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PRELIMINARY DESIGN OF TETHERED SATELLITE CONTROL SYSTEM FOR SPACE TETHER EXPERIMENT SYSTEM

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In this paper the authors present a summary of a control system for a tethered satellite of the Space Tether Experiment System proposed by the Institute of Space and Astronautical Science. This is one of the candidate systems for mission payloads of the 2nd Space Flyer Unit.

The most important feature of the system is to give repeatability of tether operations in flight. Several cycles of deployment, station-keeping and retrieval of subsatellite will be done in orbit before reentry, differing from other tether experiment programs. We can observe various motions of tether wire and subsatellite to clarify dynamics of them and verify proposed tension control laws in the program.

INTRODUCTION

A tethered satellite system is thought to have a wide variety of applications. High endo-atmospheric observation probes, micro-gravity laboratories, tether elevators or momentum transfers in space transportation systems are some of the examples of engineering and scientific applications. A subsatellite is hung from the mother satellite with a tether wire. The dynamics of tethered two bodies in space are so complicated that many methodologies for controlling in-plane or out-of-plane swings are proposed by researchers in the United State and Italy. Tethered Satellite Systems-1 (TSS-1) will be launched by Space Shuttle as a joint program of NASA, U.S.A. and the Italian Government in 1992.

Researchers in Japan have gotten into dynamics of tethered bodies in space, too, and an experiment program by Space Flyer Unit (SFU) has been proposed as Space Tether Experiment System (STEX) by the Institute of Space and Astronautical Science (ISAS). STEX is one of the engineering mission candidates for the 2nd SFU (SFU #2), planned to be launched in 1996, or after, by the H-II launch vehicle at the time.

OBJECTIVES OF STEX

In general, unmanned spacecraft have long life, and tether experiments require a long time. Thus, in STEX, it is thought to conduct the experiment taking enough time with the practical use and advantages of unmanned spacecraft. One of major

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purposes of STEX is to observe the behavior or dynamics of tether wire and a tethered subsatellite without any controls, as precisely as possible, to obtain fundamental data for further experiments. Secondly, with repetition of cycles of deployment, station-keeping and retrieval of tethered bodies, various control laws or algorithms for control are examined to verify them for future use. Figure 1 presents the STEX configuration on SFU.

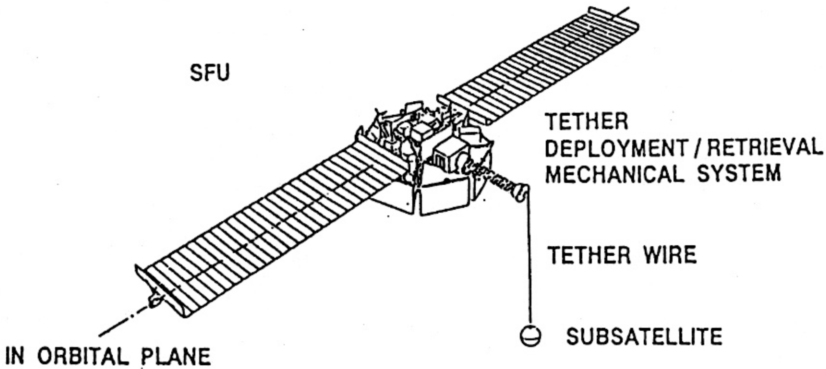

Figure 1 STEX Configuration of SFU

Major experiments of tether control will be conducted at 10 km. The length of 10 km is set, based on the engineering mission elements of minimum possible length to deploy, feasibility confirmation of tether tension control and repetition intervals. SFU #2 has another mission candidate of Microwave Energy Transmission Experiment (METS), which requires keeping the subsatellite at about 1 km from SFU. This gives the requirement of partial deployment of a 10 km tether. Then, experiments are conducted at 1 km and 10 km lengths, respectively. Schedules of a cycle for each length test are shown in Figures 2 and 3.

One cycle takes typically 120 minutes for 1 km and 520 minutes for 10 km. With 10 km length, many cycles of test will be repeated, as far as thruster fuel lasts, changing the control algorithms for phases of deployment, station keeping and retrieval.

