

# The Kyushu/US Experimental Satellite Tether (QUEST) Mission, a Small Satellite to Test and Validate Spacecraft Tether Deployment and Operations

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## Abstract

In recent years, an increased effort to design, build, and operate small satellites has taken place in universities and laboratories all over the world. These micro-satellites provide numerous flight opportunities for science experiments at a fraction of the cost of larger traditional missions. In addition, there has been an increasing trend towards international cooperation on space projects. From the International Space Station to joint commercial ventures, the future of space progress will be shared by countries around the world. Tomorrow's engineers must prepare for this challenge.

This paper provides an overview of the Kyushu/US Experimental Satellite Tether (QUEST) mission, a joint project between Kyushu University (KU), Arizona State University (ASU), and Santa Clara University (SCU). This mission will develop and test new technologies related to space tether deployment and operation. In particular, it will attempt to show very small space platforms can be used for significant tether deployments. If successful, it will provide valuable data for tether designers as well as cost and weight savings on future missions. In addition, progress on system design, ground station development, orbital simulations and related testing are reviewed.

## 1.0 Introduction

Many universities and laboratories around the world are currently developing micro-satellite projects. This effort is popular due to the inherent advantages associated with small satellites. They are easier to design and require much less in terms of testing and integration than larger satellites. In addition, micro-satellites are substantially less expensive than traditional larger missions. Their value has been demonstrated with the successful launches of the UoSAT series, AMSAT satellites, MightySat, and numerous other industry and university missions around the world. Performing meaningful science missions on

small satellites becomes a larger priority in times of diminishing space budgets.

One of the potential experiments suited to small satellite testbeds is tether research. This technology has generated substantial interest in applications such as high-atmospheric observations, electrodynamic energy generation, and orbit transfer. If deployed successfully, tethers could save millions of dollars in launch costs by reducing requirements for solar cells or on-board propulsion systems. Unfortunately, the tether systems flown to date have been on fairly large platforms with complicated deployment and braking mechanisms. To be feasible for nano-satellite use, a tether system must be approximately an order of magnitude smaller in size. This reduction can only be achieved through innovative deployment mechanisms that are simple, lightweight, and stable. Once developed, a small enough tether deployment system could be used to test many of the above mentioned tether applications. This would open the door for a whole new range of small satellite applications, as well as provide significant cost savings over current missions. It is to this end that KU first began exploring tether research several years ago.

Combining its rich background in tether research with the spacecraft (S/C) design heritage of ASU and SCU, the QUEST mission was conceived at the 1998 University Space Systems Symposium (USSS), a joint Japanese/US student conference. It was agreed KU would design and manufacture all tether components and software, while ASU would build the S/C bus and main subsystems. SCU will design the Command & Data Handling (C&DH) subsystem, as well as the on-board science experiment. Each university will therefore be able to contribute valuable insight and expertise. By utilizing the strengths of each university through an international student collaboration, the QUEST mission provides a unique opportunity to extend the usefulness of small satellites in the near future through the use of small tether systems.

## 2.0 Mission Objectives

The proposed QUEST mission has three primary and four secondary missions. These missions will be accomplished over the S/C operational lifetime of 6 months based upon an initial orbital altitude of 400 - 1200 km. The first primary mission objective is to successfully deploy a 2 km tether and study the control and dynamics associated with the deployment. This must be accomplished using a tether system small enough for nano-satellites. In addition, magnetic field interaction and space debris hazards will also be examined. The tether will remain at its 2 km deployed length through the remainder of the operational mission, and then will be cut to examine orbit transfer. The next primary mission is distributed S/C operations. To accomplish this science objective, a “virtual formation” is proposed that will demonstrate joint S/C operations. The virtual formation is a cooperative effort between satellites operating as a network where targeting and data acquisition are accomplished. These results are then transmitted to the ground segment and the other satellites via communications links without the need for strict physical proximity of the satellites. Both satellites will use the same operating system, control architecture, and thus will be able to receive commands and control each other. This is a key technology needed for future small satellite constellations. The final primary mission is inter-satellite communications. This objective will test new and innovative ways to send commands, transfer data, and operate as a formation. This will be the first tether mission to fully utilize both sides of the deployed configuration in a cooperative formation effort.

The secondary science objectives for the QUEST mission include using a modular S/C bus design, testing a Very Low Frequency (VLF) communications experiment, hosting an amateur band radio repeater, and emphasizing student education and leadership throughout the process. The entire QUEST S/C will be designed for modularity in component placement and structural layout. A generic mounting scheme for all brackets will be used, and structure will be minimized through the use of load bearing components. A “plug and play” electrical bus will also be used allowing a common interface for all parts. This will allow frequent changeout of parts and future additions to the system with minimal changes to the configuration. Santa Clara will test a VLF communications experiment based upon heritage gained through the Emerald program. This experiment will detect lightning-induced radio emissions and can be used to study ionospheric effects on communication signals as well as conduct global lightning surveys. The former objective is significantly

enhanced when performed in a local, distributed manner. Besides the primary communications previously mentioned, an amateur band radio repeater will be used to allow HAM operators around the world to communicate via the QUEST satellite. This provides global communications access to a whole range of users. Finally, the QUEST program will be entirely managed and run by students. There has been a renewed effort to train students in S/C design in both the United States and Japan. Providing students the opportunity to participate in the entire design process from concept development to design, manufacture, testing, and operation prepares them in a more effective way for future contributions to the global space industry.

