The Tether System Experiment

– Preparing for ESA's First Tether Mission

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The Tether System Experiment (TSE) has been identified by the European space community as an important initiative for demonstrating the application of tethers in space. An international project team has studied the feasibility of this tethered-capsule re-entry mission, which could be launched as early as 2002 on a Russian Progress vehicle. It will prove the feasibility of tether-assisted sample return from the International Space Station (ISS) and could ultimately lead to many other practical applications of tethers in space.

Introduction

The advantages and benefits of applying conducting and non-conducting tethers in space have been known for many years. Possible applications range from orbit and re-entry manoeuvres, to attitude stabilisation, power generation and scientific experiments. Early space tether experiments in the 1960s focussed on artificial gravity (Gemini XI and XII, 1966), and in the 1970s Giuseppe Colombo proposed using electrodynamic tethers as continuous thrusters for spacecraft. In the 1980s and 1990s, both Canada and Japan deployed conductive tethers many hundreds of metres long from sounding rockets. The longest tethers ever deployed in space were those of SEDS-1 (1993) and SEDS-2 (1994), which used 20-km wires to demonstrate momentum transfer and coordinated orbit change for the first time. In 1996, the TSS experiment, a USA–Italy cooperative venture, deployed a 19.5 km tether from the Space Shuttle.

Figure 1. Tether deployment on Gemini XII

ESA has a lot of tether knowhow. The electrodynamic tether and more recently the bare-tape tether are both European inventions. The new concepts promise a much higher efficiency and could make ISS station-keeping feasible with a tether just a few kilometres long.

Several tether deployer concepts have already been developed in Europe: the TMM&M deployer (Alenia Spazio) is a spool-reel combination with torque control, which has been extensively tested; and the RAPUNZEL (Kayser-Threde/TU München) is a low-friction spool-based deployer that uses technology from the textile industry to control the deployment A fully reel-based deployer has also been developed (FIESTA, RST Rostock) and several momentum-transfer demonstration missions have been studied (TARGET, 1995; SESDE, 1996-1998).

Tether basics

In space, the absence of matter and the small forces in vacuum make it possible to deploy extremely long wires, or 'tethers', with diameters of only a few millimetres. The polyethylene tether for the TSE application, for example, has a diameter of 0.5 mm and is 35 km long, but weighs just 7 kg. A distinction is made between mechanical and electrodynamic tethers:

- A mechanical tether is a link between satellites that forces them to maintain a constant separation, thus offering possibilities for multipoint atmospheric research, artificial gravity generation, momentum transfer, etc. The principle of momentum transfer is crucial for many applications, including TSE: if two satellites in circular orbit are connected by a vertical wire, both are forced to orbit with the velocity of their combined centre of mass. The upper mass will then orbit at a velocity higher than the local circular velocity, while the lower mass is actually too slow for its orbit. The gain of tethered momentum transfer is achieved by cutting the tether: the lower mass is then released into an elliptic orbit with decreased perigee (which will be about seven times the tether length lower than the original orbit), whereas the upper mass raises its apogee. The total momentum is preserved, but two satellites have had their orbits changed for the cost of only a few kilograms of tether mass.

