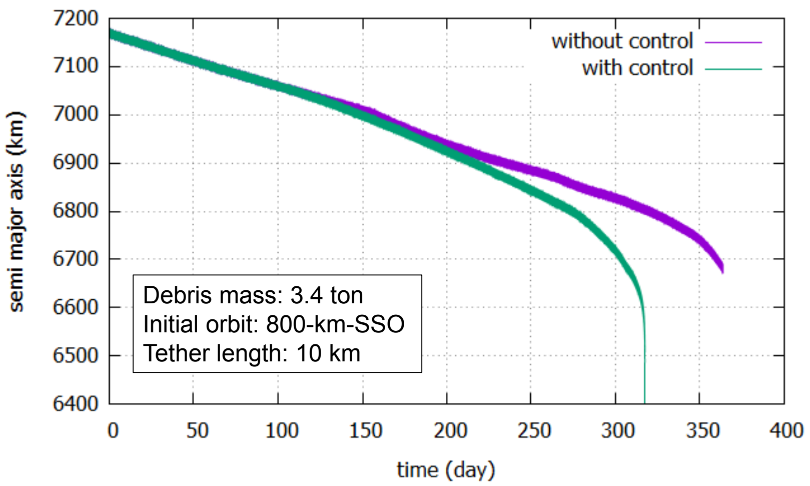
Deorbit Capability of EDT (an example)

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



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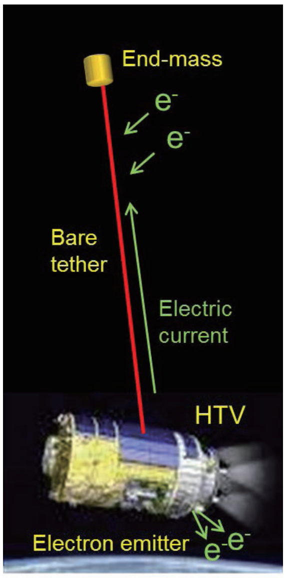
KITE - In-Orbit Demonstration of EDT -



KITE Image on Orbit

Objective: To demonstrate key technologies of EDT preparing for future ADR

KITE Specifications (Planned)

Platform	H-II Transfer Vehicle 6 (HTV-6)
Mission period	7 days
Orbit	20 km (or more) below ISS orbit Altitude: 300 – 400 km Inclination: 52 deg.
Tether length	700 m (approx.)
Tether current	10 mA (approx.)
Electron collector	Bare tether
Electron emitter	Field emission cathode

※Expected thrust: ～0.1 mN

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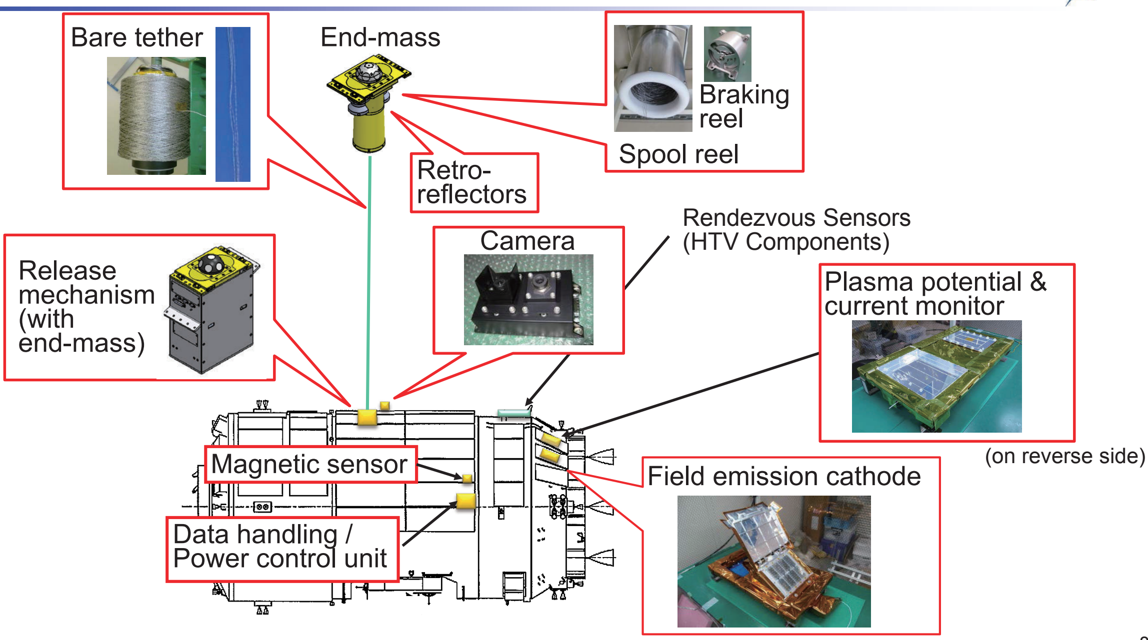
KITE Components



