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デブリ除去のための導電性テザー技術の検討

Study of Electrodynamic Tether technology for Active Debris Removal

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JAXA では，低軌道上のデブリ除去技術の有力な候補として導電性テザー（EDT）の研究を進めている．EDT はテザーに流れる電流と地球磁場との干渉を利用するため，推進剤を必要とせずに軌道変換のための推力を得られる高効率な推進系である．EDT システムを搭載したデブリ除去衛星を設計するためには，数 km 級テザーシステムの重量・体積，電力や電位，衛星への外乱トルクを確認する必要がある．そこで，デブリ除去衛星ミッションのデオービットフェーズにおける EDT 伸展および伸展終了後の EDT システムの挙動に関する数値解析を実施してきた．本発表ではデブリ除去衛星での EDT システムの概要を紹介する．

The Japan Aerospace Exploration Agency (JAXA) has been investigating electrodynamic tether (EDT) as a very promising candidate for Active Debris Removal (ADR) technology in the lower earth orbits. The EDT is an advanced propulsion system which can generate sufficient thrust for orbital transfers without the need for propellant by utilizing interactions between Earth’s magnetic field and currents through the tether. In order to design the debris removal satellite installing the EDT system, the mass and volume of several kilometers tether system, required electrical power, electrical potential, and disturbance torque to the satellite should be confirmed. Consequently, the numerical simulations for EDT system dynamics during and after tether deployment in the phase of deorbiting in the removal satellite’s mission have been conducted. This presentation introduces the overview of EDT system for the removal satellite.

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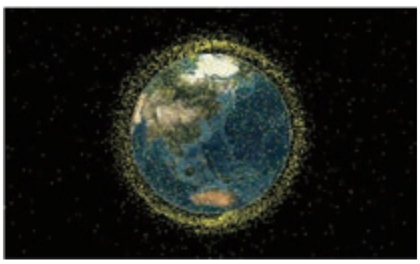
Introduction

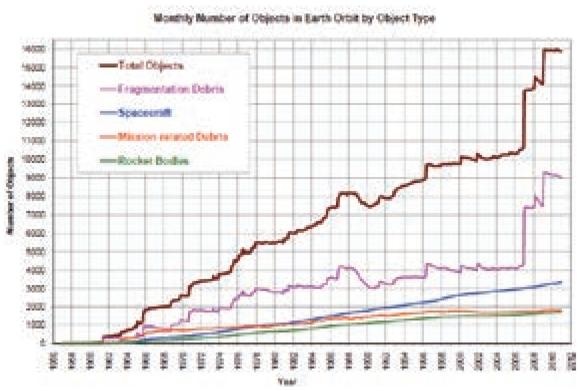
It is predicted that

- Catastrophic collisions will occur every five to ten years mainly in the crowded orbits due to rapid increase of space debris
- The number of debris objects will increase even with no new launches

➡ The active debris removal (ADR) from the crowded orbits must begin as soon as possible



Space debris in LEO



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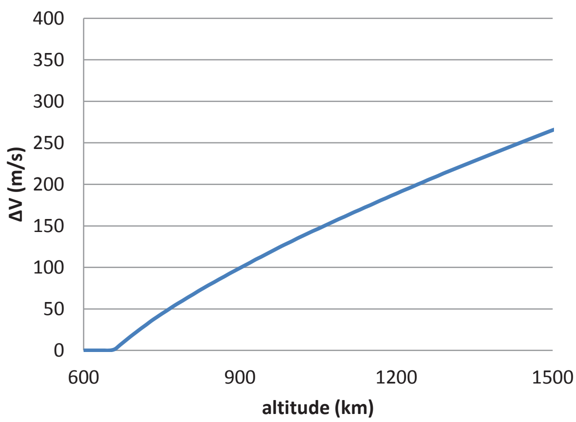
Active Debris Removal

- ΔV :~100 m/s is needed for deorbit of several tons of mass from altitude between 800km and1000km to orbit whose lifetime is 25 years (650 km)
- More propellant (ΔV) is needed for
  - ➢ deorbit to lower altitude
  - ➢ deorbit with controlled re-entry