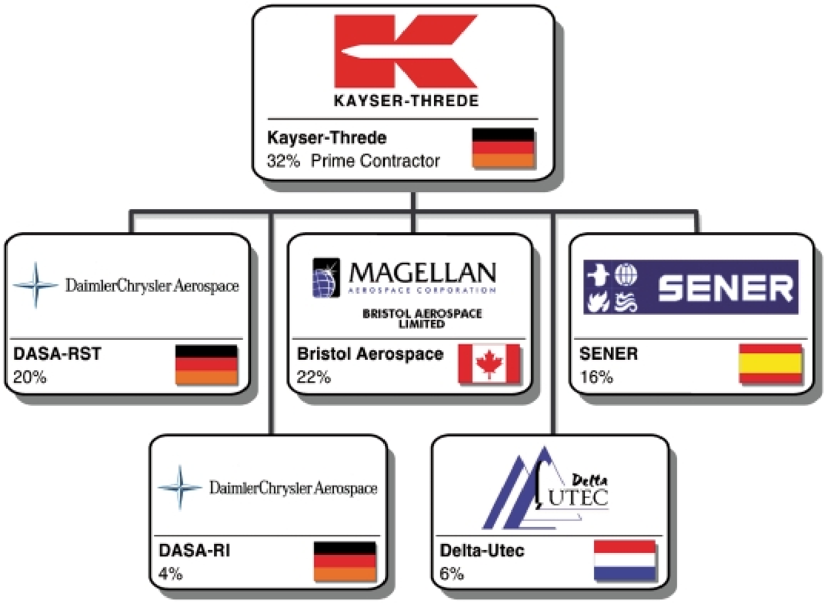

Figure 2. The TSE project team

- Electrodynamic tethers are conductive wires that interact with the ionospheric plasma when speeding at orbital velocity through the Earth's magnetosphere. If there is sufficient contact with the plasma, electrons can be collected on one side of the tether (or even by the surface of a bare tether itself), while being emitted back into the plasma on the other side. The current created will subject the tether (and its end masses) inside the Earth's magnetic field to a Lorentz-force that can be used to either raise or lower a satellite's orbit. Multi-wire or tape-like tethers can provide the meteoroid resistance required for long-duration missions relying on such tethers.

The TSE mission

In 1986, ESA's Space Mail study indicated the need for a frequent Earth sample-return capability from the International Space Station in order to stimulate the production and dissemination of in-orbit research results. In 1994, a Round Table on Tethers held at ESTEC identified such a sample-return and waste-disposal capability as the primary applications for tethers in the near future. Supported by many companies, institutes and universities, this initiative resulted in many developments in the fields of re-entry capsules and strategies, tether dynamics and tether mechanisms. Following up these developments, in 1997 the TSE study (Phase-A/B) was initiated as part of ESA's General Support Technology Programme GSTP-2.

The TSE study is being carried out by an international project team led by Kayser-Threde (D). All of the team members (Fig. 2) have participated in previous tether projects and therefore provide a broad knowledge base. The current Phase-B began with the selection of the mission's mother spacecraft and continued with the preliminary design of the complete system. The target launch date for the demonstration mission is 2002 (Fig. 3).

Mission objectives

The objectives for the TSE demonstration mission are to:

- demonstrate the operation of a tether-deployment mechanism that is suitable for ISS sample return and able to operate properly within the ISS environment
- demonstrate a robust tether-deployment control strategy for initiation of the re-entry, proving that the precision required for the accurate landing of future sample-return capsules can be achieved
- demonstrate the critical technologies associated with the re-entry capsule of an ISS tethered sample-return system
- collect experimental data on system dynamics to support the validation of models used for tether-deployment simulations, including the measuring of tether oscillations and librations.

Mission scenario

The TSE hardware will be installed on a Russian Progress cargo vehicle. The Progress will first conduct its supply mission to the ISS, before being transferred to the selected orbit to eject the sub-satellite and start the tether deployment.

In order to achieve a higher accuracy, the tether-deployment strategy involves two phases (Fig. 4). During the first phase, the tether will be deployed to 3 km vertically below Progress to stabilise the capsule and reduce sensitivity to ejection errors and other system variations. After synchronisation with the target landing site, the second phase leading to the full 35 km tether deployment will begin. At the end of the deployment, the brake will stop the movement of the tether so that it will swing back towards the local vertical. On reaching the local vertical and at a predefined optimum moment, the tether will be pyrotechnically cut by the deployer system (Fig. 5). The resulting momentum exchange will send the sub-satellite on a re-entry trajectory, dragging the tether behind it as a passive orientation device.

Thirty minutes later, the sub-satellite will hit the Earth's upper atmosphere and decay above the Pacific Ocean. From activation until burn-up, the sub-satellite will collect such experiment data as position and velocity (from GPS), angular rates and accelerations (from IMU) and temperatures. It will transmit them to the Tether Deployer System on board Progress, where the data will be stored. The sub-satellite's telemetry and similar data collected by the Tether Deployer System itself will be transmitted to a ground station in Germany after the experiment has been completed. TSE will then be deactivated and Progress will re-enter the Earth's atmosphere and decay. Post-flight analysis of the experiment data will validate whether the required accuracy for the re-entry trajectory has been achieved.

