

Preparation for On-Orbit Demonstration of Electrodynamic Tether on HTV

*Presented at Joint Conference of 30th International Symposium on Space Technology and Science
34th International Electric Propulsion Conference and 6th Nano-satellite Symposium,
Hyogo-Kobe, Japan
July 4–10, 2015*

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Abstract: A flight demonstration of an electrodynamic tether (EDT) on the H-II Transfer Vehicle (HTV) is planned by JAXA. This demonstration plan is called the Konotori Integrated Tether Experiment (KITE). KITE is the first step toward the development of active debris removal (ADR) systems using EDTs. EDTs have many advantages that make them promising candidates for deorbit propulsion systems for ADR, including the absence of consumables, low electric power requirements, the absence of thrust vectoring, and easy attachment to debris. The primary objective of KITE is to demonstrate the key EDT technologies for ADR. KITE mission will be conducted prior to re-entry of the HTV-6. A 700-m-length bare tether, which is deployed from the HTV body toward the zenith, collects electrons from the ambient space plasma, and a field emission cathode on the HTV emits 10-mA-level electrons into the plasma. This collector–emitter combination can provide complete propellant-free deorbit propulsion for ADR.

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I. Introduction

INCREASING levels of space debris in low Earth orbit have become a serious problem for human space activities. Collisions between space debris and spacecraft have occurred and it is suspected that some unexplained spacecraft malfunctions have been caused by collisions with small space debris. Some estimation models of future space debris populations predict continuous growth, even if the 25-year orbital lifetime regulation is strictly adhered to.¹

Decreasing the population of existing space debris is necessary for remediating this problem. The most effective way to mitigate the chain reaction of the space debris increase is to remove large pieces of space debris from crowded orbits. A report has indicated that removing five large pieces of space debris from crowded orbits per year will stop the continuous growth of the debris population.² “Five per year” is not an unrealistic goal for active debris removal (ADR) missions; therefore, it is worthwhile to research and develop the technologies necessary for ADR. Indispensable technologies for ADR are classified broadly into three categories: guidance and control systems for approaching debris objects, mechanisms for attaching propulsion devices to the debris, and propulsion systems for deorbiting the debris. The scope of this study is limited to the third one of these key technologies.

We have proposed the use of electrodynamic tether (EDT) propulsion for debris deorbit, as shown in Fig. 1. The EDT generates thrust by an interaction between the tether current and the geomagnetic field; therefore, it does not require a propellant. In addition, in the application to the debris deorbit, high electrical power is not necessary because the electromotive force can drive the tether current. Other strong points of EDTs for debris removal include no requirement for thrust vectoring because of the substantial EDT thrust direction determined by the current–magnetic interaction and no restriction on the attachment point to the debris because of the lack of necessity of considering the center-of-mass of the object. These points become important advantages because the ADR system should be simpler and cheaper, and lowering the cost is one of the most important indices for the development of ADR systems.

On-orbit operation of the EDT has been performed or planned several times.^{3,4} Although many important data on the EDT have been obtained in these experiments, our original experiment in space should be undertaken to design and develop the EDT system for ADR. This paper describes the details of the on-orbit demonstration experiment of the EDT planned by JAXA, known as the Konotori Integrated Tether Experiment (KITE).

II. Overview of KITE^{5,6}

A conceptual image of KITE is shown in Fig. 2. Devices and instruments for KITE are installed on a Japanese cargo transfer spacecraft, the H-II Transfer Vehicle (HTV or Konotori). Primary objectives of KITE are to obtain data on the fundamental characteristics of the original EDT components and to increase their TRL to design and develop an EDT system for debris remediation. Major mission specifications, shown in Table 1, were determined to achieve these objectives under some restrictions due to the present technology levels and other requirements. Deorbiting of the HTV using the EDT thrust is beyond the scope of KITE mission.

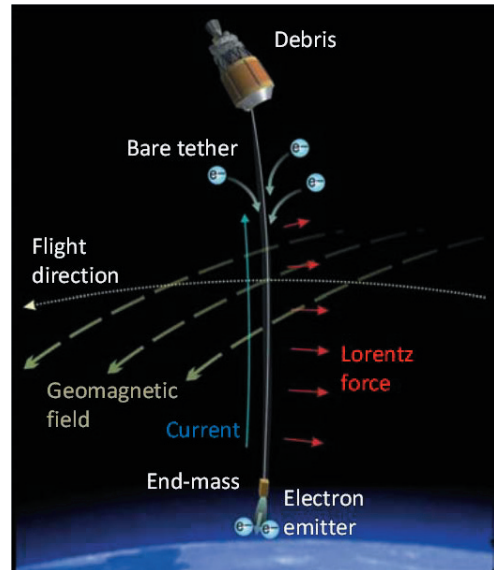


Figure 1. EDT for ADR.