ΔV needed for deorbit to orbit whose lifetime is 25 years(650 km)

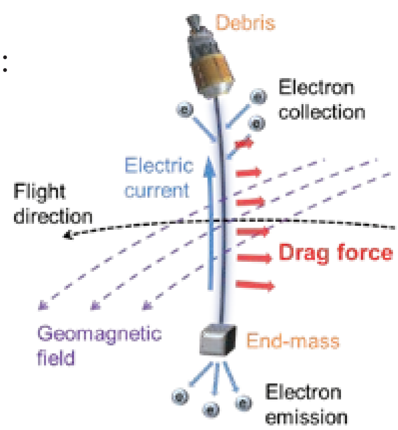
Electrodynamic tether

- Electrodynamic Tether (EDT) is "Propellant-free propulsion"
- Fundamentals
  - ➢ Attitude stabilization by gravity gradient
  - ➢ Electromotive Force (EMF) by orbital motion :

$$V_{EMF} = (\mathbf{v}_{orb} \times \boldsymbol{B}) \cdot \boldsymbol{L}$$

  - ➢ Electron collection and emission
  - ➢ Electric current through tether
  - ➢ Lorentz Force :

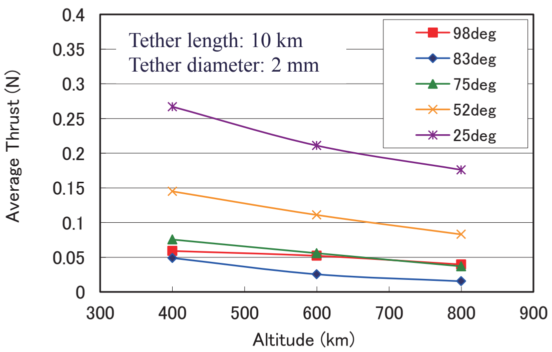
$$F_{lorentz} = (\boldsymbol{I} \times \boldsymbol{B}) \cdot \boldsymbol{L}$$



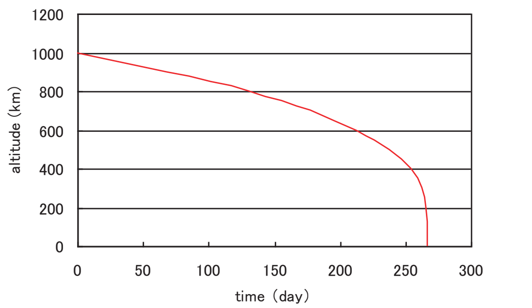
Principle of EDT System

Electrodynamic tether

- EDT thrust becomes smaller in higher inclination orbits, but is still great enough to transfer debris from SSO
- EDT with a length of 10km can transfer 1.4 ton debris in orbit altitude 1000 km, inclination 83deg to atmosphere within one year
- EDT of 5~10km is needed to generate sufficient thrust



Average thrust of EDT in altitude of each inclination



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

Advantages of EDT for ADR

- **High efficient propulsion**
  - "Propellant-free propulsion"
  - Utilizing interactions between Earth's magnetic field and currents through the tether
- **Simple system**
  - Propellant tank, valves and pipes are not required
  - System can be simple, light weight and compact
- **Easy attachment to debris**
  - Not requiring firm attachment because of small thrust of EDT
  - Not requiring alignment between thrust axis and debris' C.G because small thrust is distributed along tether
- **No need of thrust vectoring control**
  - EDT thrust is automatically directed towards lowering altitude
  - In general propulsion, thrust direction must be controlled by active attitude control for deorbit

