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A PROPOSED BARE-TETHER EXPERIMENT ON BOARD A SOUNDING ROCKET

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Abstract

A sounding rocket experiment is proposed to carry out two experiments by the conductive bare-tether; 1) the test of the OML (Orbital-Motion-Limited) theory to collect electron, and II) the test of techniques to determine (neutral) density profile in critical E-layer. The main driver of the mission is provide a space tether technology experiment in low-Earth-Orbit (LEO) deploying a long tape tether in space and verify the performance of the bare electrodynamic tape tether. The sounding rocket experiment will show no danger to other satellites as the tether missions YES1, SEDSAT, and ProCEDS, which is cancelled just for afraid of collision with the ISS orbit. Also, the sounding rocket mission is possible to demonstrate the bare tether technology in low cost, simple mission concept, fast realization for space structures. The present sounding rocket experiment is expected to be the first conductive bare tether experiment.

I. Introduction

Space tether technology is expected to be one of the promising technologies to enable the activity of human in space to construct space infrastructures in a simple, light weight, compact, and autonomous construction manner enfolding a variety of used for scientific and engineering purposes.

A space tether experiment is recently proposed to deploy a 1-km bare electrodynamic tether and conduct two scientific experiments as the first attempt in the world by an international team consists of Japanese, European, and American tether enthusiasts. The sounding rocket will be prepared by the ISAS/JAXA and will be launched in 2007 spring if the evaluation committee of the JAXA approves the proposal.

Fig.1 Tape tether (1) Fig.2 Tape tether (2)

The object of the tether experiment is to verify the performance of bare electrodynamic tether in space. The bare electrodynamic tether is a tape tether with width of the borderline of the Orbital-Motion-Limited (OML) theory and is a reinforced aluminum foil with width 50mm, thickness 0.05mm, and length 1km as shown in Figs.1 and 2.

The bare tether tape experiment in space is the first attempt in the world and is now attracting international interests concerning to the space tether technology. The first phase of the experiment is the deployment of tape tether as a new technology. In addition to the phase, we are proposing two optional science experiment, the options 1 and 2 as will be stated below. Difference between these two options is mearly the necessity of attitude control of launchers. The option 1 will employ the launcher S-520 and the option 2 the S-520-CN with expensive attitude control. Such scientific devices are same in both of the options as bare electrodynamic tape tether, a conductive boom, and the cathodic device.

II. Object of the Experiment

The main objects of the present sounding rocket experiments consist of engineering one and two scientific ones.

1. Deployment of bare electrodynamic tape tether in space: engineering experiment (Engineering experiment);
2. Test of the OML (Orbital-Motion-Limit) electron collection in orbit (Science experiment I);
3. Demonstration of electric beam generation (Science experiment II).

After the bare tape tether is deployed successfully for 1km, the sounding rocket will carry out two bare-tether scientific experiments as the first attempt in space. The test of the OML theory is a demonstration of the utility of bare tether by collecting electrons on the bare electrodynamic tether. The width of the tape tether is selected to be a boundary to apply the theory, which also could be the first attempt in space. The demonstration of electric beam generation could be applied to the study of auroral phenomenon by using an electrically floating tether in space, which also could be the first attempt in space.

These engineering and scientific demonstrations could open a door for the bare electrodynamic tether, which has a variety of applications in space infrastructures including an engine to increase/decrease orbit, an accelerator and ejector for payload, and an electric power supplier. The experiment will also be extremely effective demonstration to examine the possibility of the rotating electrodynamic tether to Jupiter mission application to enable simple entry into the atmosphere of the Jupiter. The drivers for the electrodynamic tether are underlies in the low cost, simple mission concept, and fast realization possibility.

2.1 Bare electrodynamic tape tether

The tape tether has much survivability against the debris collision in comparison with the normal string tether since its projected area in the direction of the thickness decreases and the wide width assure resistance against the severance. The bare tape tether is shown to gather much electricity in comparison with the normal string tether in the ground plasma chamber experiment. The bare electrodynamic tape tether is thus expected to have excellent advantage in the space experiment.

The tether technology has a few experiments in orbit even for the tether with normal string shape.