## 3.0 Program Management

The primary investigators (PI) for the QUEST mission are faculty members at each of the participating schools, and are listed on the title page. Chris Kitts is the PI from Santa Clara University. They will provide technical advice and funding assistance, as well as help coordinate with various government and civilian space agencies. However, graduate and undergraduate students will perform the bulk of program management, systems engineering, design, construction, testing, and operations. A set of program management documents have been generated including a Program Management Plan, System Development Plan, System Requirements Specification, and others to lay out university responsibilities, configuration management, and outline S/C development. Qualified engineers from a number of cooperating industry partners have been assisting in this effort, and providing documentation templates. In addition, efforts are underway to coordinate with the United States State Department to ensure all technology export requirements are sufficiently met.

## 4.0 Schedule

The current schedule for the QUEST program is laid out in Figure 1. System requirements have been defined for each subsystem, and preliminary designs are

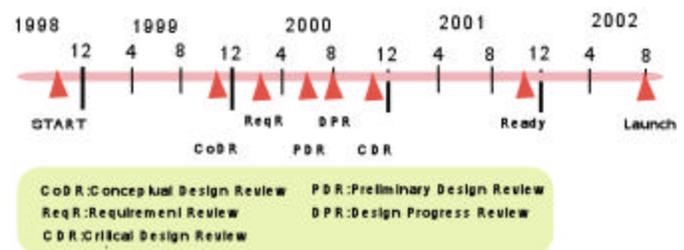


Figure 1: QUEST Schedule

well underway. A series of design reviews will take place over the next two year. It is anticipated that the S/C will be delivered to the launch vehicle provider in early 2002 in preparation for a launch in late 2002 or early 2003. This is of course dependent upon launch vehicle availability. The main launch option for this mission is as a secondary payload on the Japanese H-IIA. Currently, NASDA is reviewing potential candidates to fly as test payloads on the first few H-IIA launches. It is expected that several university payloads will be selected for these test flights. Based upon an H-IIA launch, the mission specifications are as shown in Table 1.

**Table 1: Mission Specifications**

<b>Orbit</b>	Orbit: Circular orbit Altitude: 400 ~1200 km (LEO)
<b>Size</b>	500×500×500 mm <sup>3</sup>
<b>Weight</b>	<30 kg
<b>Power</b>	<30 W
<b>Life time</b>	6 months

## 5.0 Spacecraft Design

This section will provide an overview of the current S/C configuration and subsystems. As is shown in Figure 1 above, final subsystem design will not be complete for some time. Thus, the basic system configuration and requirements for each subsystem will be reviewed.

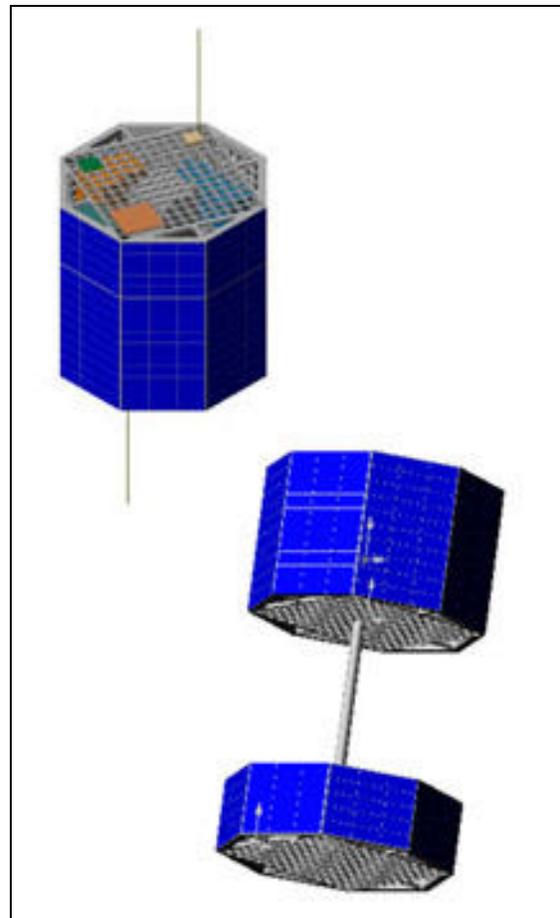
### 5.1 Spacecraft Configuration

The S/C is being designed to fit within the Japanese H-IIA launch vehicle secondary payload envelope of 500×500×500mm with a 30 kg mass. Initial trade studies reviewed the possibility of square, hexagonal, and octagonal configurations. The primary factor driving the decision was internal component placement, in particular that of the tether. Other factors included solar array area, external sensor access, and separation system layout. The main satellite and sub-satellite are designed according to a general one third to two thirds sizing requirement. This is dictated by the gravity gradient requirements of the deployed tether system. The current S/C layout is shown in Figure 2.

### 5.2 Attitude Control System

The attitude control system (ACS) will provide pointing capability and stability to the main QUEST S/C throughout the mission. If volume and mass constraints allow, the sub-satellite will also have a limited stability capability, most likely a magnetic torquer. Although

specific pointing requirements are still to be determined, it is anticipated they will be approximately +/- 5°, and +/- 0.5° per second for rotation. Pointing capability will be provided by a momentum bias system currently under development at the ASUSat Lab. A momentum wheel situated along the pitch axis of the main S/C will be augmented by at least two magnetic torquers. This will provide stiffness in three axis and the ability to bleed off momentum on the wheel when its spin rate becomes saturated. Attitude determination will be achieved using a star tracker and two horizon sensors oriented at 120° to each other. Stability requirements for the tether deployment are simply that the S/C be stable when the separation is initiated, with minimal rotational tip-off from the separation system. Dynamics of the actual deployment are discussed in more detail in the tether section. In addition to these other sensors, GPS units will be included on each satellite to provide precise positional data throughout the mission. This knowledge is essential to accurate measurement of the tether dynamics. All GPS units will be from COTS sources.