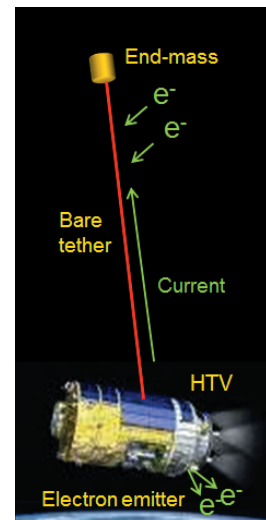


Figure 2. EDT experiment on the HTV (KITE).

KITE will commence after the HTV leaves the international space station (ISS), and the planned mission period is 7 days before the re-entry of the HTV. The tether will be deployed to its zenith considering the direction of the induced electromotive force and the position of the electron emitter to be installed on the HTV. A bare tether will be used as an electron collector, and a field emission cathode (FEC) will be used as an electron emitter. This combination can provide a completely propellant-free EDT system. An approximate tether length of 700 m has been determined to satisfy the electromotive force requirement for tether current driving and to meet the constraint set by the specification of the laser sensor of the HTV, which will be used for measuring the distance from the HTV to the end-mass. A tether current level of 10 mA has been determined to be at least comparable to the expected natural current due to charged particles from the ambient plasma.

Table 1. Major mission specifications of KITE.

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

A. Mission Schedule

The present plan for the daily mission schedule of KITE is shown in Table 2. On Day 1, the 700-m-tether is to be deployed after the checkout of KITE components and the tether vibration amplitude is to be alleviated using HTV thrusters. This vibration relaxation is to be done to facilitate the succeeding EDT operation and measurements. On Day 2, the tether vibration behavior, the tether voltage induced by the electromotive force, and the tether current due to the transfer of charged particles from/to the ambient plasma are to be measured. On Day 3, the initial checkout operation of the FEC is to be done, following which the effect of the electron emission from the FEC on the electrical potential of the HTV with reference to the space plasma is to be evaluated. On Day 4, changes in the tether current and voltage are to be measured during the repetition of the on/off operation of the FEC under several operating conditions. On Day 5, the FEC is to be operated in an automatic mode and the autonomous operation of the EDT system is to be demonstrated. On Day 6, the electron emission current from the FEC is to be set at the maximum level and the measurement of the change in the tether vibration amplitude due to EDT thrust is to be

Table 2. Daily mission plan of KITE.

Day	Event
Day 1	Checkout of KITE devices and instruments
	Deployment of tether
	Alleviation of tether vibration amplitude by HTV thrusters
Day 2	Measurement of tether dynamics and tether voltage
Day 3	Checkout of FEC
	Measurement of HTV electrical potential with and without FEC operation
Day 4	Measurement of EDT current–voltage characteristics at various operating conditions
Day 5	Autonomous EDT operation
Day 6	Measurement of change in tether vibration amplitude by EDT thrust (Extra success)
Day 7	Severing tether

attempted by appropriately controlling the on/off operation of the electron emission timing. This thrust measurement is one of the extra success items of KITE. On Day 7, the tether is to be severed to avoid causing troubles for the re-entry operation of the HTV.

III. KITE Components

Devices and instruments for KITE are to be installed on various locations on the HTV, as shown in Fig. 3. The major components for KITE are the tether, reels for housing and braking, end-mass, release mechanism of the end-mass, camera for tether dynamics observation, electron emitter, electrical potential monitor, magnetic sensor (MAGS), and data handling unit/power control unit (DHU/PCU). Functions of each component are described in this section.

