Apr 24th, 2:00 PM - 5:00 PM


Bruno Strim
ALENIA, Alenia Spazio, Torino, Italy

Francis Giani
ALENIA, Alenia Spazio, Torino, Italy

Follow this and additional works at: http://commons.erau.edu/space-congress-proceedings

Scholarly Commons Citation
TETHERED SATELLITES: EXOTIC AND POWERFUL PROBES
FOR SCIENCE EXPERIMENTS IN LOW PLANETARY ORBITS

- AUTHORS
  Gianfranco MANARINI (ASI)
  Bruno STRIM, Francesco GIANI (Alenia)

- ADDRESS
  ALENIA
  Alenia Spazio
  Corso Marche 41
  10146 TORINO (Italy)

- TELEPHONE
  011 - 71.80.933 / 71.80.708

- FAX
  011 - 723307 / 724807

- TELEX
  221235 AERSPZ I
TETHERED SATELLITES: EXOTIC AND POWERFUL PROBES
FOR SCIENCE EXPERIMENTS IN LOW PLANETARY ORBITS

Gianfranco MANARINI
Bruno STRIM, Francesco GIANI
A.S.L
Agenzia Spaziale Italiana
Roma - Italy

1. INTRODUCTION

Remarkable planetary observations have been carried out in recent months by a variety of space probes in the framework of an unprecedented solar system exploration effort. These achievements prove how much good imagery can be collected by means of spacecraft orbiting distant planets at high altitudes.

Maps of other planetary characteristics such as their gravitational and magnetic fields and their atmosphere constituent distributions are, however, more difficult to complete. In particular, they cannot be fully obtained by means of remote sensing techniques, but require extensive in-situ data collection.

Even more relevant to the subject of this paper, accurate measurements of planetary features are necessarily carried out at very low orbital altitudes, where orbit lifetimes are often severely limited by the high atmospheric densities.

This situation is quite well exemplified by the Earth’s upper atmosphere: the transition region where the atmosphere couples to the ionosphere is hard to explore because planetary orbits decay too fast and sounding rockets provide only very limited temporal and spatial coverage.

The possibility of dropping sensor packages at such low altitudes (around 100-120 km) and keeping them there for long timespans (weeks/months) looks therefore very attractive to engineers and scientists.

This is precisely what carefully designed Tether Systems may one day succeed in doing; indeed, already at their current verification stage they have raised great interest and expectations, due to their potential as scientific experiment support spacecraft.

At this time, a major joint U.S.-Italian program called the Tethered Satellite System (TSS) is nearing completion and is being readied for its manifested launch on the U.S. Space Shuttle early in 1992. TSS hardware includes a Deployer element (TSS-D) and a Satellite element (TSS-S) connected by a 22 km cable (the tether), which contains an isolated conductor.

During the TSS first mission (TSS-1), the Satellite will be deployed spaceward up to 20 km away from the Orbiter and then retrieved and restowed on the Deployer for return to ground.

The primary objective of TSS-1 [1] is to demonstrate that a tethered subsatellite can be successfully deployed, kept on station and then retrieved as predicted by computer simulations based on the understanding of its dynamics.

At the same time, TSS-1 is to show that Ampere-level electric currents can flow inside the tether as a result of its conducting-isolated element motion across the geomagnetic field lines, thus proving Tether System basic electrodynamics. TSS-1 also includes a remarkable set of science equipment, whose main purpose is to study system-ambient interactions in greater detail, in preparation for further scientific applications of the tether concept.

Other tether missions are already being studied in some detail by contractors as part of TSS-1 follow-up plans under U.S. NASA, European Space Agency (ESA) and Italian Space Agency (ASI) supervision.

This paper briefly reviews the tether fundamentals, the main proposed tether applications and the evolution of the first, and so far only, major Tether System. The paper aims at providing an outline of the tether community’s objectives and of how it is gearing up to achieve them, i.e. the ongoing progress from in-flight concept verification to the application of its full potential.

The paper is thus organized as follows: Chapter 2 is dedicated to the Tether System’s basic operating principles and to the anticipated benefits they are expected to bring about once operational. Chapter 3 then describes the joint NASA-ASI Tethered Satellite System first mission, TSS-1; its main design and operational aspects are reviewed with the purpose of illustrating the problems encountered and experience gained in preparation for further missions. Chapter 4 summarizes the paper’s main points and conclusions. In particular, TSS-1’s role as the data-gathering basis for further applications and the main planned follow-ons are outlined.