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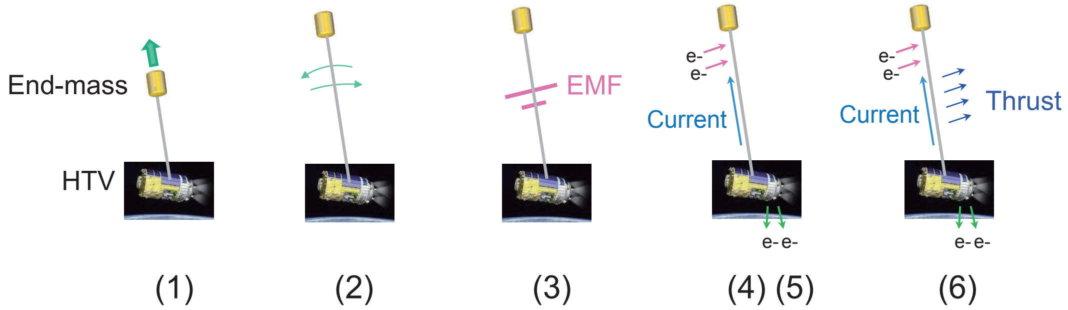
Planned Mission Outline of KITE

- (1) Deployment of bare tether
- (2) Motion monitoring of tether and end-mass
- (3) Electrical potential generation by self-induced electromotive force
- (4) Electron collection by bare tether
- (5) Electron emission by field emission cathode (FEC)
- (6) Thrust estimation



Results of KITE - Summary -

- KITE mission began on January 28, 2017
- End-mass could not be released due to malfunction of its holding & releasing mechanism, so, tether deployment was unsuccessful
- Mission conducted through January 28 to February 4
- Field emission cathode (FEC), Plasma potential monitor (LP-POM) and other components operated well throughout mission period and many meaningful data were obtained

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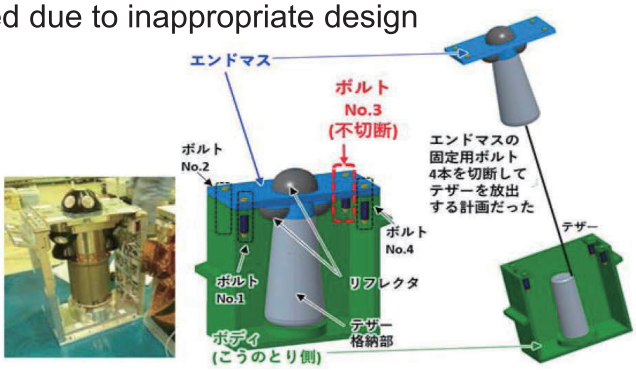
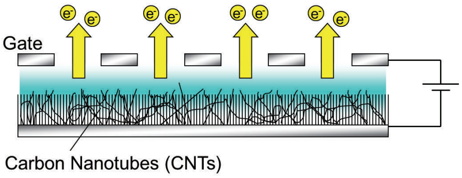
Malfunction of End-mass Holding & Releasing Mechanism

- At the first step of KITE, command for releasing end-mass was executed, but release was not detected
- Although various attempt were performed throughout mission period, end-mass could not be released finally
- Investigation team concluded that one of four separation volts, which fix end-mass to HTV body, was not separated due to inappropriate design

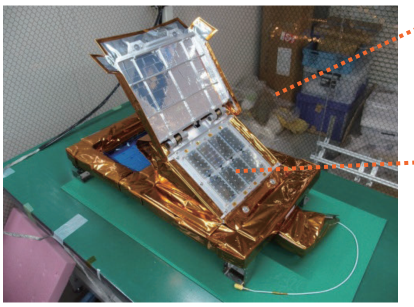


End-mass holding & releasing mechanism

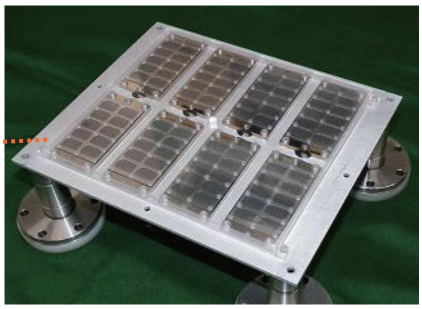
Successful Operation of Carbon-Nanotube Based FEC