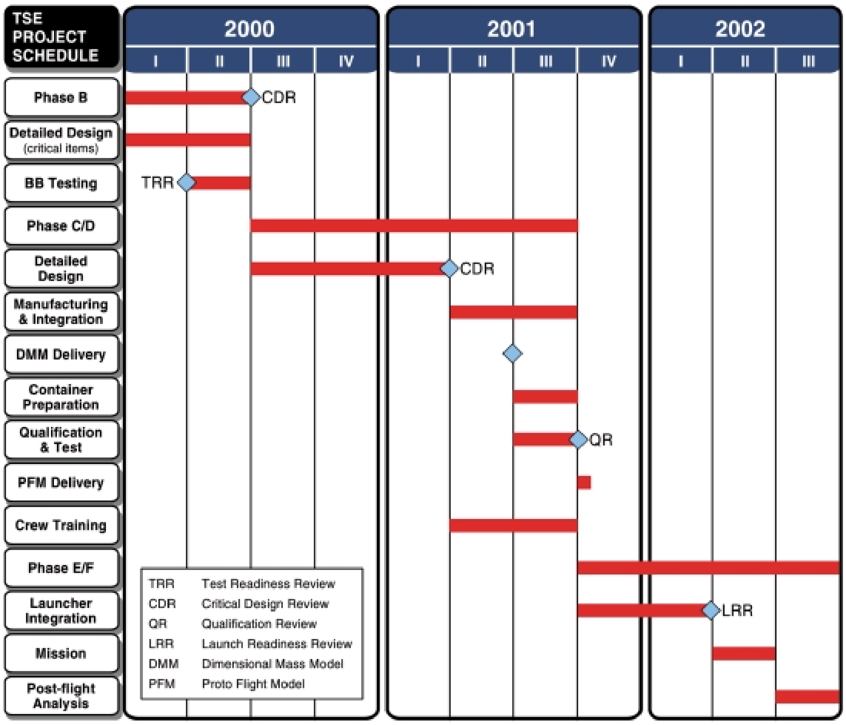

Figure 3. Project schedule

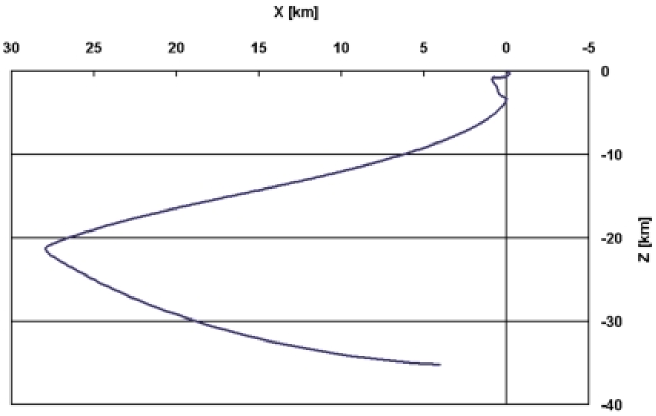

Figure 4. Tether deployment

Design as a low-cost system
TSE is strictly designed as a low-cost mission and uses existing hardware (Fig. 6) wherever possible to minimise development time, cost and risk. The data-handling, power-supply and communications subsystems will be assembled mainly from existing components available from European space hardware suppliers. The sub-satellite also relies also on a large number of existing components and data is available from earlier projects to support its aerodynamic shape.

The new developments are mainly the deployer structure with the sub-satellite separation system, and a new active sub-satellite guidance system using a moving mass. The latter moves the centre of mass relative to the centre of pressure of the sub-satellite and will improve the achievable landing accuracy.

The preliminary design for the system, the tether deployer, the sub-satellite and the electrical subsystems, is now established. The control algorithms have been developed and tested in end-to-end 2D and 3D simulations and the accommodation on the mother