**Figure 2: Spacecraft Configuration**

### 5.3 Command & Data Handling

The command and data handling subsystem will be developed by SCU and will be based on a simple commercial off-the-shelf microcontroller. Two of these microcontrollers will function as the master flight computers for both the primary and secondary QUEST spacecraft. Accordingly, their functionality will include the decoding and execution of spacecraft commands as well as the management of science data and spacecraft health telemetry.

The current C&DH design is a Motorola 68HC11-based system although a PICMicro 16C74 may be used in future iterations of the design; SCU has experience using both microcontrollers in previous small satellite projects. This system will include a simple 32K error detection and correction memory design, 8-bit analog to digital conversion, the capability to sample telemetry at 10 Hz, and watchdog timer protection. In addition to the microcontroller core, a radiation-tolerant digital logic controller will be incorporated as a limited, back-up flight processor in case of a microcontroller failure. This auxiliary controller will function as a simple state machine capable of executing a basic sequence of operational activities and relaying results to the ground.

Depending on related research activities, the microcontroller may be replaced with a more capable PC-compatible computer configured to operate as a modified web server. Such an architecture is currently being prototyped on other SCU robotic vehicles such as a terrestrial rover. If this initiative is pursued, the digital logic auxiliary controller will still be included as a radiation-tolerant back-up unit.

### 5.4 Communication System

Command and control communications will be accomplished using narrowband FM communications. Digital communications will use GMSK encoding at rates of 9600/19200/38400 bits per second (bps) for uplink and downlink. Such a link will enable the satellite and the ground-station to use cheap commercial radio equipment for communications equipment. Such use of COTS equipment has a huge economic advantage in the design and construction of the satellite. The amateur band repeater on-board will allow HAM operators around the world to utilize the QUEST S/C for long range communications.

A Satellite Tool Kit simulation of several possible orbits provides an average daily pass time of 16 minutes per day over the ASU ground station. Given this limitation, a downlink data rate of 19.2 kbps would

be sufficient for video images of the tether deployment, the largest data requirement. However, to account for possible adverse conditions where no downlink would be possible for several days, up to 16 MB of on-board storage capacity will be provided.

### 5.5 Electrical & Power System

The electrical and power system (EPS) will be designed as a stand-alone high efficiency subsystem. In order to achieve high efficiency, switching regulators and smart monitoring schemes will be used. Traditional topology will also be employed. A body mounted GaAs solar array will be the primary source of S/C power. A preliminary power calculation determined adequate power could be generated from the solar arrays given a side-mounted configuration. This assumes the cells are at least 18 – 20%. Thus at least single or dual junction GaAs cells must be used. Silicon cells were rejected because of excessive thermal losses.

The solar array will feed a Peak Power Tracker (PPT) which will feed the satellites battery pack. The PPT will achieve optimum power capacity by monitoring array thermal characteristics. All S/C power will be drawn directly from the battery pack. Common system voltages of 5V and 12V will be generated using high efficiency DC/DC regulators, and payload specific voltages will be generated directly from the unregulated battery voltage by the component boards. Solar-Array, PPT, and regulator performance will be controlled by a low power micro-controller, which will also monitor system performance. This data will be included in a regular downlink of S/C health status.

### 5.6 Structure

The QUEST mission will use an aluminum isogrid structure to support the tether and other S/C components. Isogrid was selected due to its reduced weight, structural stiffness, and flexibility for mounting. Standard 6061-T6 Al will be used because of its reduced cost and adequate strength. A preliminary finite element static and dynamic analysis of the proposed structure shows design margins of 2.0 to 3.8 for the H-IIA launch environment. Fasteners will be from COTS stock, and brackets will be custom designed according to component specifications. Solar arrays will be mounted on thin carbon composite facesheets that will be stood off and damped from the main structure. Access will be provided at various points on the structure for horizon sensors, GPS antennas, and the star tracker. The FM antenna will be deployed after launch from a stowed “rolled tape” configuration. The separation system between the two

sides of the S/C will most likely be shaped memory based. Explosive bolts and other high shock devices were rejected due to the tip-off requirements of the sub-satellite. It is hoped an economical COTS component can be located for this application.

## 6.0 Tether

This section outlines the Tether Deployment System (TDS) under development for the QUEST mission. Some of the history of recent tether missions will be reviewed as well as the theoretical and mathematical basis for tether deployments. Then results from recent experimental tests performed at KU will be presented.

### 6.1 Past Tether Studies

In 1885, Tsiolkovsky suggested connecting large masses in space by a long thin string to exploit weak gravity-gradient forces. Space systems using tethers have been developed since then. Many applications are proposed for tether technology such as high atmospheric observation, electro-dynamic energy generation, transportation, and orbit transfer, but all these systems can be achieved only on the assumption that all the sequences of tether actions can be controlled.

Some of the tether applications and experiments on recent missions were TSS (1992), TSS-1R (1996) using the Shuttle Orbiter, SEDS (1993,1994) and TiPS (1996~). However, the experimental tether technology used on these missions was quite massive, in most cases weighing 50 – 100 kg. This implies the complexity of the behavior of large-scale flexible tether system under space micro-gravity.