When the subsatellite approaches near by SFU, tether tension comes down less than 1 N to make tension control very difficult, then thrust control seems to be required in an initial phase of deployment and a final phase of retrieval, being tension lessened further in these phases. So it is another goal of STEX to explore or clarify the limits of tension control and thrust control capability. We present the main characteristics of STEX in Table 1.

DESCRIPTION OF CONTROL SYSTEM

Composition

The STEX system consists of a Tether Deployment/Retrieval subsystem (MECH), and experiment Controller (CONT) and Subsatellite (SUBS). Figures 4 and 5 show a system block diagram and schematic structure of STEX, respectively. MECH consists of an arm, reel drive control system, tether wire, S-band telemetry, thermal control system and jettisoning mechanism. CONT is composed of a dedicated experiment processor, power supply and interface unit with bus power system. SUBS is composed of a power system, S-band telemetry system, data and command management system, tension monitor, thermal control system, space environment sensors, RF wave band receivers and vacuum gauge.

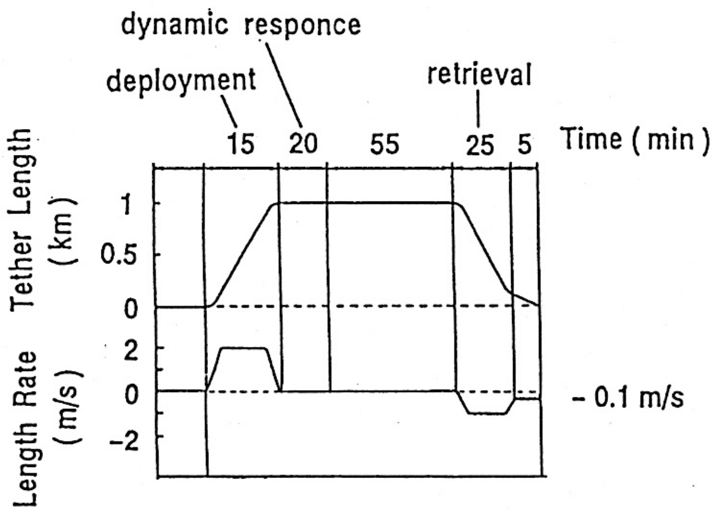

Figure 2 Experiment Profile (1 km Tether)

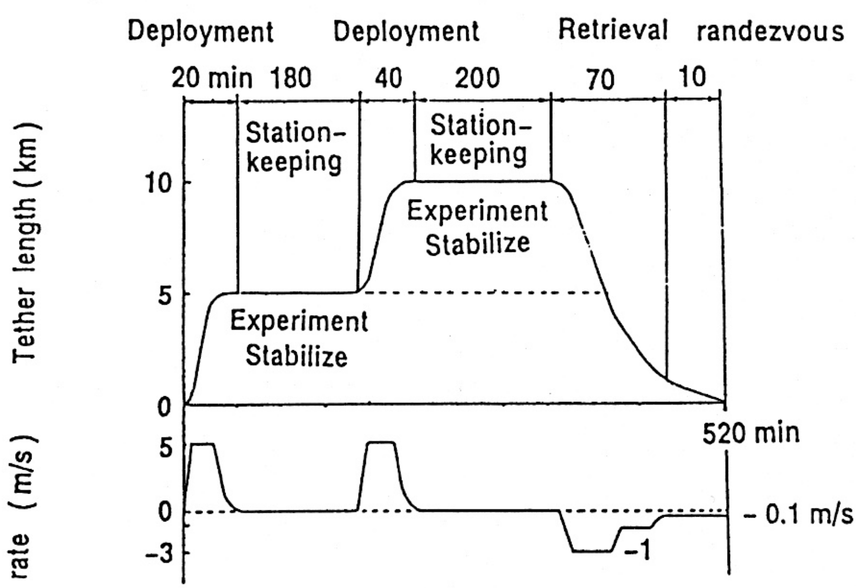

Figure 3 10 km Tether Experiment Profile (Example)