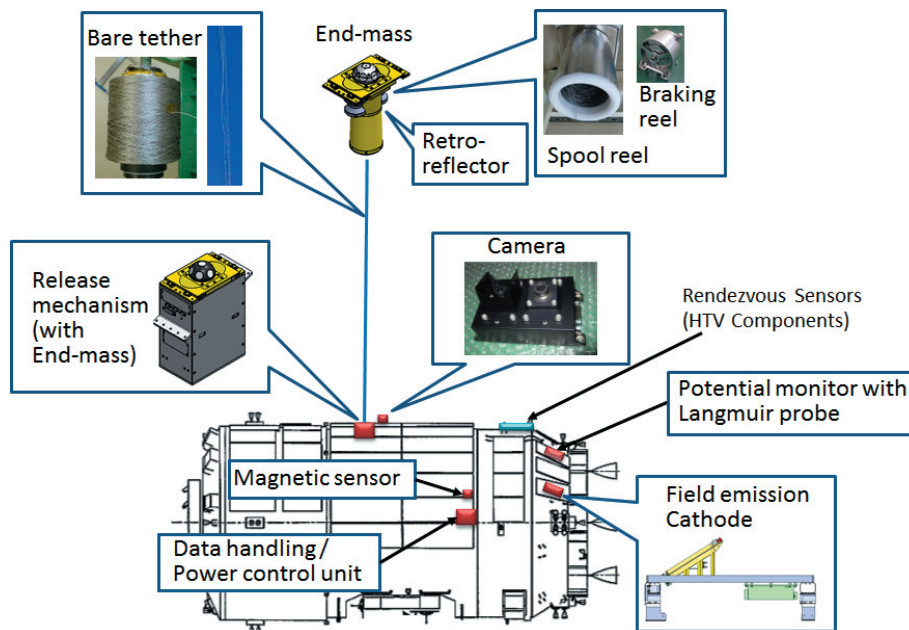


Figure 3. KITE components on the HTV.

A. Tether and Reel ⁷

The roles of the bare tether include electron collection from the ambient space plasma, tether current driving by the electromotive force, and generation of the Lorentz force. The total length of the tether is approximately 720 m. The tether has a mesh structure, as shown in Fig. 4, in order to avoid tether severing by impacts from small-sized debris. Each yarn comprises a thin aluminum and stainless-steel wire. The surface of the yarn is coated by a solid lubricant material possessing electrical conductivity.

The 720-m-length tether, which is rolled as shown in Fig. 4, is housed in the end-mass in the initial condition. The last 10 m of the tether is connected to a braking reel, which is a drum-type reel with intentional mechanical friction. As the end-mass leaves the HTV, the tether is drawn from the inside of the roll. At the end of the deployment, the velocity of the end-mass is decelerated gradually by the braking reel and the

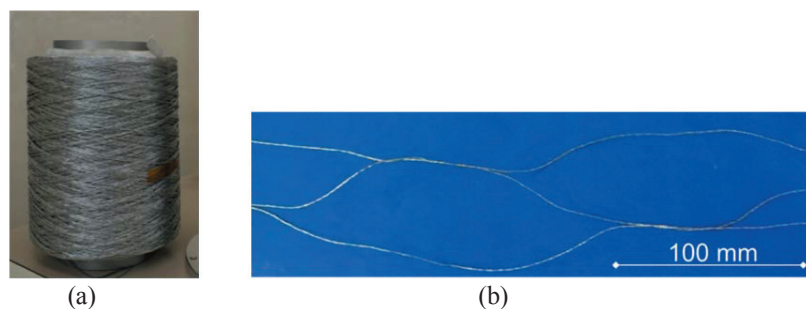


Figure 4. Bare tether. (a) Rolled 720-m-length tether, (b) Close-up view of tether. (Gaps between yarns are widened intentionally.)

deployment terminates gently without rebounding or severing due to excessive tension.

B. Release Mechanism

The release mechanism comprises a spring for pushing out the end-mass and non-explosive actuators for holding the end-mass before its release. The action of the release is initiated by the execution of three individual commands for satisfying the safety requirement from the HTV. The initial velocity of the end-mass given by the spring is designed to be approximately 1 m/s.

C. Rendezvous Sensor (HTV Component) and Camera

The motion of the end-mass is observed and analyzed by rendezvous sensors of the HTV, which are located on its electrical module, and a camera, which is placed adjacent to the release mechanism. The rendezvous sensors are originally used for approaching the ISS. The KITE system has been simplified using the rendezvous sensors to detect the end-mass, so as to free the end-mass from position sensors, communication devices, and power sources. Retroreflectors are mounted around the end-mass instead. The tether length of approximately 700 m was determined by the specifications of the rendezvous sensor.

The camera system comprises two individual sets of lens and CMOS sensor; one of which is used for observing the motion of the end-mass just after the release so that the lens is telephoto, and the other is used for monitoring the tether motion so that the lens is wide-angled. The onboard processing logic, such as feature point recognition and image trimming, is to be implemented to reduce the size of the downlink data.

D. Field Emission Cathode

An FEC is used as an electron emitter in KITE. The major reasons for this cathode selection are the potential features of the FEC, such as low power and light weight, and to simplify the EDT system by excluding tanks, valves, and pipes. An FEC module is installed on the thruster module of the HTV so that the electron emission site is separate from the tether, as shown in Fig. 3. The FEC module (see Fig. 5) comprises the FEC-Head (FECH), which emits electrons into the ambient plasma, the FEC-Controller (FECC), which provides high-voltage (HV) power to the FECH, the FEC-Guard (FECG), which covers the FECH before the mission start, and the support stage for these components. The FECG is to open just before the electron emission sequence commences on Day3. The electron emission surface of the FECH is set parallel to the orbital direction to avoid the direct impact of atomic oxygen flow.