### 6.2 Tether Deployment System

In past studies, the tether control system has been designed in order to decrease the tether libration angle during the tether retrieval stage. These systems need measurement of the state of the sub-satellite for its feedback control algorithm, and hence the tether control system must be large and complex. However, the TDS system, which we propose, does not have a retrieval system. The reasons for this are:

1. The QUEST mission does not require tether retrieval
2. There will be another future missions in which tether retrieval is required
3. Tether may be cut by space debris during its lifetime.

Eliminating the tether retrieval system enables the TDS to be very small and simple. Tether deployment will be

carried out with an open-loop control system determined in advance. If the tether length gets longer, measurement accuracy of the states of the satellite may become worse. In addition, tether libration angle decreases as the tether is deployed due to conservation of angular momentum. Therefore, appropriate settings for the tether deployment profile can be enough for a stable tether deployment.

The TDS consists of a Tether Reel Mechanism (TRM), and Sub-satellite Ejection Mechanism (SEM). This is illustrated in Figure 3 below. The SEM gives an initial velocity to the sub-satellite as a first step for the deployment.

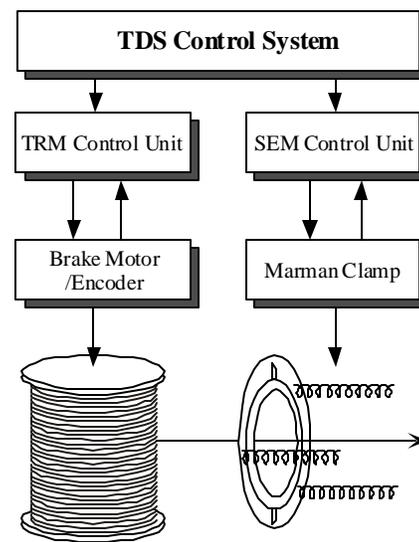


Figure 3: Tether System Block Diagram

#### 6.2.1 Tether Reel Mechanism

The Tether Reel Mechanism consists of a reel, a brake motor, an optical encoder and its control unit. In the deployment stage, the motor acts only as a brake so that the tether never slacks. Tether length and tension are not measured directly but calculated from the revolution of the reel instead. This section provides a mathematical explanation for some of the concepts associated with tether deployment.

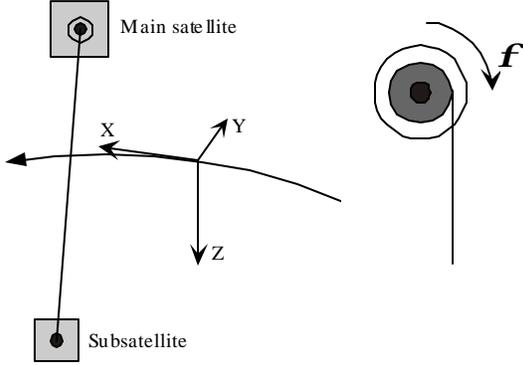
The relation between revolution angle  $\mathbf{f}$  and current tether length  $\ell_t$  is written in this simple form where  $r_{sp}$  is the radius of the spool.

$$\frac{d\ell_t}{dt} = r_{sp} \frac{d\mathbf{f}}{dt} \quad (1)$$

Considering the volume of the spool,  $r_{sp}$  and  $\ell_t$  can be written in the following relationship.



orbital velocity vector, the Y-axis is vertical to the orbit plane and the Z-axis is along the local vertical.



**Figure 7: Model Parameters**

Applying Lagrange's equation of motion to this system, the following equations can be obtained.

$$M_i \ddot{x}_i = H_i \frac{(x_1 - x_0)}{d} \mathbf{t} - M_i (\Gamma_i - \Omega^2) x_i - 2\Omega \dot{z}_i, \quad (7)$$

$$M_i \ddot{y}_i = H_i \frac{(y_1 - y_0)}{d} \mathbf{t} - M_i \Gamma_i y_i, \quad (8)$$

$$M_i \ddot{z}_i = H_i \frac{(z_1 - z_0)}{d} \mathbf{t} - M_i (\Gamma_i - \Omega^2) (z_i - R) + 2\Omega \dot{x}_i, \quad (9)$$

The subscript  $i$  denotes the main satellite when  $i=0$  and sub-satellite when  $i=1$ .  $H_i$  is an operator whose value is 1 when  $i=0$  and  $-1$  when  $i=1$ .  $\mathbf{G}$  effect of gravity, and  $\mathbf{t}$  tension of the tether, are written in following forms.

$$\Gamma_i = \mathbf{m} \left( x_i^2 + y_i^2 + (z_i - R)^2 \right)^{\frac{3}{2}} \quad (10)$$

$$\mathbf{t} = \frac{E_t A_t}{\ell_t} (d - \ell_t) + \frac{C_t A_t}{\ell_t} (\dot{d} - \dot{\ell}_t) \quad (11)$$

$E_t$ ,  $A_t$ ,  $C_t$  and  $d$  represent Yang's rate, cross section, damping rate of the tether and distance between satellites respectively. As for the reel, the equation of motion is expressed as follows:

$$(I_r + I_{sp}) \ddot{\mathbf{f}} = \mathbf{t} r_{sp} - (Tq_m + Tq_r) \quad (12)$$

$I_r$ ,  $I_{sp}$ ,  $Tq_m$  and  $Tq_r$  are the inertias of the reel structure, inertia of the spool, torque of the control motor and regular torque of the reel respectively. Using equation (12), the tension of the tether is given as follows:

$$\mathbf{t} = (Tq_m + Tq_r + I \ddot{\mathbf{f}}) / r_{sp}. \quad (13)$$

Conditions of the simulation are shown in Table 2.