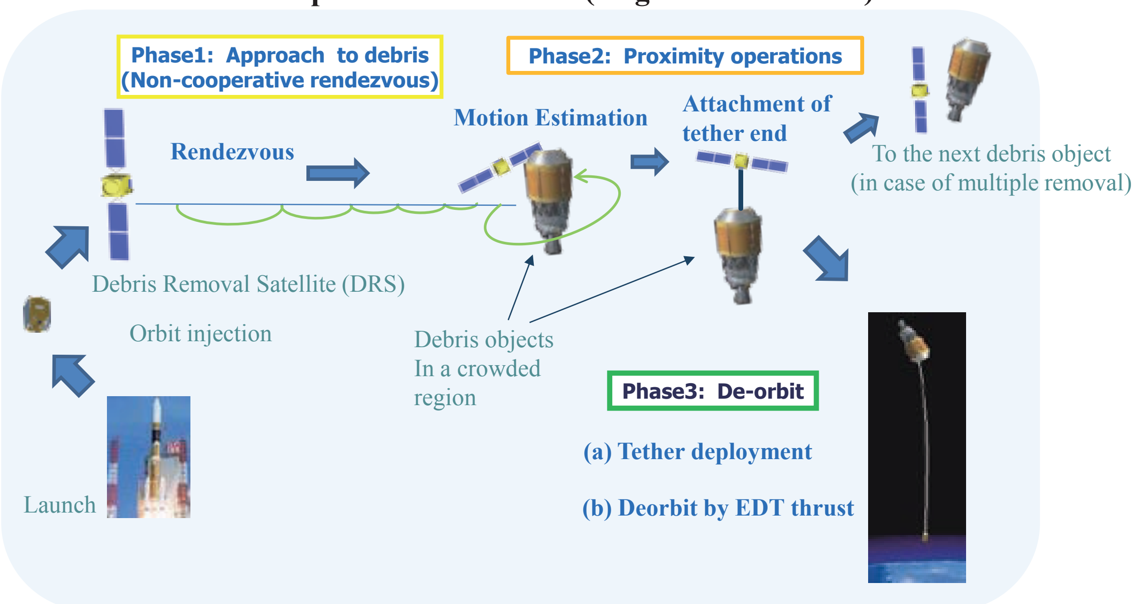
Deorbit Propulsion System for ADR

Method	Fuel	Electric power	Attachment to debris	Thrust vector control	Applicable orbit	Applicable debris
Electro-dynamic tether(EDT)	◎ 0 kg	○	○ only tether end	◎ not necessary gravity gradient stability	○ LEO	Intact debris in LEO that does not require controlled reentry
Chemical (Liquid/ Solid)	△ > 100 kg	◎	△ strong force considering thrust axis	△ necessary	◎	Intact debris in LEO that requires controlled reentry
Ion beam irradiation	○ high efficiency	△ high	◎	△ necessary	◎	GEO debris
Drag augment-ation	◎ 0 kg	◎	○	◎ not necessary	△ lower LEO	Small satellite in lower LEO

Operation Scenario for Active Debris Removal

- JAXA's roadmap for realizing ADR with EDT

①Key technology demonstration (target : 2016)
②System demonstration : single debris removal (target : 2020)
③Practical ADR : multiple debris removal (target : 2020s middle)