Schematic of CNT-FEC



FEC Module



FEC-Head

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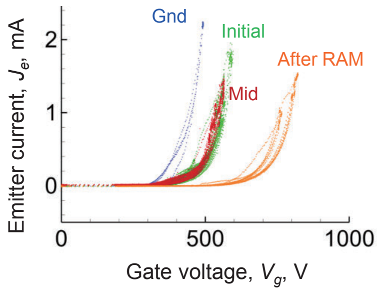
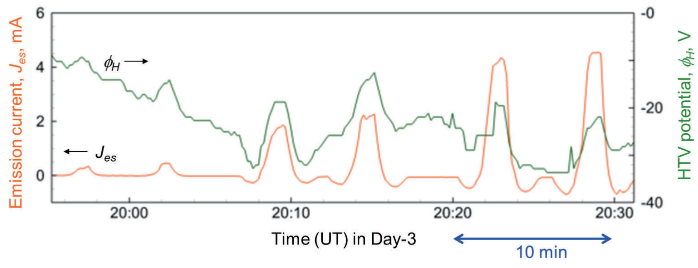
Successful Operation of Carbon-Nanotube Based FEC

- Highest electron emission current by FEC ever demonstrated in space (5.8 mA)
- FEC showed decent tolerance to atomic oxygen in LEO
- HTV potential changed by active electron emission



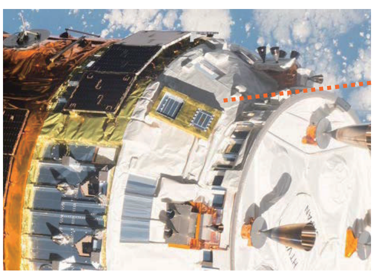
I-V Characteristics during KITE

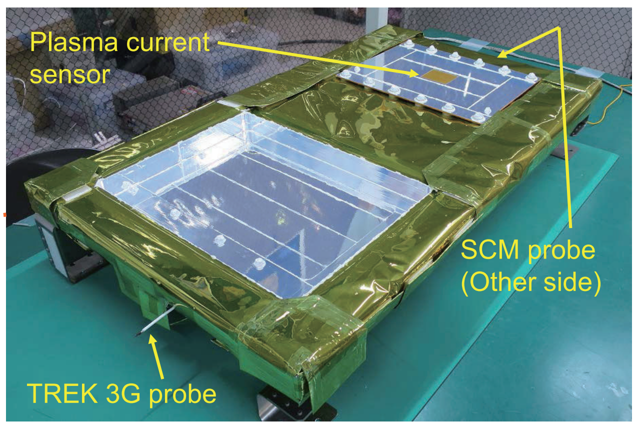


HTV Potential change by active electron emission

Successful Operation of LP-POM

- Electrical potential difference between HVT body and ambient plasma was measured by Potential Monitor (called LP-POM)
- Two potential sensors
  - TREK-3G Probe
  - SCM Probe
- Plasma current sensor





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Successful Operation of LP-POM

- HTV potential and plasma current was monitored throughout HTV flight (launch to reentry)
- Results are being verified by comparing them with existing physical models and ISS sensors

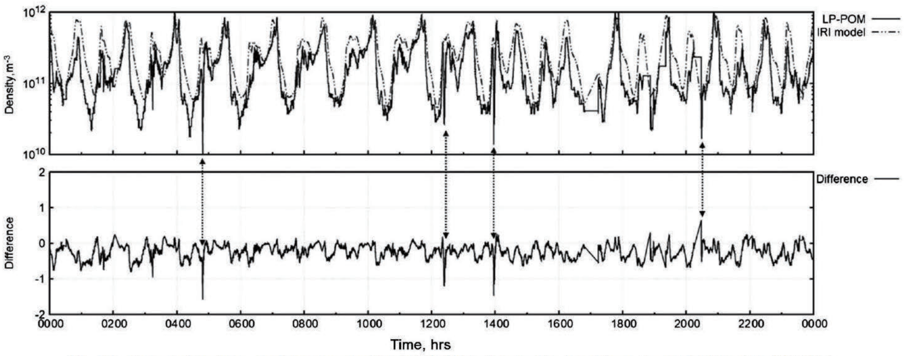
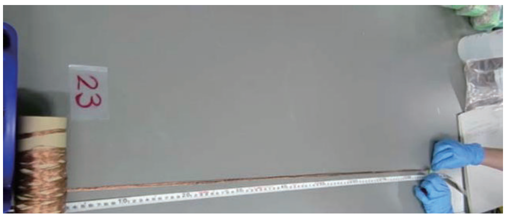


Fig. 14　Comparison between data measured by LP-POM and data calculated from the model based on IRI-2016.