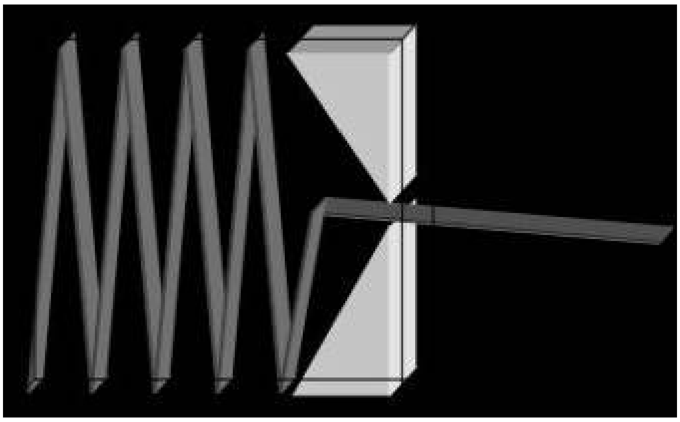


Fig. 3 A folding of the tape tether deployment

The present tape tether has no experience in orbit and a new system is necessary to assure its certain deployment in orbit. An original method is proposed and will be employed in the present experiment to deploy the tape tether in a small time period and with high reliability. The tape tether is as shown in a schematic figure of the deployment method, Fig.3. The reliability of the method is under experiment on ground and will be tested precisely before the launch.

2.2 Options 1 and 2

The option 1 conducts the scientific experiment I using the launcher S-520. The option 2 is to conduct the scientific experiment II in addition to the scientific experiment I. The bare electrodynamic tape tether is employed as an atmospherics observation probe in the scientific mission II, and attitude control is necessary for the rocket and the payload. The employment of the S-520-CN is necessary for the option 2 being much expensive in comparison with the option 1. The option 2 in its scientific experiment II has much scientific significance in testing the method to determine neutral density profile in critical E-layer and study of artificial auroral experiment. The launch in the option 2 will be at a night in order to observe the artificial auroral effect. The difference of the two options totally lays on the cost of the launcher. The equipments of experiment in the option 2 is the electrodynamic tape tether, a conductive boom, and a cathodeic device as same as that in the option 1 and could be conducted within a small time period as about five minutes.

2.3 Specific advantageous features

The proposed experiment is most appropriate to the sounding rocket experiment at the present situation. One of the advantageous features is that the sounding rocket mission is so short in time period and in a relatively low earth orbit lower below the International Space Station. The present experiment has then no danger to interfere with other satellites including the International Space Station. It is noted that the tethered system is regarded as a satellite with the diameter of the tether length, which is usually very long as 10 km. The reason of the cancellation of projects is solely the afraid in collision with other satellites for such space experimental missions of tether technology as YES1, SEDSAT and ProSEDS. The other advantageous is the present sounding rocket mission is an ideal demonstration of tether technology to verify the low cost, simple mission concept, fast realization.

2.4 Launch situation

The altitude of the ballistic trajectory is preferred to be 300km. The main driver for the present mission is low and short ballistic trajectory provided by the sounding rocket, which is an inherently safe orbit for the tether technology experiment. The trajectory is also able to present the most preferable launch situation for the scientific experiments. The altitude needs to be high enough as to distinguish between air drag effects and the Lorentz drag, and also the period during solar minimum, which is easily selected in the sounding rocket experiment. It is noted that the latitude of Japan is appropriate. This is because high latitude orbit is not preferable due to low electrical magnetic force since the Lorentz force decreases for a non-rotating tether with sub-optimal angle between tether and the magnetic field line.

III. Experimental method

3.1 Previous missions

The use of a sounding rocket is employed as a reasonable solution for the demonstration mission. Previous tether related experiments onboard sounding rockets have been performed by the Canadian Space Agency (Oedipus A and C) and NASA/Japan (CHARGE-1 and 2) [S.Sasaki, K.I. Oyama, N. Kawashima, T. Obayashi, K.Hirano, W.J. Raitt, N.B. Myers, P.M. Williamson, P.M. Banks, and W. F. Sharp,. "Tethered Rocket Experiment (CHARGE-2): Initial Results on electrodynamics," Radio Science, Vol.23, No.975, 1988.]. The Oedipus mission comprised two identical sub payloads separated by a 1-km insulated conducting tether line and the subsatellites were spun up about their longitudinal axis (along the tether line) and the mission was mainly meant to study the plasma characteristics of the Aurora. Flight duration was about 15 minutes. The earlier CHARGE experiments were designed to study the interaction between electron beam emission and electrical charging of the satellite. Release of neutral gas for charging mitigation was one of the interesting experiments.