Table 1
STEX SYSTEM CHARACTERISTICS

Mechanical and Electric properties	SIZE	
	MECH	500(W)×1000(D)×500(H) mm
	CONT	400(W)× 400(D)×300(H) mm
	SUBS	300(D) mm (attached to MECH on SFU)
	Weight	171 kg (MECH 116 kg, CONT 15 kg, SUBS 40 kg)
	Power	operational 100 watt (average)
		500 watt (maximum)
		non-operational 30 watt (average)
	Tether length	10 km (~30km)
Communication	COMS:Interface	RS-422
	Data Rate	4 kbps
Experiment Functional Objectives	Operation Mode	4 Functional Objectives (FOs)
	Duration	10 min (FO-1), 300 min (FO-2) 250 min (FO-3), 620 min (FO-4)
	Number of FO	12 (FO-1), 7 (FO-2), 10 (FO-3) 2 (FO-4)

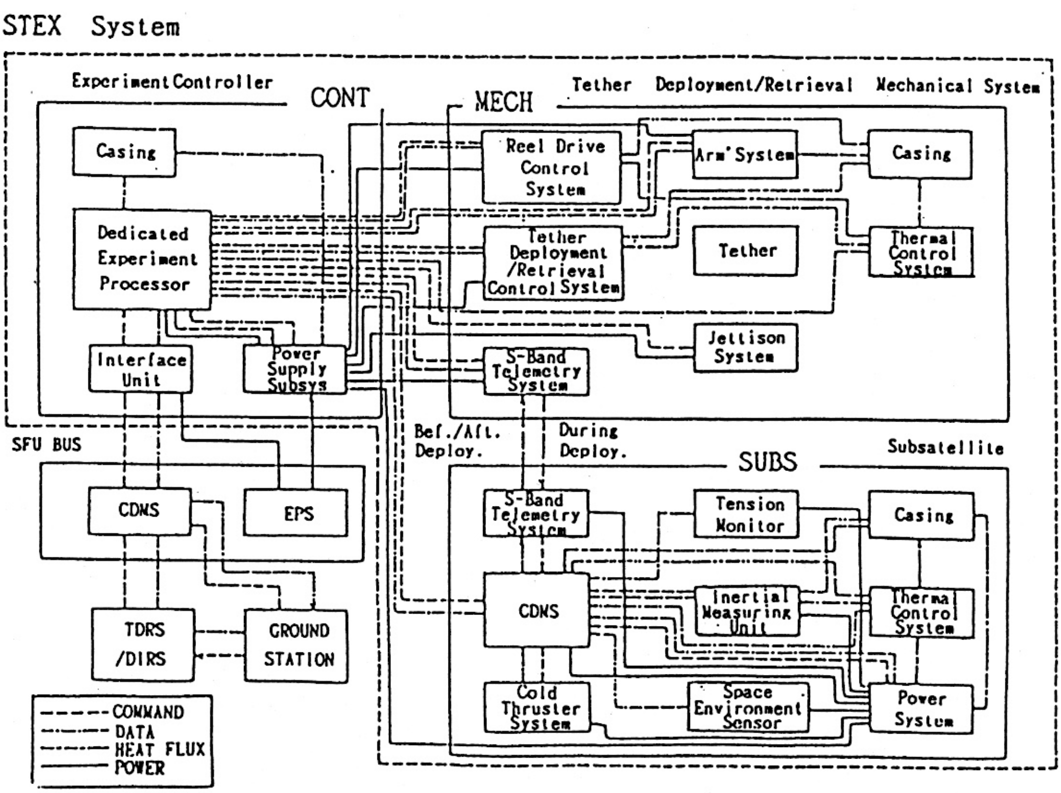

Figure 4 System Block Diagram

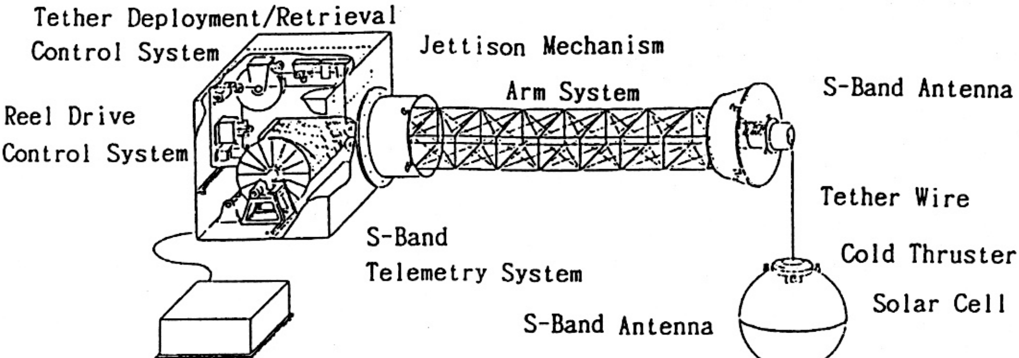

Figure 5 Schematic Structure of Control System

The structure of MECH is represented in Figure 5. Major components of MECH are Reel Drive Control Mechanism (TCONT) and Arm Deployment Mechanism (ARM). Extendible ARM gives proper displacement of tether wire releasing point from structural body of SFU to avoid unnecessary tangles of wire during operation as seen in Figure 2.