**Table 2: Initial Conditions of the Simulation**

Orbit	Classification	Circular
	Altitude	500km
Mass	Main Satellite	20kg
	Subsatellite	10kg
Tether	Material	KEVLAR®29
	Diameter	0.33mm
	Length	2km
Reel	Moment of Inertia	$32.0 \times 10^{-5} \text{kg-m}^2$
	Regular Torque	$3.2 \times 10^{-4} \text{N-m}$

### 6.3.2 Tether Deployment Sequence

The sub-satellite is given an initial velocity by the ejection spring. The tether deployment profile after the ejection is given with a numerical simulation using tension control. Tether swing libration can be stabilized through coupling with tether longitudinal oscillation. Equation (14) and (15) are the controlled tether spring and damping coefficient.

$$k_s = 6M_m \Omega^2 \left( 1 - \frac{\ell_c}{R} \left( 1 + 2 \frac{M_m}{M_0 + M_1} \right) \right) \quad (14)$$

$$k_d = 2\sqrt{3} M_m \Omega \mathbf{x} \quad (15)$$

$\ell_c$  denotes commanded length,  $\mathbf{x}$  is a damping ratio and conversion mass  $M_m$  is expressed as follows:

$$M_m = \frac{M_0 M_1}{M_0 + M_1}. \quad (16)$$

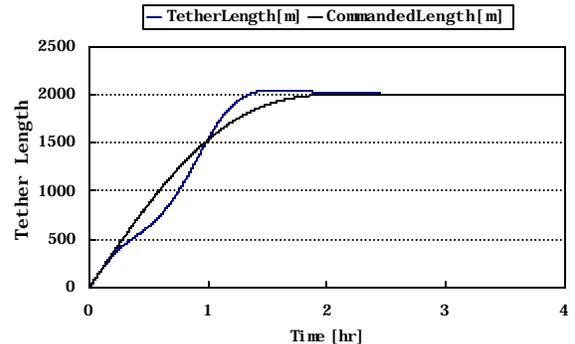
Thus, controlled tension  $\Delta \mathbf{t}$  is expressed as follow:

$$\Delta \mathbf{t} = k_s (d - \ell_c) + k_d (\dot{d} - \dot{\ell}_c). \quad (17)$$

The commanded length is defined to stop smoothly at 2km in the following equation.

$$\ell_c = \frac{L_t}{\mathbf{p}} \sin \frac{\dot{\ell}_{t0} \mathbf{p}}{2L_t} t + \frac{1}{2} \dot{\ell}_{t0} t + \ell_{t0}. \quad (18)$$

Figure 8 shows the deployed tether length versus time. This profile was obtained with the controlled tension in equation (17).

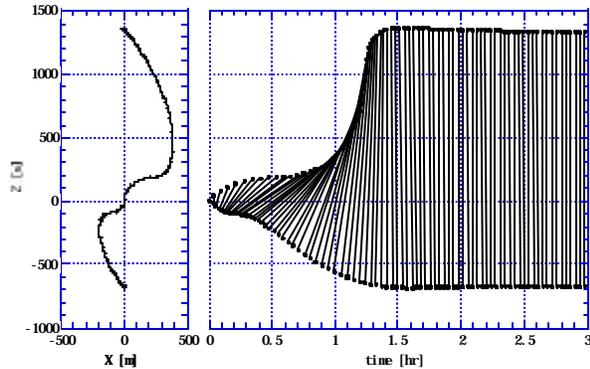


**Figure 8: Tether Deployment Profile**

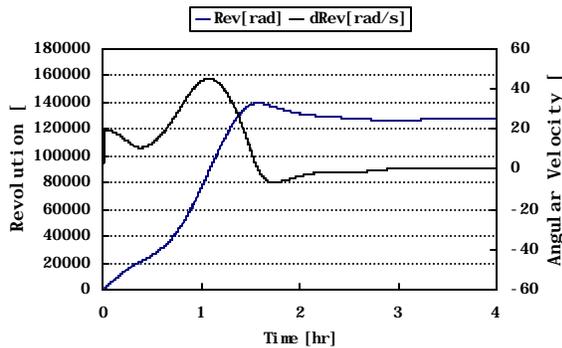
### 6.3.3 Example of the Simulation

The actual tether deployment analysis is performed with an open-loop control using the profile in Figure 8. An example of the numerical simulation is shown in Figure 9. Equation (19) is the initial condition for the simulation.