3.2 The present mission

For the purpose of the present demonstration mission, the sounding rocket can potentially employed to obtain results in the fields of; 1) engineering experiment (bare electrodynamic tape tether deployment); 2) science experiment I (Test of the OML electron collection in orbit: bias voltage required.); and 3) science experiment II (Demonstration of electric beam generation: testing the method to determine neutral density profile in critical E-layer.).

The induced electrical magnetic force for the ballistic flight is low because of the low speed of the sounding rocket payloads. A bias voltage about 3kV is thus necessary to be supplied to study the collection of electrons on the passive bare tether. The sounding rocket S520 (mission 1) and S520-CN (mission 2) have much higher apogee and flight duration and preferable for the present mission to launch payload of about 70kg on the altitude of 300km. Sufficient plasma density is obtained at the altitude of 300km for the test of the OML theory in the science mission 1 and for the study of the atmospheric probe in the science mission II. The launch in the scientific mission II also requires the night launch at the middle latitude area with the Earth dipole angle (dip) is between $1/2 < \tan(\text{dip}) < 2$, in which Japanese launch site is appropriate. The separation of the payload in the capsule will be necessary to deploy the tether from one of the separated payload as shown in Fig. 4.

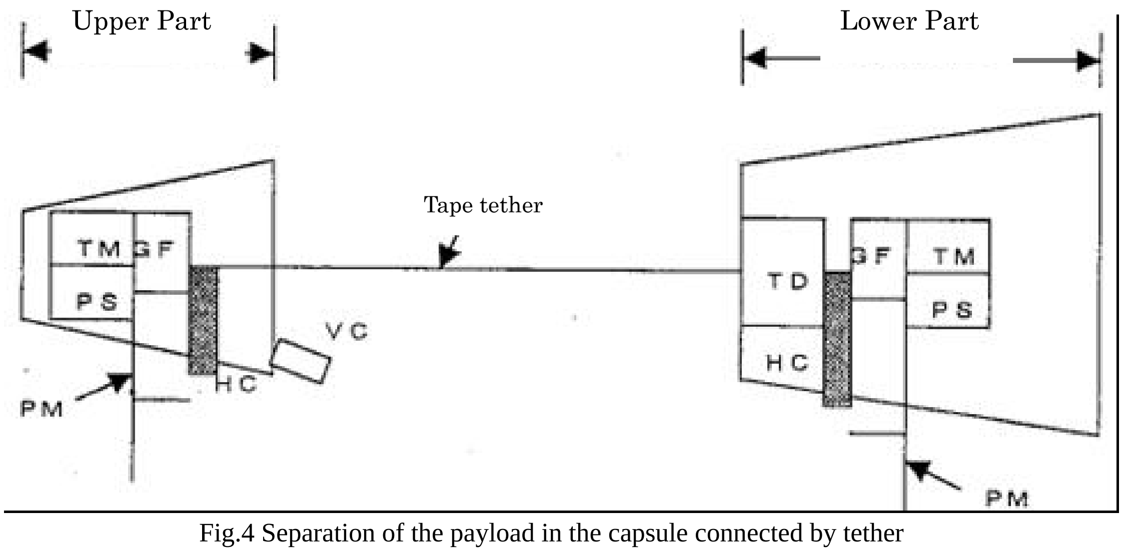
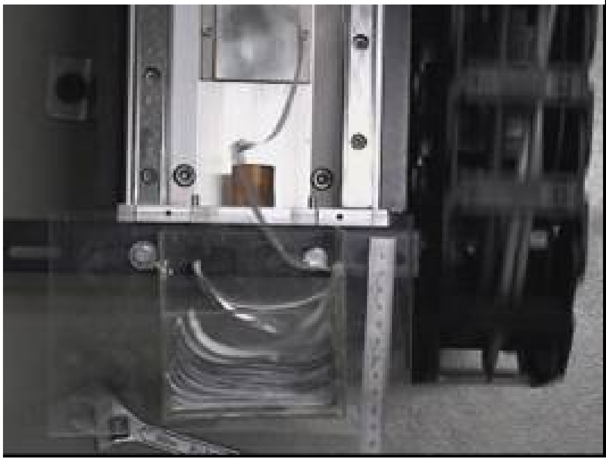