Figure 6 shows a CAD image of the FECH comprising eight units of a carbon nanotube cathode,⁸ a chassis, and connectors. Each cathode unit (CU) is operated using an independent HV DC converter in the FECC. An engineering model of the CU and its structural image are shown in Fig. 7. A carbon nanotube is used as an electron emission material in this device, because of its high aspect ratio for lowering the extraction voltage. A typical current-voltage characteristic of a CU at the beginning of life is shown in Fig. 8. An emission current of 2.2 mA was obtained at a gate voltage of approximately 560 V in this case. In this graph, the emission current indicates the total electron current emitted from the emitter surface and the gate current indicates the drain current to the gate, which does not contribute to the electron outflow to the ambient plasma. The anode plate, which was set approximately 100 mm above the CU, was biased to

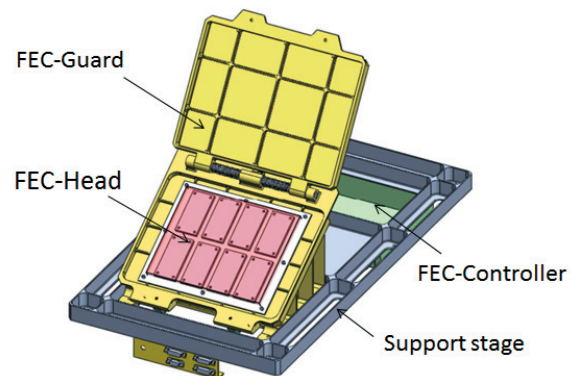


Figure 5. FEC module.

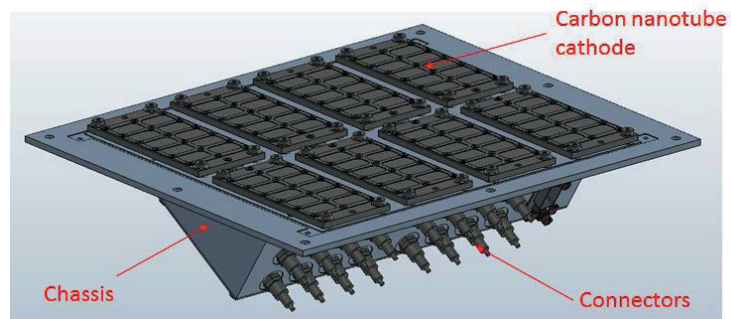


Figure 6. FECH.

positive 300 V with reference to the emitter potential in this experiment. In the practical operation on orbit, the potential difference between the emitter and plasma is estimated to be around 100 V at maximum, and therefore, the ratio of the drain current to the emission current is to become higher in the on-orbit experiment.

The impact of atomic oxygen on the cathode operation in low Earth orbit is not negligible because the emitter material is made of carbon. The increase in the gate voltage needed to maintain constant electron emission under the atomic oxygen environment was characterized⁹ using the environmental test facility at Kobe University, and the voltage increase in the 7-day mission on the HTV orbit is expected to be made acceptable with the adoption of a HV converter with a maximum output voltage of 900 V in the FECC. The measurement of the actual cathode degradation characteristics on orbit is needed to estimate the cathode life in future ADR missions.

A simplified schematic of the electrical circuit including the FECH and FECC is shown in Fig. 9. The cable from the tether is connected to the emitter of the FECH through a switching unit containing three relays for avoiding discharge failure. A single HV converter drives one CU so that the gate voltage of each CU is independently controlled and the malfunction of a single HV or CU does not lead to a complete loss of function.

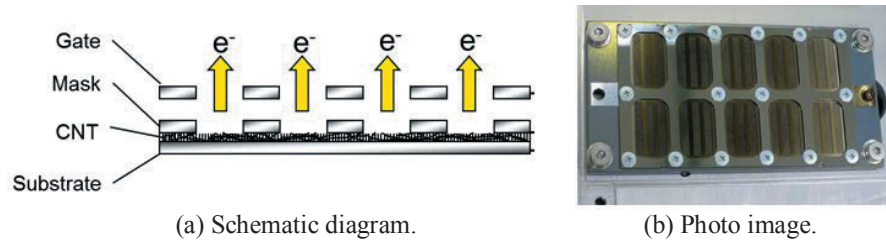


Figure 7. Carbon nanotube cathode.