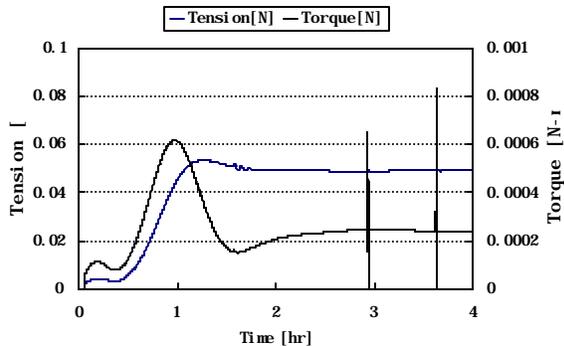
$$\begin{aligned} & (x_0, \dot{x}_0, y_0, \dot{y}_0, z_0, \dot{z}_0, x_1, \dot{x}_1, y_1, \dot{y}_1, z_1, \dot{z}_1, \mathbf{f}, \dot{\mathbf{f}}) \\ & = (0, 0, 0, 0, -0.053, -0.166, 0, 0, 0, 0, 0, 0.107, 0.333, 0, 0) \end{aligned} \quad (19)$$



(a) Motion of each satellite



(b) Reel revolution and angular velocity



(c) Tension of the tether and torque of the reel

Figure 9: Numerical Simulation Results

Seen from the figure, the tether is deployed smoothly without any slack. In Figure 9, at the final stage of the deployment ( $t=1.8\text{hr}$ ), some longitudinal oscillation can be found. This oscillation soon decreases by the structural damping of the tether.

### 6.3.4 Effects of Initial Errors

Since the tether is controlled with an open loop, initial conditions in the sub-satellite ejection and disturbances found during tether deployment will seriously affect the motion of the satellite. Especially in the sub-satellite ejection stage, the attitude of the main satellite must be stabilized toward the earth. Figure 10 and 11 show the final maximum libration angle according to the initial pitch angle error and the initial roll angle error.

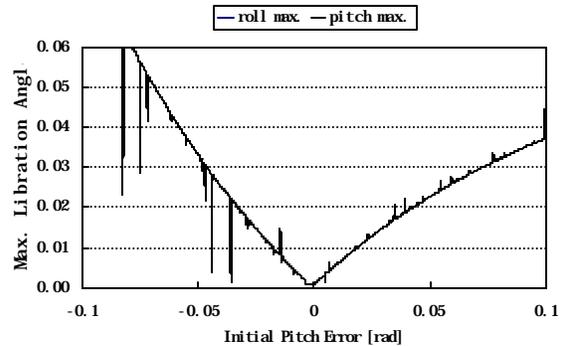


Figure 10: Effect of Initial Pitch Error

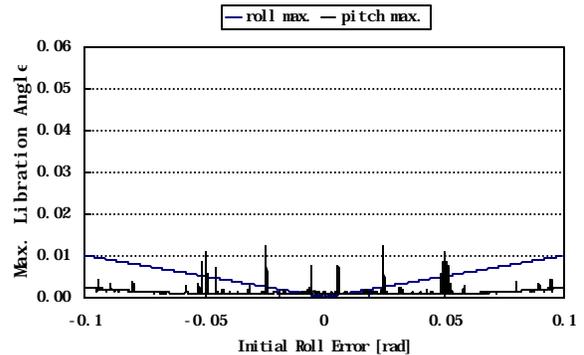


Figure 11: Effect of Initial Roll Error

In Figure 10, the final libration angle is very tiny compared with the initial roll angle error. On the other hands, the initial pitch error significantly affects the final maximum libration angle. The requirement for the final libration angle on the QUEST mission is not determined yet, but pointing requirement of  $\pm 5$  degrees are enough for the stable deployment of the tether.

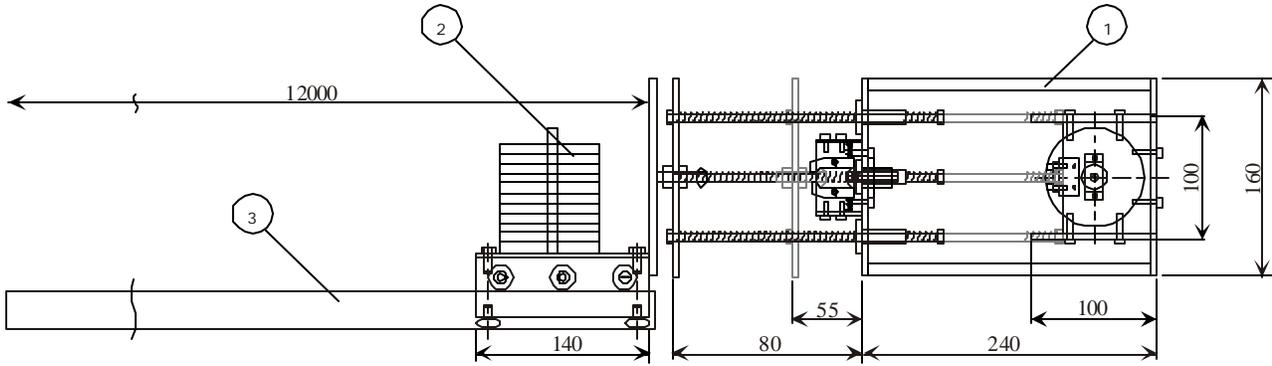


Figure 12: TDS Ground Experiment System using a Linear Rail

## 6.4 Ground Experiments

In order to confirm the ability of the TDS, ground-based experiments are necessary. In this experiment, the ability to control minute tension and deploy the tether up to 2km must be confirmed. A linear rail experiment is an answer to this first requirement, while another experiment must be performed to meet the latter requirement. This second experiment will occur sometime in the near future.

### 6.4.1 Linear Rail Ground Experiments

Figure 12 is a drawing of the experimental system. In the figure, No.1 indicates TDS, No.2 indicates the sub-satellite and No.3 indicates the 12m linear rail. The sub-satellite moves along the rail as the tether is deployed. The rail is declined slightly so that gravity can help eliminate the effects of friction between the rail and the sub-satellite. The dummy has the same weight as the actual sub-satellite to simulate the same environment in the first period of the deployment such as the minute tension and gravity. Table 3 shows specifications of the experimental model for the TDS.