Fig.4 Separation of the payload in the capsule connected by tether

3.2.1 Engineering experiment (Deployment of the bare electro- dynamic tape tether)

Space tether is usually deployed from a wound spool by controlling the tension. (No retrieval is necessary in the present



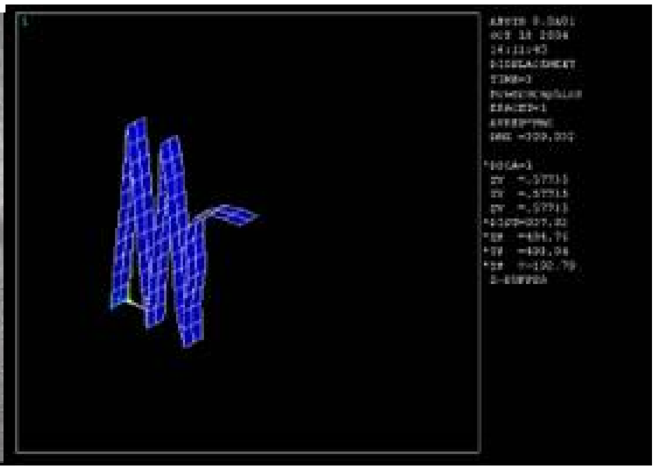


Fig.5 Deployment study using a paper tape   Fig.6 Numerical simulation of deployment

mission.) Deployment is necessary to be sufficiently swift and reliable for the tape tether employed in the present sounding rocket experiment, which is conducted in a short period of time. A new method is thus devised for the tape tether deployment by folding tapes. Some simple ground experiment (Fig.5) and a numerical simulation is under study to confirm the performance.

The fundamental study shows preferable performance of the folding deployment. It is necessary for the deployment of the folded tape tether to study practical performance including estimation of the friction coefficients in vacuum circumstances, development of a braking system, and measurement method of the deployed length. Investigation is also under study for the hose deployment method for fire extinguishers with simple and high reliability method as an amateur could handle. (Fig.7).

Fig.7 Folded water hose for fire extinguisher

3.2.2 Science experiment I (Test of the OML theory in orbit) (H.A.Fujii, H.Takegahara, K-I. Oyama, S. Sasaki, Y. Yamagiwa,.M. Kruijiff, E. van der Heide, J.R. Sanmartin, and M. Charro, "A Proposed Bare-Tether Experiment on Board a Sounding Rocket," AIAA 2004-6718, 2nd IECEC, Providence, RI. August 2004.)

The Science experiment I is the test of the OML electronic collection in orbit. The OML theory constructed in the age of 1920 is necessary to be confirmed in orbit. The test was expected to be carried on the ProSEDS project, which is cancelled due to the possibility of hazardous collision with the International Space Station. The present experiment will thus be the first experiment in space.

Before the start of the experiment, a round conductive of a diameter 1cm and length 20m is deployed and then the tape tether of length 1km. The deployment of the boom is enough possible by the present state of technology. Collected electrons can be measured by adding different bias voltages to the tape tether as shown in Figs. 8-1 and –2.