RCONT winds up and releases the tether wire from a reel, giving properly controlled tension to the wire with tension force monitored and preventing the wire from being put aside on the reel during operation.

TCONT is assembled with a grip pulley, grip pulley motor, pinch rollers, deployment/retrieval tension monitor. This TCONT is used to put forward the tether wire. The tension monitor signal is fed back to RCONT to control the subsatellite motion.

Figure 6 shows control block diagram of STEX. Distance and in-plane or out-of-plane angle of subsatellite relative to SFU are detected by tracking radar.

Tension is picked off by 3 tension meters (2 in MECH and 1 in subsatellite). Tension meter #1 in MECH is used so as not to loosen the tether wire. The signal of tension meter #2 also in MECH is fed back to Tension/Length Control Processor where various tension control laws are applied for positioning subsatellite properly. Tension meter #3 in subsatellite is for monitoring purposes only.

Subsatellite attitude relative to tether line at the connecting point is very important for subsatellite control so that an attitude sensor is installed at the point to supply attitude angle, as feed-back signal to CPU in the subsatellite itself. Then the attitude is controlled with thruster or reaction wheel.

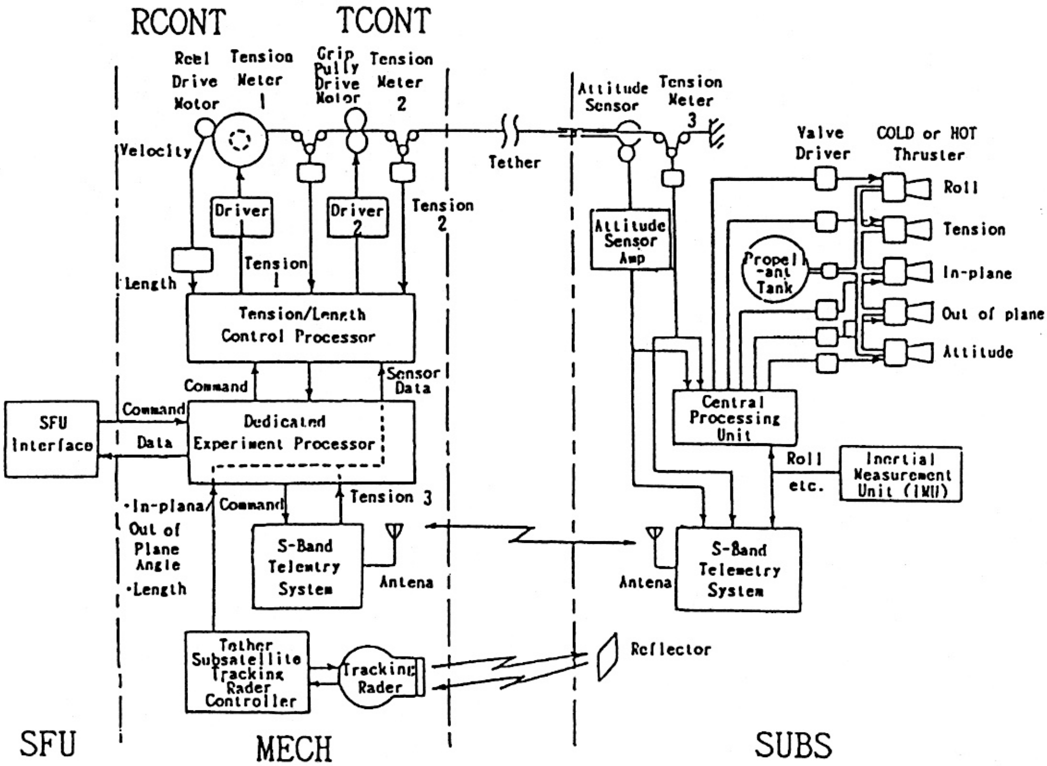

Figure 6 Control System Block Diagram

We represent STEX system characteristics in Table 1. FO-1 is to check out the STEX system before FO-2. After FO-1, before the deployment, the battery in the subsatellite is fully charged in FO-2. FO-3 and FO-4 are the experiments with the 1 km tether and 10 km (~30 km) tether.