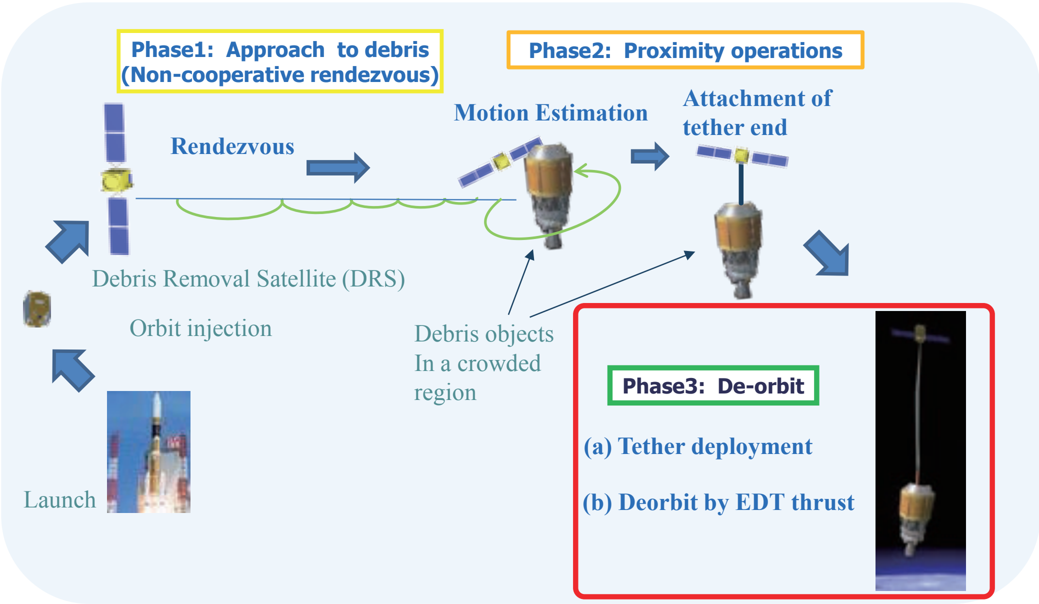


Operation scenario of practical ADR

Operation Scenario for Active Debris Removal

②System demonstration (target : 2020)

- target debris object : H-IIA rocket upper stage (altitude: 620km, inclination: 98deg)
- Single debris removal



Operation scenario of System demonstration

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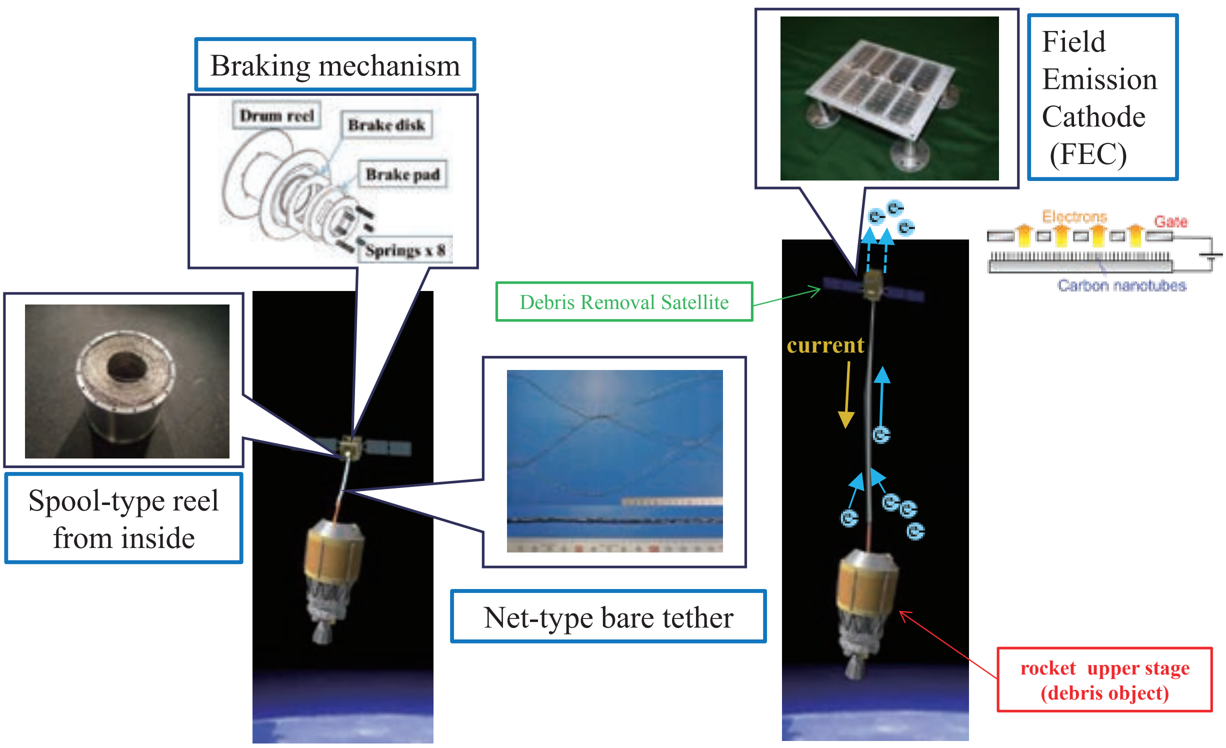
Key components of EDT system