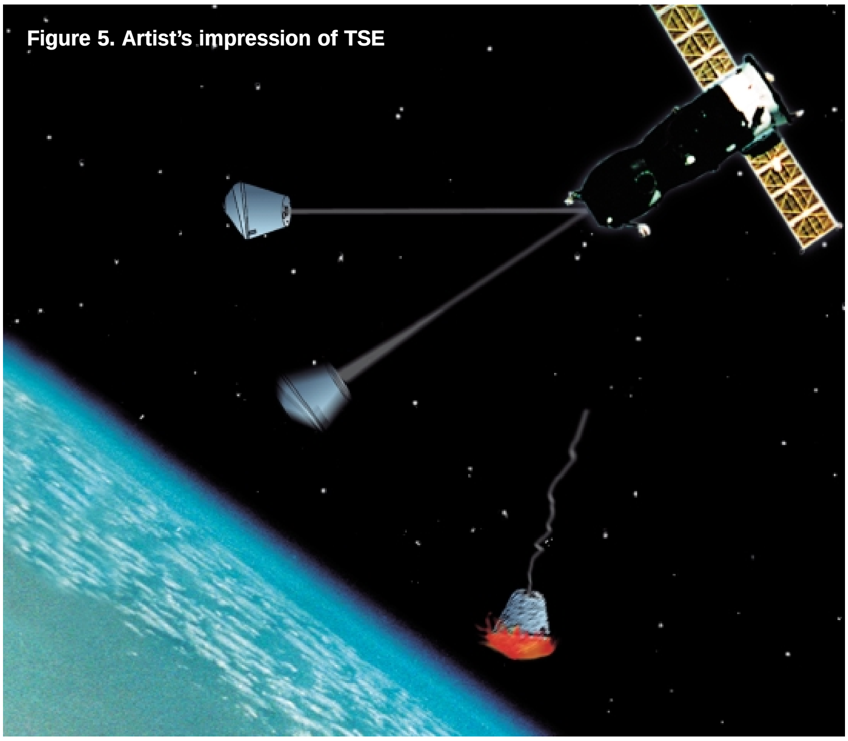

Figure 5. Artist's impression of TSE

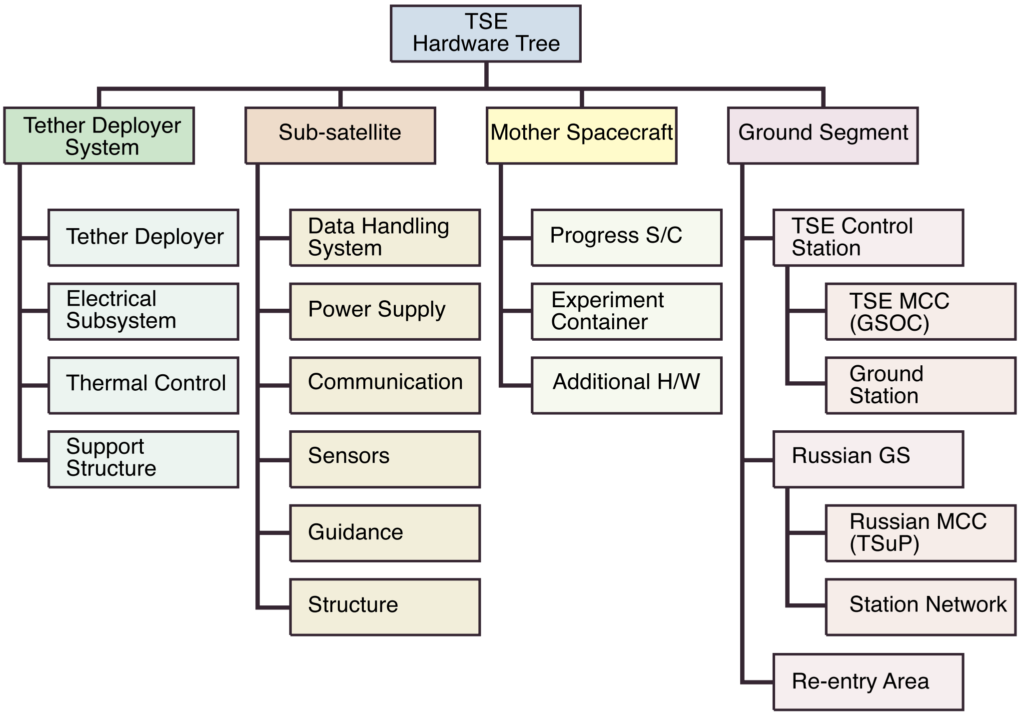

Figure 6. The TSE hardware tree

spacecraft Progress has been discussed and agreed with RSC-Energia (Fig. 7).

The tether deployer

The success of TSE depends heavily on the design of the Tether Deployer System (TDS), as the deployment of the sub-satellite is a very sensitive operation. The Tether Deployer is designed to fulfil the following functional requirements:

- storage of the tether during transportation, launch and pre-experiment phases
- ejection / acceleration of the sub-satellite at the beginning of the TSE experiment
- guidance of the tether during the experiment to prevent tether damage
- monitoring of tether system behaviour
- control of tether deployment by tether tension and tether velocity
- cutting of the tether in nominal and off-nominal modes
- providing status signals to the data-handling system.