Reel Drive Specifications

The requirements to Reel Drive are summarized in Table 2. These requirements are derived from the results of stability analysis and nonlinear computer simulations with control law (1) which is discussed later, for the tethered satellite. We determined the gain and the bandwidth of the reel drive tension control system in the stable domain as shown in Figure 7.

Compensation gain Ka becomes,

$$Ka = ln \cdot 2 \cdot W \cdot K / EA \cdot Di)$$

Where

ln = tether natural length

K = nondimentional gain specified in Figure 8

EA = tether elasticity X tether cross section area

Di = diameter of reel drum included tether

And we selected the design point as described in Figure 7.

Delay of Reel Drive by second order of transfer function, which causes inability to compensate the fast longitudinal vibration of tether, gives the lower limit to frequency domain for stability as shown in Figure 8.

Power requirement are decided to satisfy the requirement of Figure 8.

Figure 9 describes the block diagram of tension controller with reel drive model.

Table 2
REEL DRIVE SYSTEM REQUIREMENT

Item	Requirement
Torque	Rating 8 kgf·cm (1000 rpm) Maximum 15 kgf·cm (1400 rpm)
Rotational speed	Rating 1000 rpm Maximum 1600 rpm
Power	Fig. 9
Frequency	more than 1 Hz (TBD) at the load 8 kgf·cm (Rating Torque) or 170 kg·cm²(Inertia)