(*) ALENIA is the new Company resulting from the merger of Aeritalia and Selenia, taking over full responsibility for their functions, responsibilities and activities.
(r' - r₀) = 7 (r - r₀)

where:

- r is equal to (r₀ - r₁) or (r₀ + r₂)
- r' is orbit perigee/apogee after half an orbit following release

**Fig. 1 - Orbits of masses after release from a tether (from [4])**

2. TETHER SYSTEM BASICS AND THE PROMISES THEY HOLD

Although originally proposed as ULF wave generators [2] and as transportation infrastructures [3], Tether Systems have been receiving increasing attention as support tools in different science disciplines. Consequently, their dynamics and electrodynamics have been studied over the last two decades in greater and greater depth, so that they are by now well understood and extensive literature is available describing their basic and specific features.

This chapter illustrates Tether System basics and explains how they could be exploited to the advantage of scientific experiments in such fields as Plasma and Atmospheric Physics, Microgravity and Earth Observation.

References [4] and [5] should be looked at for a more detailed and formal discussion of Tether System (electro)dynamic physical principles and technical aspects.

For the purposes of this paper, a Tether System is a set made up, as a minimum, of two spacecraft connected by a km-long cable, the tether. In principle, no constraints exist on tethered object mass and on tether length. Both tethered spacecraft may well be as large and massive as the U.S. Freedom station and the tether may well be a thousand km long.

Systems with more than two tethered spacecraft are called constellations; one, two and three dimensional constellations have been examined [6]. Systems with more than one tether connecting the same two spacecraft are called complex- or multi-tether systems; they have been studied too [6].

Only the simplest Tether Systems are considered here, since the more complex ones, i.e. constellations and multi-tethers [6], require much more analysis than commensurate with the goals of the present paper and they add little to the conceptual knowledge.

The basic principles on which space-based Tether Systems operate relate to their interactions with the best known features of any planet, i.e. the gravitational and magnetic fields. More specifically, the interaction of any tether with the planetary gravitational field supports the operations of the so-called dynamic Tether Systems, i.e. those which include a non-conducting tether.

Likewise, the interaction of the conducting element of a tether with a planet's magnetic field is the operational basis for any so-called electrodynamic Tether System, i.e. one whose tether includes an isolated, conducting element.

These exploit the very basic fact that any point in an orbiting spacecraft, other than its center of force (or orbital center), experiences a net centripetal or centrifugal force. It is noted that the center of force and the center of mass coincide only in small spacecraft, while they may be hundreds of meters apart for extended (several km across) and massive spacecraft.

This net imbalance can be used to let the spacecraft at either tether end achieve orbit altitude changes by just separating it from the tether. The altitude change is roughly equal to seven times the distance L between the released spacecraft and the center of orbit, where R is the center of force orbital radius (see Figure 1).

L can be identified with the tether length if the releasing spacecraft more massive than the released one by a factor of ten at least, if the tether is short compared to the orbital radius by a factor of ten at least and if tether motions are neglected.
Orbit

Note: torques are restoring

- \( \frac{d^2 \theta}{dt^2} = -3\Omega^2 \theta \), in-plane libration frequency: \((\sqrt{3})\Omega\)
- \( \frac{d^2 \phi}{dt^2} = -4\Omega^2 \phi \), out-of-plane libration frequency: \(2\Omega\)
- \( \Omega \) is the Tether System orbital angular rate

Fig. 2 - Tether librations (from [4])

The above considerations take care of tether dynamics once the tether is fully extended. The Coriolis accelerations due to tether deployment and retrieval under non-inertial conditions and those due to the Earth's oblateness give rise to tether oscillations [7]. These occur both in the orbital plane (in-plane librations) and in the plane orthogonal to it (out-of-plane librations). Their periods are multiples of the system orbital period, but they do not coincide even in the simplest approximations, as summarized in Figure 2.

Furthermore, as Tether Systems are intrinsically flexible and elastic because of the tether, longitudinal and transverse tether vibrations are generated by the librational motions. Tether vibrations couple with end spacecraft attitude motions about the tether attachment point. As a consequence, no computer code exists to date which can simultaneously model all the mentioned aspects and still be predictive.