Table 1. TSE technical data

System mass	143 kg
- Tether deployer & electrical subsystems	60 kg
- Sub-satellite	42 kg
- Experiment container	41 kg
TSE dimensions (w/o container)	1267 mm x 588 mm x 588 mm
Power consumption	88 W during tether deployment
Tether type	Dyneema 4 x 400 denier, diam. 0.5 mm
Tether length	35 km

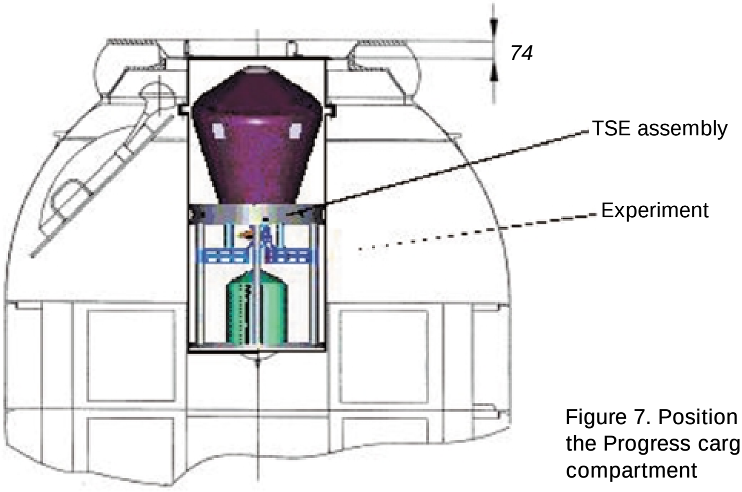

Figure 7. Position of TSE in the Progress cargo compartment

During all pre-experiment phases and at the start of the experiment, the whole tether is stowed on a core, which is protected against mechanical damage by the canister of the tether storage device. The 35 520 m long tether passes out of the canister into a guidance system, brake, tensiometer and finally a cutter.

The brake is able to provide accurate braking forces of up to 100 N if deceleration of the tether or sub-satellite is required. The tensiometer is designed to measure tether forces and tensions in two different ranges, for TSE post-flight evaluation. The guidance system ensures a sufficient tether deployment angle to avoid contact between the tether and the edge of the experiment canister. Cutters are arranged in the tether path to sever the tether at the end of the swing-back phase or if something unforeseen occurs.

Critical technology development, manufacture and testing

In the course of the studies, several critical components and technologies, which are therefore included in the breadboard test programme, have been identified:

- Tether Motion Device/Brake: required to control tether deployment, this is the most critical component of the deployer. The ability to properly control the deployment process and the final braking determine the accuracy of delta-v that can be achieved in the swinging release of the tether. It is therefore essential to acquire sufficient knowledge and experience with the brake in order to achieve the TSE mission objectives.
- Tether: its properties (stiffness and friction) affect the deployment process as well as collision risk, and mission safety.
- Tether Motion Sensor: used to measure the deployed tether length, and to derive the deployment velocity. These optical turn counters have been tested, qualified and already flown, but are classified as critical because the deployment algorithms rely on proper functioning of these sensors.
- Tether Guidance/Tether Cutter: minimisation of the internal friction during early deployment phase is a prerequisite for successful sub-satellite deployment. The friction generated by the deployer components will therefore be evaluated in the breadboard test campaign.
- Control Algorithms: ensure that the tether deploys along the pre-defined reference profile.

The main objectives of the breadboard tests are:

- familiarisation with the tether hardware
- measurement of deployer characteristics to support analytical simulations (canister + brake + cutters/tensiometer)
- measurement of system friction at various deployment stages and velocities
- testing of the algorithms and feedback
- demonstration of controllability of the hardware assembly.

The test campaign covers component testing as well as functional system testing. During component testing the tether modulus of elasticity, breaking strength and component/brake friction will be determined. In the functional system test, a tether deployment will be executed in real-time with a controller and tether simulator in the loop. The controller responds to measurements of the deployed length, while the space dynamic simulator responds to a tension measurement and drives the deployment via a motor. The functional system tests will re-use a test set-up originally manufactured for the TMM&M project by Alenia Aerospazio.

This test campaign will complete the Phase-B activities, and will provide key inputs for the TSE Critical Design Review.

Conclusion

Over the past 18 months, the feasibility of tether-assisted sample return has been proven and the TSE project team have prepared a solid, cost-efficient design for the ESA tether mission. In addition to providing European industry with an efficient near-term technology solution to meet many challenges in space, this demonstration mission will provide valuable flight experience that will put European industry in a competitive position for the development of an operational system for International Space Station users.