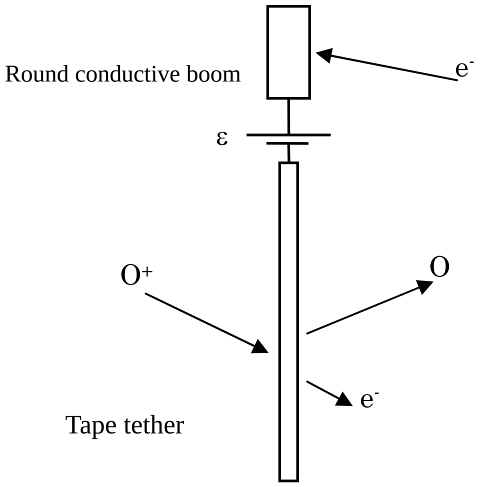


Fig.8-1 Test of the OML theory-1

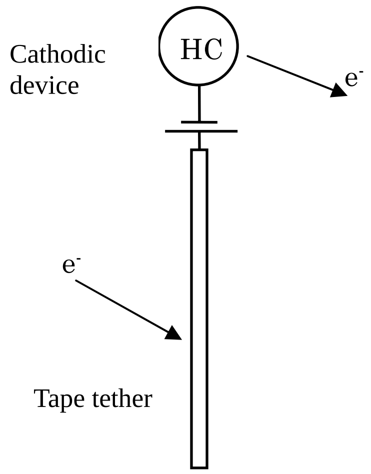


Fig.8-2 Test of the OML theory-2

At the first stage of the experiment, the positive terminal of power supply is the round conductive boom with length L_b (L_b : $20m$) and the negative terminal of power supply the tape tether with width w_b. (Fig.8-1). Electrons collected by the boom cross supply to tape, where they leak at the rate of ion impact plus secondary yield. $L_b(boom) = I_i(tape)\times(1+\gamma\alpha\varepsilon)$ where γ : $0.15e/kV\ ion$ and the following equation is obtained:

$$eN_\infty L_b 2R_b\sqrt{\frac{2e(1-\alpha)\varepsilon}{m_e}} = eN_\infty L_t \frac{2w_t}{\pi}\sqrt{\frac{2e\alpha\varepsilon}{m_i}}\times(1+\gamma\alpha\varepsilon) \qquad (1)$$

The experimental results are compared with the theoretical results.

Then at the next stage of the experiment, the negative terminal of the power supply is switched being connected to a cathodic device and the tape tether to the positive terminal. The cathodic device is a device to enhance electronic current including the tungsten filament and the hollow cathode. Electrons collected by the tape tether cross the supply and ejected at the catohdic device are obtained from the OML theory as follows:

$$I_e(tape) = eN_\infty L_t \frac{2w_t}{\pi}\sqrt{\frac{2e\varepsilon}{m_e}} \qquad (2)$$

The supply voltage ε sweeps range centered with the supply voltage at about 2kV in the experiments. Each shot by either varying the voltage supply or plugging in the resistances will take 20 seconds and takes 10 to 20 different values for the experiment to be useful. The total experiment could be done optimally within five minuets. The electrons collected by the tape are measured and are compared with theoretical values.

. The cathodic device is now studied as a device to enhance electronic current including the tungsten filament and the hollow cathode. It was considered that several minutes are necessary for heating up of the hollow cathode. The present team has examined the cold start of the hollow cathode since the available time is much short in the present sounding rocket experiment and has come to conclusion that the hollow cathod can be put in operation very shortly as in a few seconds if attention is paid to the storing environment. This conclusion comes from the discussions of the members for the “cathodic device”. The members consists of G. Vannaroni (ESA), P. Wilbur (CSU), L. Johnson (NASA/MSFC: Invited), J.Sanmartin (UPM), and S.Sasaki(ISAS/JAXA) and includes some persons engaged in the project of ProSEDS. The hollow cathode should be previously degassed and maintained in a controlled ambient of dried gas (e.g. the same used for the hollow cathode operation as Xenon or Argon.). A small hermetic box filled with the gas and placed on the rocket could open automatically when the altitude for the hollow cathode operation is achieved. The ignition and thus operation could take just a few seconds if heating power is high enough. The team is now studying further practical details.

3.2.3 Science experiment II (Demonstration of the Electric Beam Generation) (J.R. Sanmartin, M. Charro, J. Pelaez, I. Tinal, S. Elaskar and A. Hilgers, "Floating Bare Tether as Upper Atmosphere Probe, "AIAA 2004-5717, 2nd IECEC, August 2004, Province, RI.)

The science experiment II is a test of technique to determine neutral density profile in critical E-layer and study of artificial auroral experiment. The tape-bias is varied by sweeping through a set of values in the supply voltage up to 3KV and the emitted secondary electrons will penetrate in some different manners in the E-layer as shown in Fig.9.