This is due to the different frequencies typical of each motion. Indeed, libration frequencies are close to the orbital frequency, while vibrations have higher frequencies (about one-two orders of magnitude) and attitude motions are in between.

As a result, an all-encompassing computer code would have to integrate the equations of motion so many times and over such a long timespan that uncertainties would propagate beyond manageability. As a consequence, different codes have been developed for specific applications [8].

It is pointed out that tether librations could be used to raise a Tether System's orbital altitude by adjusting its libration period (proportional to its length) so that it resonates with the Earth's oblateness [4,9].

Turning now to electrodynamics, an electro-motive force (e.m.f.) is generated at the ends of a conducting-isolated tether because the conductor inside the tether cuts across the planetary magnetic field lines [4,10]. The amplitude of the motion-induced e.m.f. is proportional to the orbital velocity \((v)\), to the magnetic field amplitude \((B)\) and to the sine of their mutual angle.

The accelerating voltage achievable between the tether ends depends on the e.m.f., on the tether length \((L)\) and on the cosine of the angle between the tether local direction and the local e.m.f. (both may vary from point to point along the tether).

Since the e.m.f. varies along the orbit with the velocity-to-magnetic field relative angle, it is maximum (and nearly constant) for orbits tracking the planetary magnetic equator.

If low-impedance contacts are set up between both tether ends and the surrounding plasma, then electric current can flow through the tether and electrical energy is obtained at the expense of the orbital motion energy, i.e. the system orbit decays.

The converse is also true: if electric current is forced into the tether opposite to its "natural" direction, then its interaction with the planetary magnetic field will boost the Tether System orbit up.

In either case, the current path closes along the plane-ary magnetic field lines (see Figure 3, page 4) and the overall energy conversion efficiency can be quite high [4,11].
Active electron emission occurs at the Orbiter, while electron collection takes place at the Satellite. Magnetic field-aligned currents are caused in the ionosphere by the transfer of electrons from Satellite to Orbiter; when the perpendicular resistivity is sufficiently low, transverse currents connect the two magnetic flux shells.

Fig. 3 - Electrodynamic Tether System current path and operating principles (from [10])

Tether librations affect the accelerating voltage through the e.m.f.-to-tether angle. As a consequence, tether dynamics need to be controlled to optimize their electrodynamic conversion efficiency. At the same time, the current flowing into the tether needs to be controlled in frequency so that its interaction with the magnetic field does not resonate with tether string modes (e.g. skiprope).

Over the past fifteen years, several applications which exploit the Tether System fundamentals outlined above have been proposed. Most of them are variations of a few basic applications; applications gauged to shorter term implementation and focused on operational aspects have received greater attention so far [6,12-16]. Nevertheless, some studies have been performed on more exotic (and remote in time) uses of tether systems for science and engineering purposes. These envisage, amongst others, harpoons for asteroid sample collection, Jupiter probe braking [17], moon-based slings [18], orbit self-boosting [9] and laboratories for experiments requiring finely tuned low-level accelerations [19].

Although potentially very rewarding, these concepts are beyond the reach of current or anticipated technology, while others assume space-based infrastructures far more complex than currently planned into the next century. Some applications, however, look promising and feasible in a closer future. They have to do with the use of Tether Systems for generating electric power and thrust at very high efficiencies, for orbit transfer, de-orbit and re-entry [18]. The application of the tether concept to ULF-ELF communications [2] and submarine detection, to large spacecraft center of gravity management and attitude control and to rendez-vous and docking have also been considered [20].

Likewise, Tether Systems have been proposed as tools to isolate sensitive instruments from potential contaminants [18,20], and to support hazardous operations such as refueling in a manned environment [6,18]. The suggestion to use a tethered platform to provide accurate pointing for instruments which may not justify dedicated free flyers but which are unable to share pointing with other instruments has also been studied in quite some detail [20]. It turns out that the best way to exploit the tether concept is to combine applications in such a way as to take advantage of one another’s problems [21].

Electric power generation may, for instance, be combined with tether-assisted re-entry; if a spacecraft were to be injected into a re-entry orbit by means of a tether attached to a space platform, the de-orbit energy, which is wasted using chemical propulsion, could be ‘recycled’. This would be possible because the platform would be boosted to a higher altitude while releasing the spacecraft returning to ground. Such an altitude gain could then be used up to generate electric power at the expense of orbital energy. Fuel savings would be substantial (tons) and would grow with usage cycles.
Although outstanding, such a combined application is based on a space infrastructure scenario still to be planned. It also relies on the repeated use of the same tethers (two at least) over many cycles, which is far from being guaranteed. These remarks apply to several other applications and have led the tether community to focus on less ambitious but equally rewarding applications, such as planetary studies.