(a) Tether deployment **(b) Deorbit by EDT thrust**

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EDT System

In order to generate enough thrust for deorbiting large debris objects from crowded orbits

- ❑ Tether length : 5~10 kilometers
  - ➢ Gravity gradient is increasing
    →Tether should be made of hi-specific strength material
  - ➢ Deployment velocity and tether libration during deployment are increasing
    → Braking mechanism for deceleration is needed
    Tether libration suppression by thruster is needed
- ❑ Electrical current: Several Amperes

Mission of System demonstration

- target debris object : H-IIA rocket upper stage debris
  (altitude: 620km, inclination: 98deg)
- Single debris removal
  - ❑ tether deployment dynamics
  - ❑ EMF, Current, thrust during deorbit

} Numerical simulation

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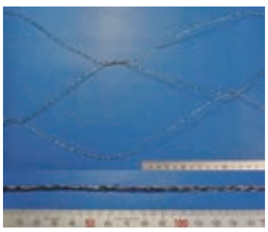
Tether

Tether : net-type bare tether

Tether	Al-SUS tether	Al-Aramid tether
Development step	Key technology demonstration (~2 km)	System demonstration / Practical ADR (5~10 km)
diameter	1.01 mm	2.08 mm
line density	0.96 g/m	1.69 g/m
material	Aluminum wires + Stainless steel wires • Al : Conductive • SUS: tensile strength	Aluminum wires + conductive aramid filaments • Al : Conductive • conductive aramid: high-specific strength, preventing discharge
Withstand tension force	55 N	140 N



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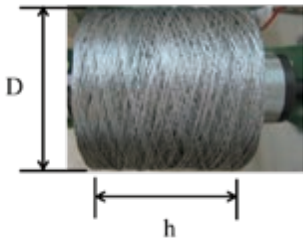
Mass and Volume of tether spool

Tether	Al-SUS tether	Al-Aramid tether	
length	2 km	5 km	10 km
mass	1.92 kg	8.45 kg	16.9 kg
volume	2.48×10^6 mm^3	2.47×10^7 mm^3	4.86×10^7 mm^3
Height	150 mm	300 mm	300 mm
Diameter of tether spool	170 mm	**330 mm**	**460 mm**

Estimated value

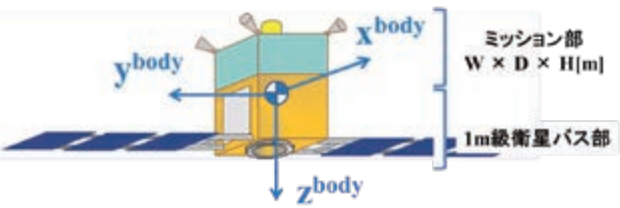
Tether spool（2 km Al-SUS tether）
h:150mm



Debris Removal Satellite

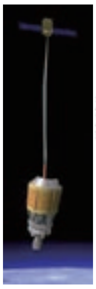
			Size W × D × H	Mass
Debris Removal Satellite			**1.0 × 1.0 × 1.5 [m]** **	**360 kg**
	Bus		1.0 × 1.0 × 1.0 [m]	—
	Mission		1.0 × 1.0 × 0.5 [m]	—
		Tether spool	・10 km: φ0.46 × 0.3 [m] ・5 km : φ0.33 × 0.3 [m]	—
H-IIA rocket upper stage debris (620km, 98deg)			**φ4.0 × 10 [m]**	**3000 kg**