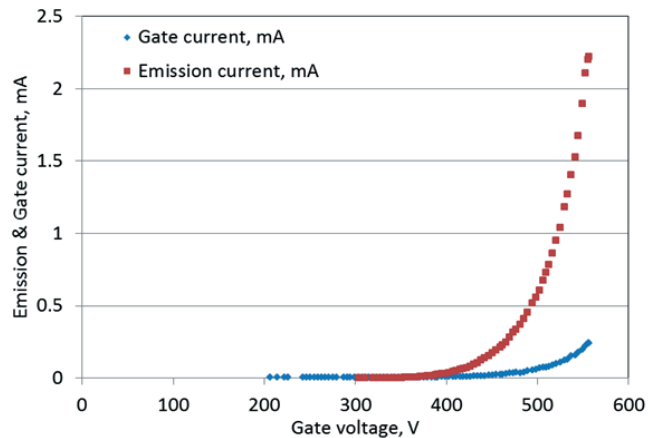


Figure 8. Typical current-voltage characteristics of a single carbon nanotube cathode.

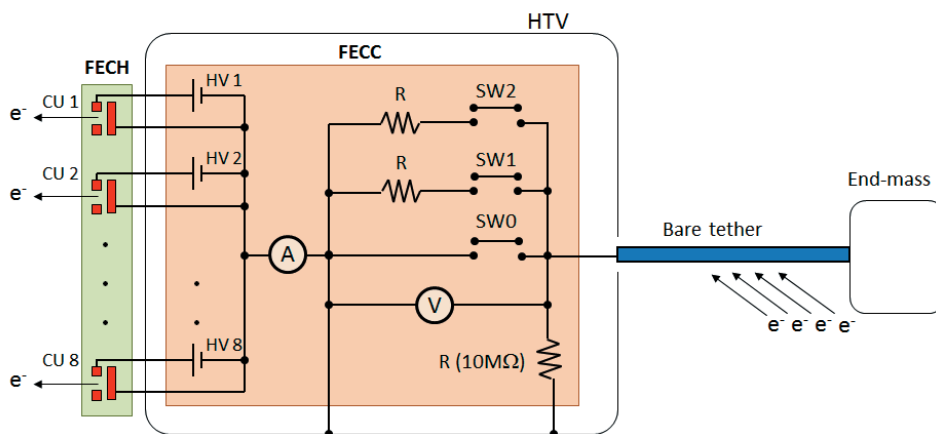


Figure 9. EDT electrical circuit including FECH and FECC.

E. Potential Monitor

An electrical potential monitor with a Langmuir probe (LP-POM) is installed on the thruster module of the HTV, as shown in Fig. 3. One of the major functions of the LP-POM is to measure the electrical potential of the HTV body with reference to the ambient space plasma. This function is indispensable for estimating the end-to-end tether voltage because the voltage is calculated as the summation of the absolute electrical potential of the HTV and the tether voltage measured at the switching unit in the FECC, as shown in Fig. 9. The function of the potential monitoring has been verified by the ATOTIE experiment¹⁰ on the HTV-4. Another function of the LP-POM is to measure the electron saturation current of the ambient plasma using a large planar probe. The number densities of the ambient plasma can be roughly estimated from the electron saturation current. This function will be tested by the KASPER experiment on the HTV-5 in August 2015.

F. Magnetic Sensor

A MAGS is to be fixed inside of the main body of the HTV. The role of the MAGS is to measure the magnetic flux density of the geomagnetic field. The background magnetic noise in the HTV will be canceled by the initial checkout operation, following which a three-dimensional geomagnetic field will be obtained. Although the data from the IGRF model is probably enough to investigate the EDT characteristics, the MAGS is needed to complement the data in case unexpected fluctuations of the geomagnetic field occur.

G. Data Handling Unit/Power Control Unit

The data handling and power control of KITE components are to be ruled by a single device called DHU/PCU. DHU/PCU possesses the functions of data acquisition for KITE components, telemetry/command interpretation between the HTV and KITE, and electrical power distribution to KITE components. DHU/PCU is to be installed next to the MAGS in the HTV main body.

IV. Conclusion

A mission overview and a list of major components of KITE, an on-orbit experimental test of the EDTs planned by JAXA, have been introduced. Data on the fundamental characteristics of the EDT are to be obtained by a 7-day mission with KITE in order to design and develop a tether system for future debris remediation. Various KITE components are to be installed on the HTV for the experiment, and the flight components are currently under development. This experiment will be the first step toward realizing an ADR system using EDTs.

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