By applying some 3KV of potential (Note we only need this high voltage for some minutes) on the tether the ambient ions are accelerated to KeV and the energy librates secondary electrons. The secondary electrons race down magnetic field lines and ionize/excite neutrals in the E-layer. Note that the applied potential here is assumed negative such to attract the ambient ions which will release the secondary electrons. This means a switch in power with respect to the pare tether experiment in the science experiment I. The length of the tether and the energy of the secondary electrons are directly proportional for the length of the aurora footprint at the E-layer (∶ 95km). With a CCD camera (requires attitude control) the electrons can be spotted at night. The procedure of the voltage sweep as same as the science experiment I is also applied to this experiment and will take less than 5 minutes in this experiment.

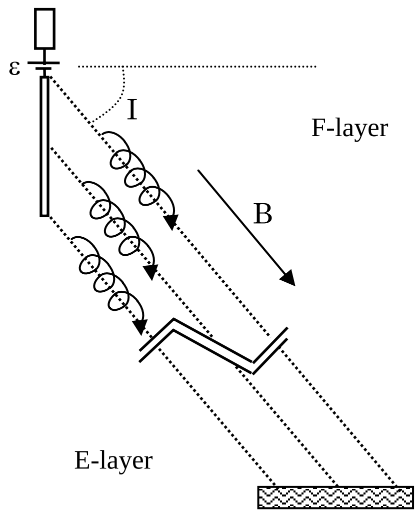


Fig.9 Schematic of beam propagation.

The experiment II is to investigate whether a conductive tether left un-insulated could serve as an effective e-beam source to produce artificial auroras. An tether biased negative over of its most length. Ambient ions impacting with KeV energies liberate secondary electrons, which are locally accelerated through the 2D tether voltage-bais, race down magnetic lines, and result in peak auroral emissions at about 120-16-km altitude.

Beyond auroral effects proper, a bare-tether could provide measurements of neutral density along its E-layer footprint track. The real time mapping becomes possible on neutral density at beam foot along the orbit. This will effectively contribute to all simulations concerning to the lower atmosphere and thus could provide useful orientation to the GPS calibration, weather forecast, and the estimations for orbit decrease or reentry orbit. (Martinez-Sanchez and Sanmartin, J. Geophys. Research, 1997; Sanmartin, Ahedo and Martinez-Sanchez, Proc. 7th Space. Charging Tech. Conf., 2001).

3.3 Mission description

A possible mission description will be similar to the Canadian flight experiment 'Oedipus' (The altitude of the present mission will be 300km) and will proceed as follows:

1. Nominal sounding rocket launch up to separate and spin up the payloads;
2. Attitude maneuver with respect to magnetic field (In the case of the scientific experiment II: Option 2)
3. Deployment of tether by ejection of upper payload
4. Scientific part of mission including,

1) Test of OML current collection on bare tether of 1km long by applying bias voltage using a conductive boom and a cathodic device (Science experiment I).

2) Experiment to employ the bare-tether as an atmospheric probe. (Science experiment II: Option 2).

5. End of mission (re-entry)

The following measurements are possible in the mission:
1. Plasma diagnoses (Langmuir probes)
2. Local magnetic field (3 axis Magnetometer)
3. Current (Ampere meter)
4. Motion of a tethered subsatellite (Accelerometers)
Additional LIDAR measurements of local density would be required for post processing of data in case of the option 2.

The mission profile for tether experiment with a sounding rocket is shown as an example by taking an image from the Oedipus-C mission (Fig.10).