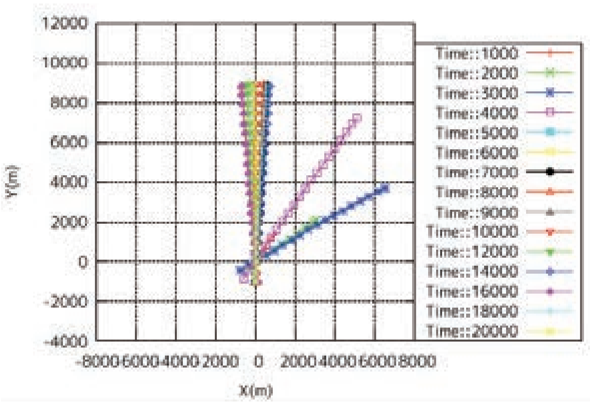
** SAP is neglected



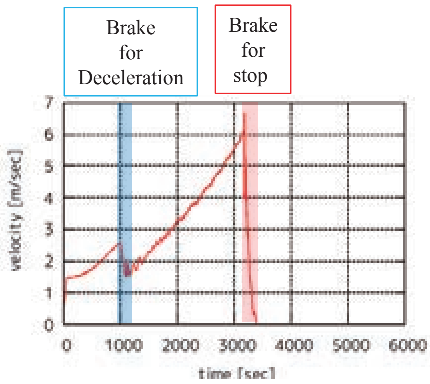
Tether Deployment

- In order to deploy the whole tether length (10km),
  - Deceleration braking is activated at in-plane libration angle 45 deg (100 sec)
  - Thruster is activated for tether libration suppression (9.2N, 600 sec)
- Braking for deceleration has been studied
  - Deployment friction
  - Passive braking mechanism





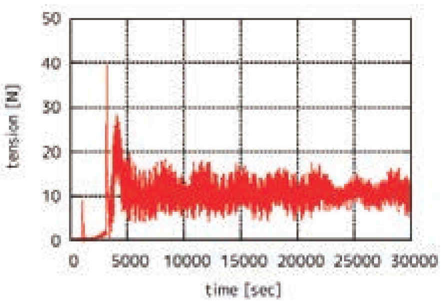
Change in form of tether (Hill's frame)



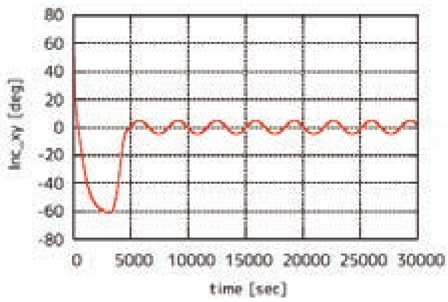
history of deployment velocity (~6000 sec)

Tether Deployment

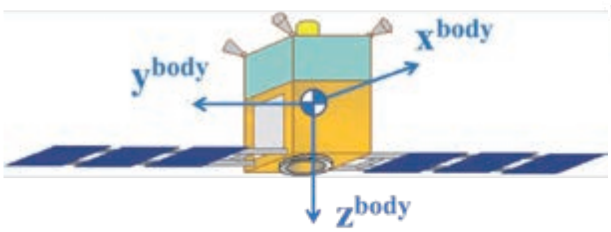
- Max tension : 40 N < withstand tension force of tether : 140 N
- In-plane libration angle after deployment : ±5 deg
- Disturbance torque : ±1 Nm