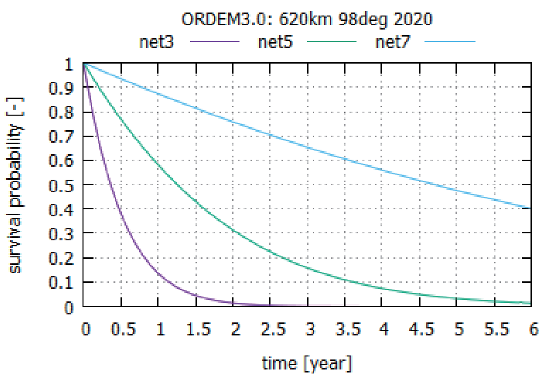
Okumura et.al."Charging of the H-II Transfer Vehicle at Rendezvous and Docking Phase", Journal of Spacecraft and Rockets

Current Activities on Tether

- "Converging" tether for lowering collision risk
  - Automatically converges in case tether is severed or malfunctions
- Tether survivability estimation



"Converging" tether



Example of tether survivability estimation

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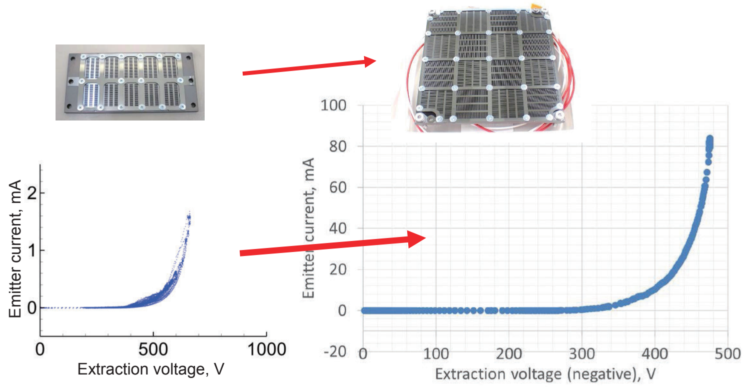
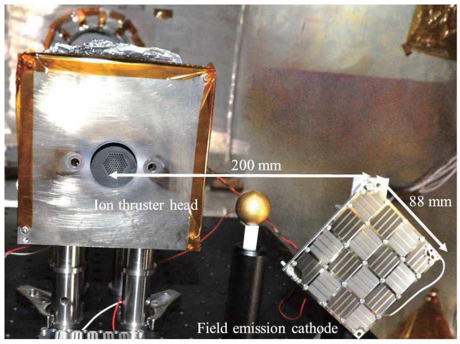
Current Activities on FEC

- Improvement in emission current density and durability
- Application to electric propulsion



I-V comparison between KITE and current FEC



Coupling operation with ion engine

N. Yamamoto et al. "Demonstration of Wide Throttling Range Ion Engines," Joint Prop. Conf., AIAA-2018-4815.

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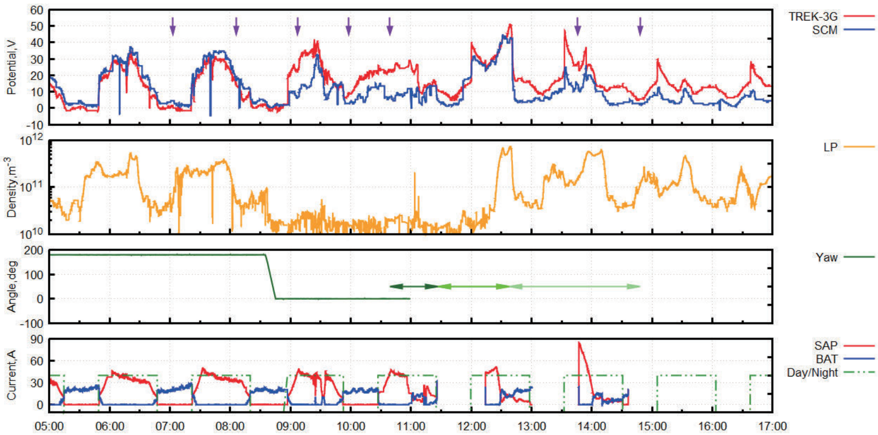
Current Activities on LP-POM

- Further investigation of In-orbit data in scientific sense
- Application to debris capturing phase



Time, hrs	Event	Note
703	5km behind ISS	Solo flight phase
806	Arriving at 500 m under ISS	
907	Depart from 250 m under ISS	
958	Depart from 30 m under ISS	
1039	Capture	SSRMS operation
1346	CBM latching operation starts	
1448	CBM berthing	ISS attached phase

Okumura et.al."Charging of the H-II Transfer Vehicle at Rendezvous and Docking Phase", Journal of Spacecraft and Rockets

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Summary

- Pros and cons of electrodynamic tether (EDT) for ADR were shown
- KITE mission (In-orbit experiment of EDT), conducted in early 2017, was reviewed
- Studies on EDT elements are on-going for enhancing advantages of EDT and for exploiting KITE results to other applications

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