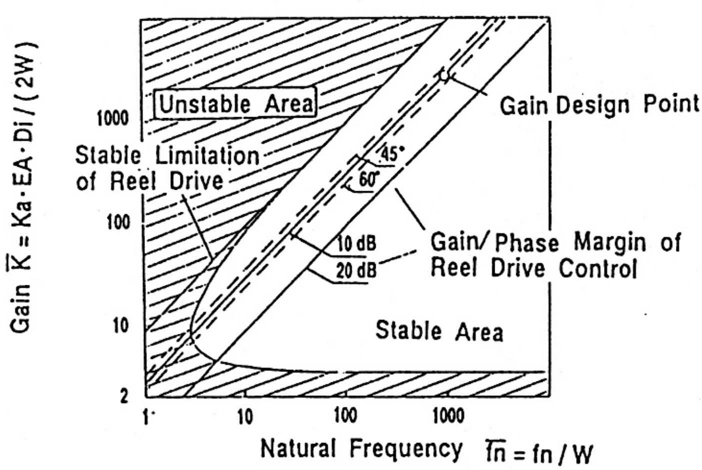

Figure 7 Stable Domain of Subsatellite Tension Control System

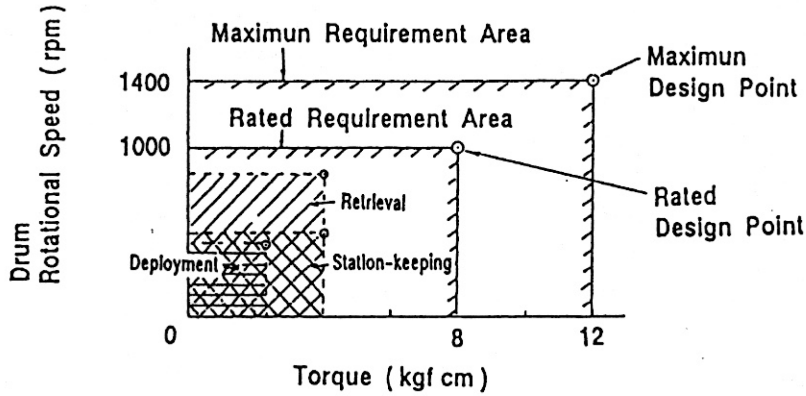

Figure 8 Power Requirement

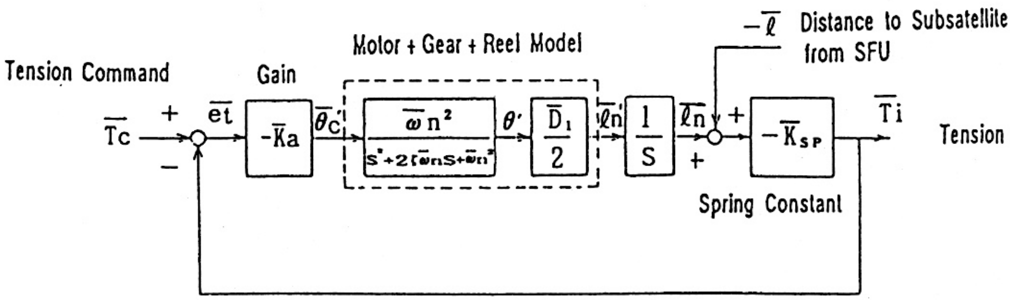

Figure 9 Tension Controller Block Diagram

SIMULATION RESULTS

Control Law

As an example, we calculated the subsatellite dynamics in deployment station-keeping and retrieval with the optimal tension control law with which in-plane swing is controlled (Ref. 1, Bainum 1980), assuming that (1) SFU is in 500 km circular orbit, (2) tether wire has elasticity and is straight and (3) the aerodynamic load is negligible there. Reel drive is modeled as second order transfer function. Tension command is obtained (Ref. 1, Bainum 1980)

$$Tc = Tf - K\ell \cdot (L - Lc) - K\dot{\ell} \cdot (\dot{L} - \dot{L}c) - K_{\alpha} \cdot \alpha - K_{\dot{\alpha}} \cdot \dot{\alpha} \quad (1)$$

where

$K\ell = M \cdot W^2 \cdot \overline{K\ell}$	We decided	$\overline{K\ell} =$	10.680
$K\dot{\ell} = M \cdot W \cdot \overline{K\ell}'$		$\overline{K\ell}' =$	7.11
$K_{\alpha} = M \cdot W^2 \cdot Lc \cdot \overline{K_{\alpha}}$		$K_{\alpha} =$	7.92
$K_{\dot{\alpha}} = M \cdot W \cdot Lc \cdot \overline{K_{\alpha}}'$		$\overline{K_{\alpha}}' =$	4.81

$\overline{K\ell}, \overline{K\ell}', \overline{K_t}, \overline{K_t}'$ = optimal feed back gain with nondimensional linear tether satellie control model

L = tether length (distance between subsatellite and SFU)

$\dot{L}$ = length rate along tether line direction

Lc = tether length command (Integration of $\dot{L}c$)

$\dot{L}c$ = tether length rate command

α = in plane angle

$\dot{\alpha}$ = in plane angle rate

Tf = equilibrium tension at tether length Lc

W = orbital angular rate (1.107×10^{-3} rad/s)

M = subsatellite mass (40 kg)

Tension Control Results

Figures 11-13 describe the loci of subsatellite in two stages of station-keeping and retrieval by tension control law (1), with reel drive model.

Deployment is successfully done with constant and sufficiently slow deployment rate of less than 1 m/s as shown in Figure 14. But retrieval does not succeed within a realistic time period, even though constant rate is slow enough.

Figures 10 and 12 describe the differences of control efficiency by the different elasticity of tether in station-keeping and retrieval. The reel drive motor cannot compensate for the tether's longitudinal villation when the elasticity of tether is high.

The retrieval with tension control is very difficult in final stage, because tension level is so low that final misdistance between SFU and subsatellite at the docking is several tens of meters. We think thruster control is necessary in the docking phase.

Fast Deployment and Fast Retrieve with Thruster

Figure 15 describes the loci of the fast deployment and the fast retrieval. In these cases, thruster control is used within the distance of 5 km. In-plane or out-of-plane thrust level is proportional to retrieval rate (Figure 16), and its minimum value is 1 N. It can take less than 2 hours to complete the deployment or the retrieval with thruster.

The retrieval rate must be decreased down to 1 m/s at the middle stage, in order to prevent the subsatellite from divergence of in-plane and out-of-plane swing when 1 N thruster is used and until the final 50 m, but the rate must be decreased to 0.1 m/s for safe rendezvous, docking. In-line thruster is used to recover tension level up to about 1 N within 5 km tether length.