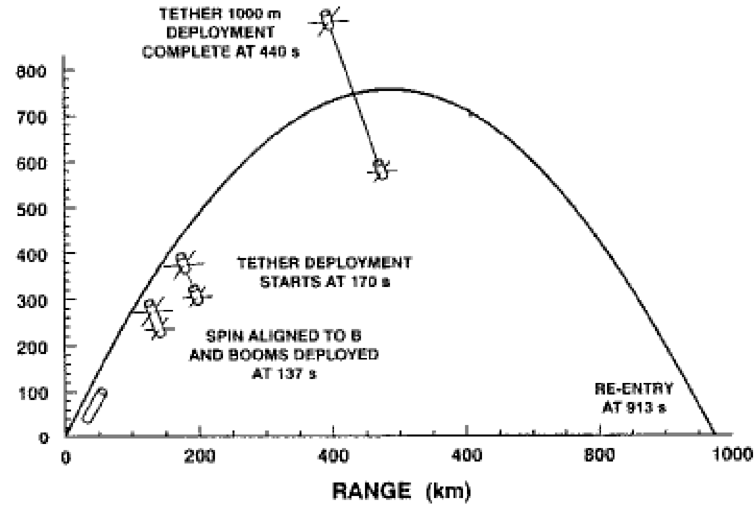


Figure 10 Example of a mission profile for a tether experiment
with a sounding rocket (image taken from Oedipus-C mission).

4. Experimental devices

The total science payload mass is assumed to be about 75kg and is shown by breaking down in the Table 1.

5. Requested launch site

The launch in the scientific mission II requires the night launch at the middle latitude area with the Earth dipole angle (dip) is between $1/2 < \tan(\text{dip}) < 2$, in which Japanese launch site, Kagoshima in Japan is preferred.

6. Period of launch and time

The launch is expected on the spring season of 2007, which is one year after the approval of the present proposal. The option 2 with the science experiment II is requested to be night launch.

It will take about one year after the present proposal is accepted to fix the details of the present project and to prepare the hard wares. The period of preparation includes the design and development of the tape tether and its deployer in their flight model and that of the cathodic device and its device to mount on the rocket. Note that no new development is required except for the devices concerning to the tape tether and the cathode since all hardware is based on heritage. This will reduce development time.

Table 1 Payload mass breakdown

	Mass [kg]
Upper payload	
Tether deployment device	4
Cathodic device	5
Langmuir Probe	0.25
Electronics, measurements & control package (OBC GPS etc.)	8
Power Distribution Unit [PDU]	2
Magnetometer & accelerometers	0.1
Wave receiver	1
CCD camera (Science experiment II: option 2)	1
Structure & harness	8
Downward payload	
Passive end mass(No telemeter nor measurement)	15.25
Tether	
(1km, 50 mm x 0.05 mm aluminum foil, enforced)	7
Power/batteries (200 Wh/kg → 3000 V, 1A 15 min=750W)	5
Conductive boom (20m, 1cm diameter aluminum cylinder)	8.4
Margin	10
Total	75.0

7. Schedule of development

No newly developed technology is included in the present project, except for the devices for the tape tether deployer and the quick start of the hollow cathode. The concept of the tape tether deployer is already examined in its performance of quick and reliable deployment at the Tokyo MIT as was stated in the section 3.2.1. The bare tape tether and its deployer will be examined by a variety of experiments in order to correspond to the launch conditions. The concept of the quick start of the hollow cathode is also examined in its performance by the professionals of the international team as stated in the section 3.2.2. These two main objects, the tape tether deployer and the quick start of the hollow cathode, will be examined precisely and prepared in their design before the launch. The experiment will be ready before the spring of 2007. The concept is almost established and the possibility of the experiment is confirmed enough.

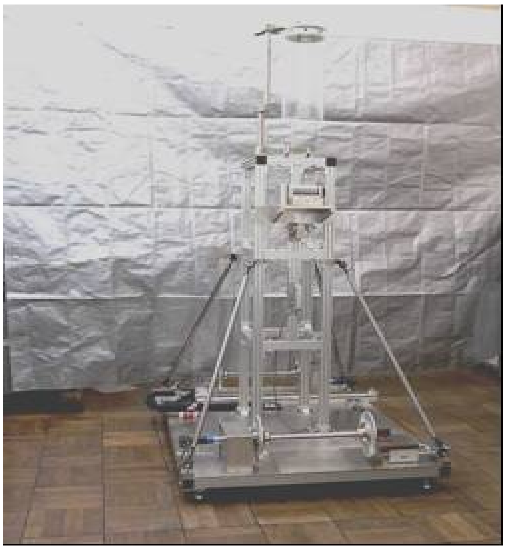


Fig. 11 on-ground experimental device for deployment of tethers with both configurations of string and tape (Tokyo MIT)