Table 3: TDS Specifications

Size (Reel)	100×100×150 mm <sup>3</sup>
Weight	1.5 kg
Power	5 W
Max. Tether Length	3600 m
Spring Constant (in total)	0.03 kgf/mm
Max. Controllable Torque	20 gf-cm

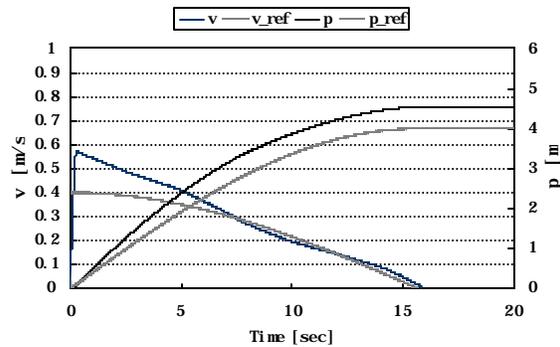
At first, the dummy sub-satellite is ejected by the springs, then the TRM start measuring the revolution of the reel and sends command torques to the brake motor. The experiment was performed with various values of controller gains  $K_p$  and  $K_d$  referred to earlier. In this

experiment, reference tether length  $l_{ref}$  was defined as a function of time shown in the following equation.

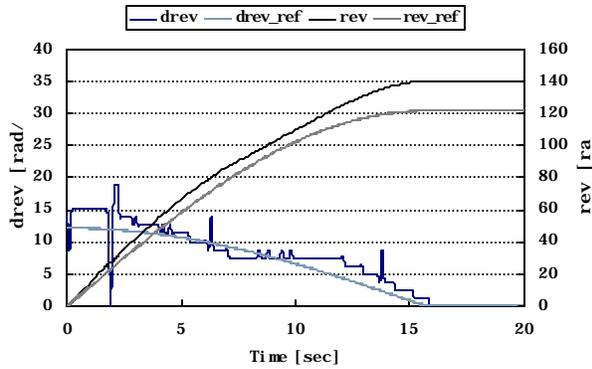
$$l_{ref} = \begin{cases} 4\sin 0.1t & (0 < t < 5p) \\ 4 & (t > 5p) \end{cases} \quad (20)$$

### 6.4.2 Experimental Results

Figure 13 shows the results of this experiment when  $K_p=0.5$  and  $K_d=0.5$ . In this case, controller gain was too small to stop the sub-satellite at the proper position and the sub-satellite overshoot the reference tether length. In the figure 14, controller gains were changed to  $K_p=1.0$ ,  $K_d=0.33$ , and the sub-satellite moved along the reference path. In both case, the tether never slacked throughout the deployment.

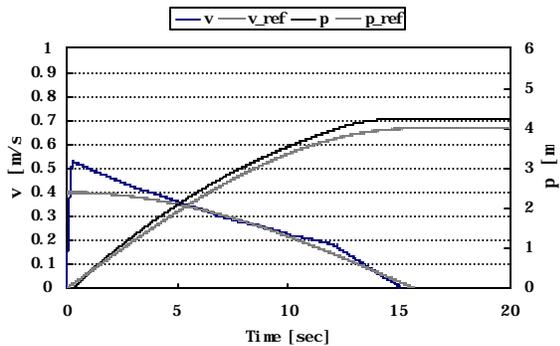


(a) Position and velocity of the dummy subsatellite

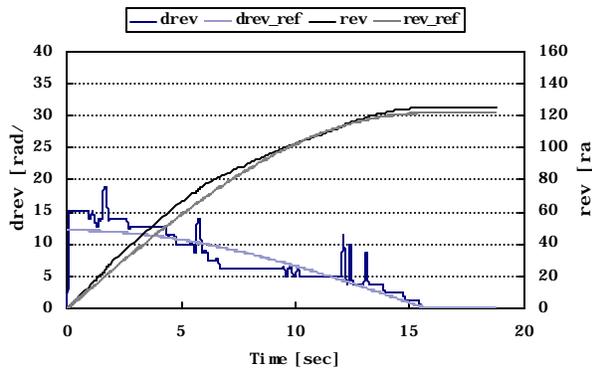


(b) Revolution and angular velocity of the reel

Figure 13: Experimental Results,  $K_p=0.5$ ,  $K_d=0.5$



(a) Position and velocity of the dummy subsatellite



(b) Revolution and angular velocity of the reel

Figure 14: Experimental Results,  $K_p=1.0$ ,  $K_d=0.33$

When controller gains were set to too large of a value, the sub-satellite stopped before it reached the reference position. In this case, the TRM can do nothing to recover from this state. One possible solution is to attach a thruster to the sub-satellite, but of course this

makes the smaller S/C much more complicated than the initial scope of this effort. Therefore, the control gains must be carefully set through analytical calculation and extensive testing before the system is utilized on-orbit. Images of the setup used for these tests are shown in Figures 15 and 16.