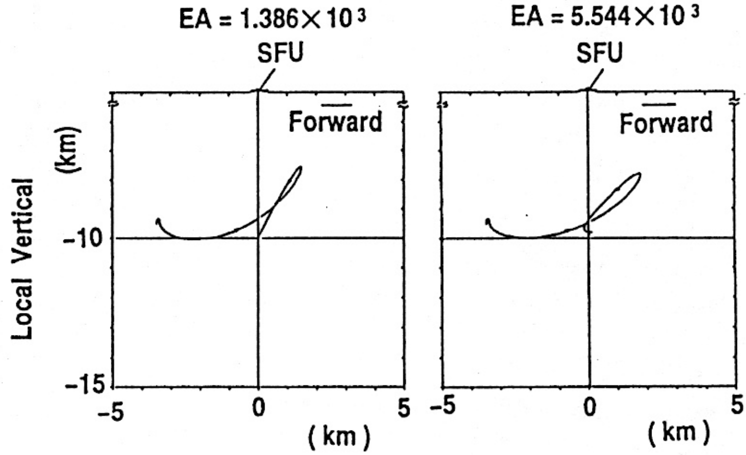

Figure 10 Loci (Station-Keeping)

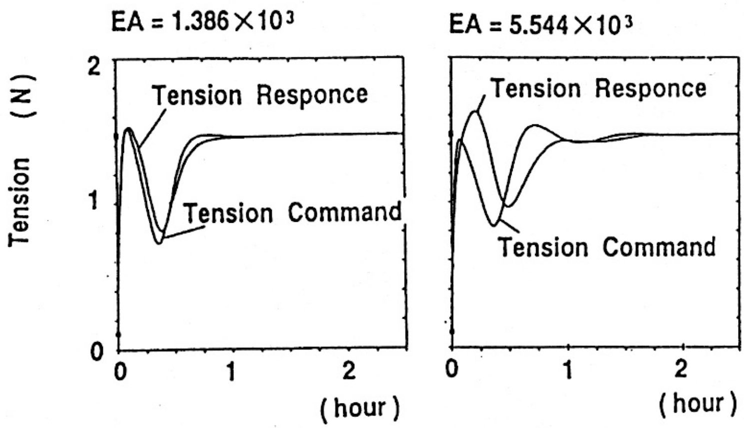

Figure 11 Tension Response (Station-Keeping)

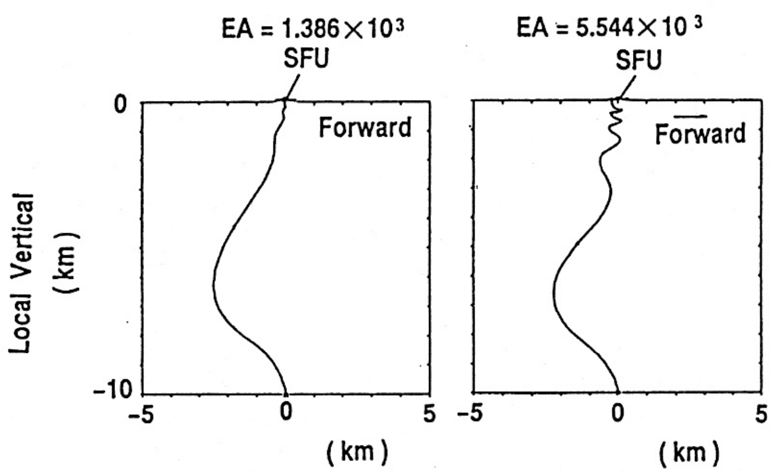

Figure 12 Loci (Retrieval)

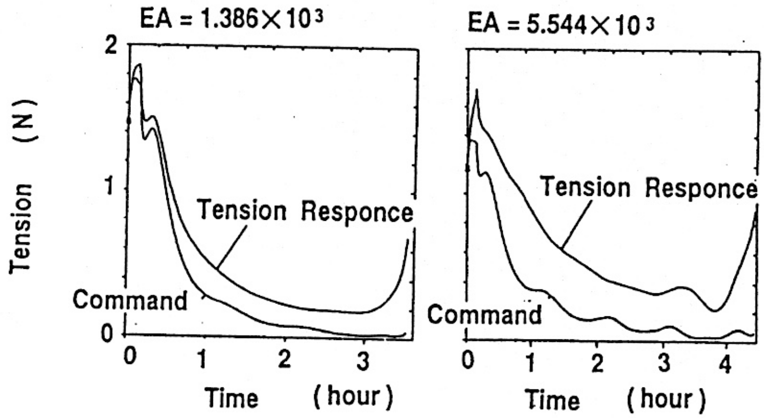

Figure 13 Tension Response (Retrieval)