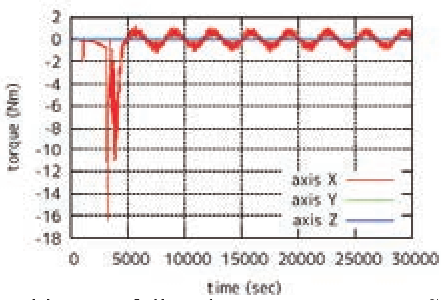


history of tension



history of in-plane libration angle



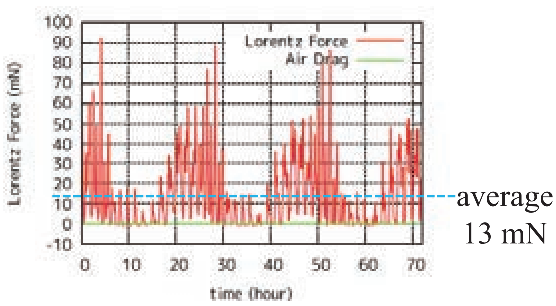


history of disturbance torque to DRS

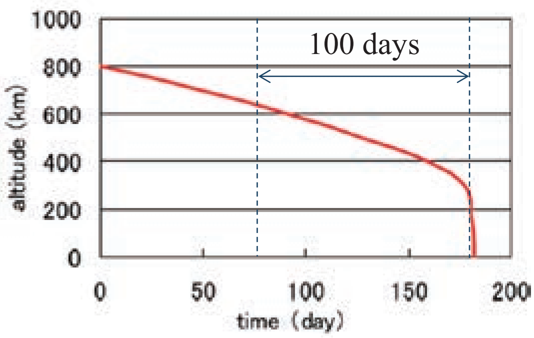
* axis y, z : 0

Deorbit by EDT thrust

- Lorentz force : 13 mN (average)
- The term of deorbit by thrust of EDT of 10km : about 100 days
  - In the mission of system demonstration, the deorbit phase is supposed to be stopped in 1 month



history of lorentz force



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

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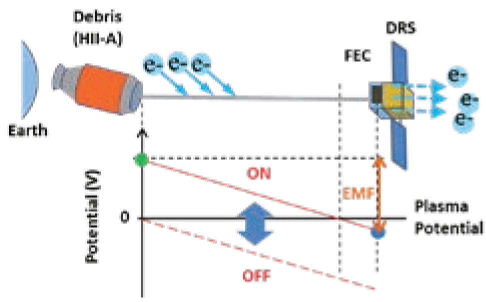
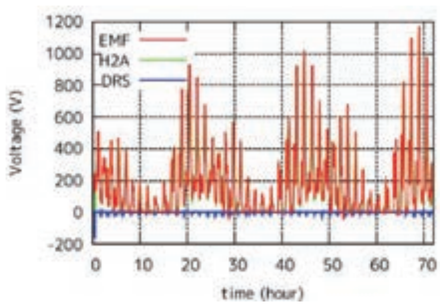
Deorbit by EDT thrust

- electrical potential
  - Debris side >> plasma (0V) > DRS
  - Electromotive Force V_{EMF} : 1000V (max)

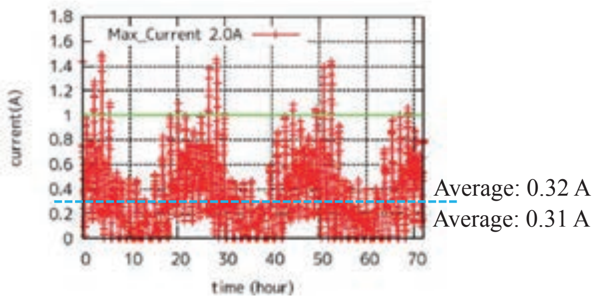


- Current
  - Current max value: 1.5A
  - High limit value 1.0A: 0.31A(average)
  - High limit value 2.0A: 0.32A(average)

not much different



history of electrical potential



history of current

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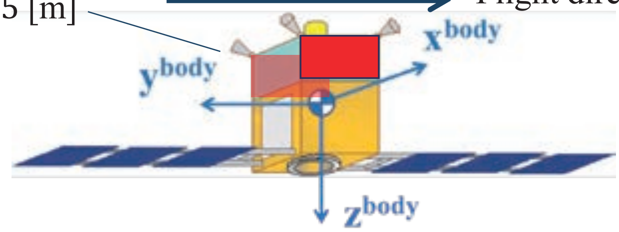
FEC on satellite

- Field Emission Cathode (FEC) should be attached on 2 parallel faces
  - Ram face: CNT is deteriorated by AO
  - Wake face: decrease of plasma density
  - Area: 1.0 × 0.5 [m^2] × 2 [face] = **1.0 m^2 (max)**



Expected performance of FEC

High limit value	Required area	Electrical power	
		Average	max
1.0 A	0.43 m^2	40 W	130W
2.0 A	0.87 m^3	40W	260 W

Conclusion

- EDT is a very promising candidate for ADR propulsion because of
  - high efficiency
  - Simple system
  - easy attachment to debris
  - no need of thrust vectoring control
- JAXA has a roadmap for realizing Active Debris Removal with EDT
  - Key technology demonstration
  - System demonstration
  - Practice ADR
- Deorbit by EDT thrust using debris removal satellite has been studied
  - Tether deployment dynamics
  - EMF, current, thrust during deorbit