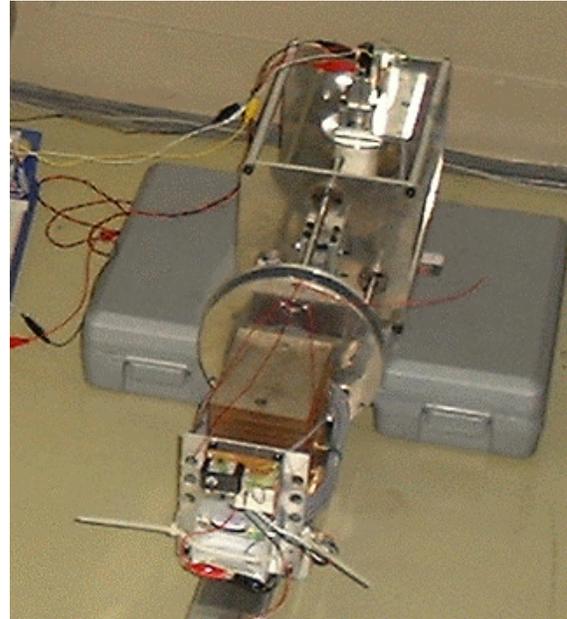


Figure 15: TDS Testing Apparatus

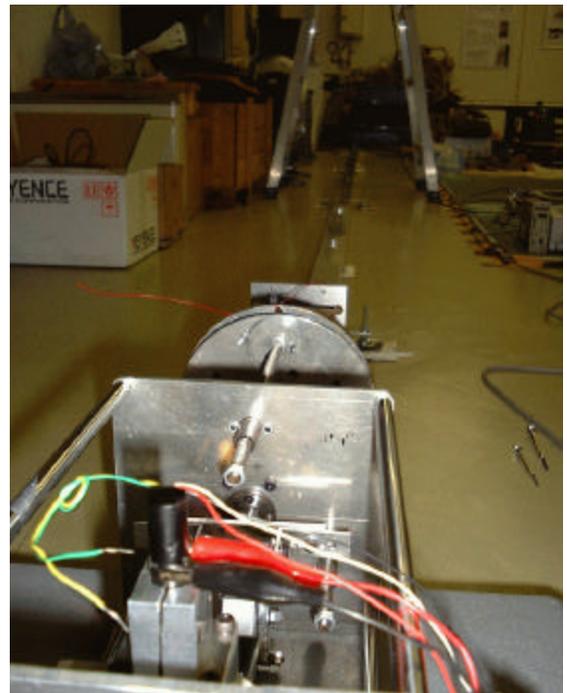


Figure 16: Linear Rail System

Now that the first prototype of the TDS is nearing the completion of its testing, several other important components are being built. First, a rotational device under construction will be attached to the sub-satellite as it deploys to simulate rotational motion and its effects on the tether. In particular, it is important to examine the effects of tether twisting and rotational impulses from the separation system. Also, a 3-axis gyroscopic mount is being built that will test limited deployment in three dimensions. Although this mount will require a fair amount of fine-tuning, it is hoped the use of a more complicated air table or other low friction mount can be avoided.

Once the testing segment of development is completed, construction will begin on a flight scale version of the TDS. It is anticipated that this version will be approximately 40 – 50% the size of the current version. This will create an extremely compact tether deployer that can be used on almost any small satellite. For larger missions requiring tether lengths greater than 2 km, the system can be scaled up accordingly.

## 7.0 Science Payload

Tether deployment and operations is the primary objective of the QUEST mission. However, once the tether is fully deployed and testing has finished, several other new technologies will be examined. These include the VLF experiment and distributed spacecraft operations.

One specific candidate for the science mission is to include a Very Low Frequency radio receiver on each QUEST satellite. These receivers detect lightning-induced radio emissions and can be used to study ionospheric effects on communication signals as well as to conduct global lightning surveys. The former objective is significantly enhanced when performed in a local, distributed manner. SCU has developed science VLF receivers for similar studies on other small spacecraft and currently has an operational engineering model suitable for inclusion on each of the QUEST spacecraft.

An alternate candidate for the science mission is distributed Earth photography using digital cameras in order to produce stereo images and/or super-resolved photographs. This would be accomplished through the incorporation of a low-cost, commercial digital camera on both vehicles. These cameras would also permit photographic examination of tether operation and dynamics. Selection depends upon available funding and available time on-orbit as well as downlink allowances

Another optional science mission is that of distributed “virtual formation” operations. This effort follows a similar objective in several other ASU missions. The virtual formation is a cooperative effort between satellites operating as a network to accomplish targeting and data acquisition. Satellite health, status, and science data are transmitted to the ground and to the other satellites via communications links without the need for strict physical proximity between the satellites. This allows the communication links to carry the command and control data necessary to accomplish the mission regardless of the physical location of the satellites. The locations of the satellites will need only to be “in range” and mutually known in order for each to support its portion of the mission, but exact physical separation is not a requirement for the formation network. The tether will keep the two satellites within range for all formation operations.

## 8.0 Conclusion

The proposed QUEST mission will test and examine small-scale tether deployment and operations from a nano-satellite. If successful, this mission will enable a variety of potential tether applications for future small satellite missions. The key to this tether technology is the ability to use a tether system that is small, lightweight, does not require a complicated braking or deployment system, and can be operated reliably for a minimal cost. The QUEST mission hopes to demonstrate all of these objectives.

Currently the QUEST mission is in the preliminary design stage. Subsystem layout and operation have been identified, and many of the individual components have been selected. However, it is not anticipated the project will advance to more detailed design until a specific flight opportunity is identified. Tether development is in the later stages of prototype testing. Soon, a flight scale version of the system will be built for more comprehensive testing. Thus far, results are positive, and there are no major technical problems envisioned.

It is hoped the QUEST mission will be manifested as a secondary payload aboard the Japanese H-IIA launch vehicle. It is felt the benefits obtained from this mission more than justify such an opportunity for launch.

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