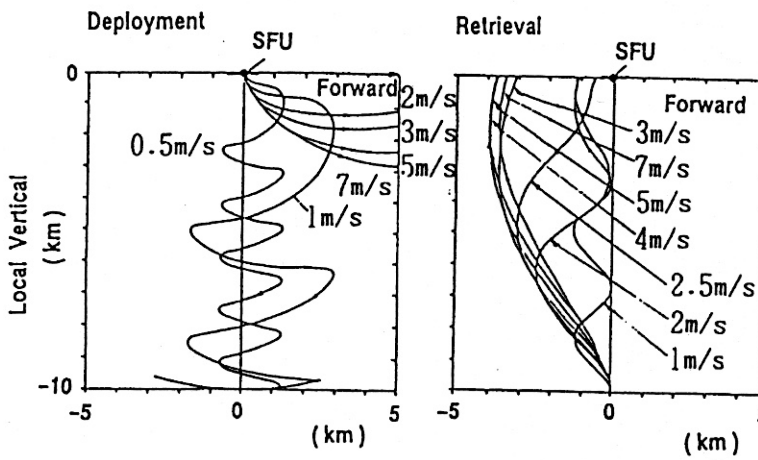

Figure 14 Constant Rate Deployment/Retrieval Loci

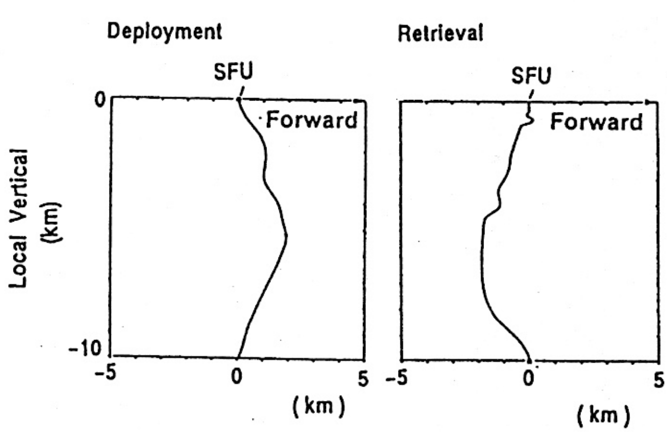

Figure 15 Fast Deployment/Retrieval with Thruster

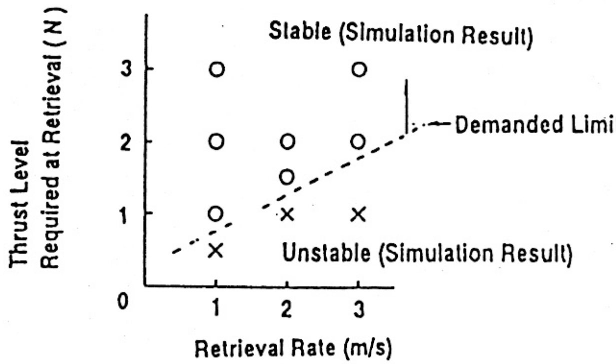

Figure 16 Requirement of In-Plane/Out-of-Plane Thruster

CONCLUSIONS

Objectives of STEX are:

1. To study the dynamics of tether system in the three phases; deployment, station keeping and retrieval,
2. To verify the theories to control the tether system in three phases and
3. To survey the environmental data around spacecraft by tethered satellite.

One of the characteristics of STEX is a repeatability of tether control experiments because SFU can provide long experiment time.

We showed the results of the preliminary study of STEX control system, but many other problems to be analyzed still remain; sensors, friction and thruster fuel consumption are some examples. We also presented the simulation results by tension control laws which we proposed as well as the results by Bainum's method.

ACKNOWLEDGEMENT

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