Other devices for the measurements of plasma diagnoses (Langmuir probes), local magnetic field (Magnetometer) , and current (Voltmeter) are available and their further possibilities

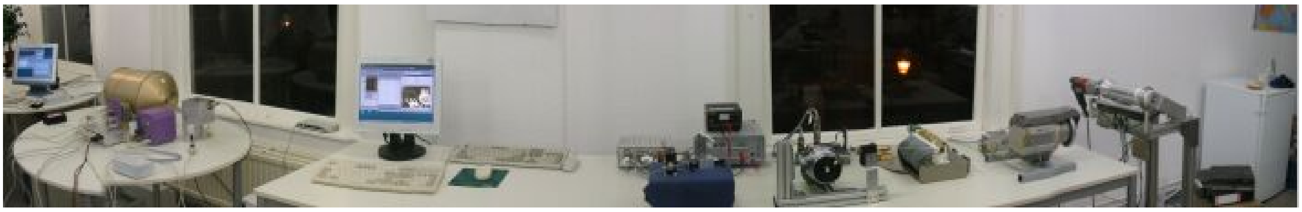


Figure 12 YES2 Tether testing rig (Deployment reel device for thin tether)

for decrease in size and weight, and increase of their performances are expected. Other onboard devices have no significant element subject to development.

The members of the present team have the experience in on ground tests concerning to the deployment devices of tethers. Figure 11 shows an on-ground experimental device for tether with both configurations of string and tape as is under examination by H.A. Fujii. Figure 12 shows a spindle type tether deployer employed to the YES II project of ESA which was examined by E. van der Heide and M. Kruijiff at the Delta-Utec.

8. Cost estimation to produce onboard experimental devices

Cost estimation is shown in the table 2 for the onboard experimental devices. It may be noted that the hollow cathode and the batteries are supposed not available as the Japanese products and are necessary to be examined on their import.

Table 2 Cost estimation

Name of the device	Estimated cost (JY in unit of 1,000yen)
Upper payload (Main subsatellite)	
Tether deployment device	2,000
Cathodic device	4,000
Langmuir probes	4,000
Electronics, measurement & control package (PC104 + 2 PC104 measurement cards)	1,000
Batteries & Power Supply Unit (3,000V)	10,000
Magnetometer & accelerometers	7,000
CCD Camera (science experiment II: option2)	1,000
Downward payload (End mass)	
Passive end mass (No thrust motor nor measurement)	5,000
Tether	
Tape tether foil (1km, 50 mm x 0.05 mm aluminum foil, enforced)	1,500
Payload separation device	
Spring ejection followed by tether length control (Ejection velocity --- 2.5m/s)	5,000
Conductive boom	
(Length 20m, 1cm diameter aluminum cylinder)	1,000
Man/hour awards	
(Design, Development, Construction, Tests)	20,000
Total	61,500

9. Conclusion and Comments

A proposed sounding rocket experiment is introduced to carry out two experiments by the conductive bare-tether; 1) the test of the OML (Orbital-Motion-Limited) theory to collect electron, and II) the test of techniques to determine (neutral) density profile in critical E-layer. As was stated in the section 2, the present experiment using a sounding rocket could be extended to a low cost LEO mission with an electrodynamic (i.e. M-V and VOLNA launcher) with a short duration of two weeks or longer. The present team with addition of some excellent researches on the Alfven wave is now proposing a small satellite project to the ISAS/JAXA to employ the M-V launcher. The small satellite project is to study two major applications of the space technology the engineering mission; i.e., the orbit elevation without using fuel, and the scientific experiment on the Alfven wave.

These demonstrations will extend many useful methods of employment of the bare electrodynamic tether including engine to increase/decrease orbit, supplier of electricity, spring-shot, and lifter for payloads. The drivers for the electrodynamic tether are underlies in the low cost, simple mission concept, and fast realization possibility. The demonstration will be also be very effective to examine the possibility of the rotating electrodynamic tether to Jupiter mission application to enable simple entry into the atmosphere of the Jupiter. Note that a commercial application lies in the de-orbiting of defunct satellites.

The success of the present international joint-mission between Europe, United-States, and Japan will bring a new technology of the electrodynamic tether technology as a new possible space technology with much useful applications in future.