The opportunity to perform planetary observations at very low altitudes for extended periods has raised considerable interest, particularly among researchers working in the fields of Atmospheric Physics and Earth Observation. Such an application is based on the possibility to decrease an instrumented probe orbit decay rate by lowering its area-to-mass ratio, i.e. drag effects.

This is achieved, in turn, by tethering it to a massive host spacecraft, which is then kept on a higher orbit where the atmospheric density does not impact the overall system lifetime too heavily.

The proposed set-up offers two major advantages: first of all, it allows keeping instrumented probes at lower altitudes longer than normally allowed by the atmospheric density at that altitude. Furthermore, measurements can easily be repeated at different altitudes without major orbital manoeuvres.

Due to the momentum transfer achieved by means of the tether, the probe also orbits at a slower orbital rate than appropriate to its altitude. The main problems with such atmospheric applications are with tether design, communications and dynamics monitoring.

Indeed, the tether would have to operate under thermal and mechanical stresses that may vary by orders of magnitude over its length.

Satellite-to-deployer communications may require optical links; the same may, however, also be used to monitor satellite position. The related tether design-manufacturing and laser communication/tracking technologies are under study [22] by the company responsible for the TSS, Martin Marietta Aerospace (MMA).

3. TSS-1: VERIFYING TETHER BASICS IN FLIGHT

This chapter briefly describes the features of the major Tether System built to date which constitutes a sort of worked-out example supporting the understanding of general problems likely to be met in Tether System evolution.

The TSS-1 represents the first long spaceborne Tether System; its origin can be traced to SAO Professor M. Grossi's proposal (submitted in 1972) to fly a tether system on board the U.S. Shuttle to generate electromagnetic waves at frequencies lower than 1 Hz [2,23].

In 1974 Professor G. Colombo, also at SAO, realized the potential of more general uses of Shuttle-borne tethers and rigorously proved the tether's dynamic feasibility. Because of this, the 1974 "Skyhook" report [3] containing such numerical evidence is a milestone in the field of both tether development and of tether applications to space enterprises.

The study also marked the initiation of NASA in-house tether research and development efforts. These were intensified in the mid and late 1970's via a NASA MSFC-led investigation which produced a tension control law for tethered satellites. Universities and industries also contributed, performing tether dynamics studies that generated a wide range of conceptual and mathematical models and new applications [8,10].

By the early 1980's, a facility requirement definition study [10], a conceptual design phase (phase A) and an engineering definition study (phase B) had been performed under NASA MSFC leadership.

In 1984, the project entered its advanced development phase and an Announcement of Opportunity was jointly issued by NASA and by the Italian National Space Plan, PSN, now ASI. It called for experiments to be performed over three successive missions of a reusable system; as for the system, the selected experiments would be jointly funded by NASA and PSN.

Experiment selection was completed in late 1985: it resulted in the firm selection of experiments for the first mission (TSS-1) and in the preliminary identification of promising candidates for the TSS-2 and TSS-3 missions.

Experiments for the first TSS mission would be carried out in parallel to the main engineering verification goals and on a non-interference basis with them [1].

At this time, the complete equipment is undergoing final processing at NASA KSC for launch, and all operational issues have been sorted out and solved to prepare a nominal mission profile extending for about 60 hours end-to-end.

The TSS-1 mission foresees spaceward deployment of a 500 kg instrumented subsatellite from the Space Shuttle, up to 20 km away from it. The planned nominal orbital altitude for the Orbiter is 296 km. Intermediate stops at 10 and 2.4 km have been inserted for science and engineering purposes, so that experiments can be repeated under different conditions and system behaviour can be assessed prior to final subsatellite recovery and restow inside the Shuttle cargo bay [24].

The TSS-1 mission is made up of two major phases: the first (attached phase) will last about 24 hours and will take place with the system stowed inside the Shuttle bay.

The second (detached) phase will last about 33 hours from subsatellite fly-away to docking, through tether unreeling (deployment), station-keeping and two-step tether reel-back (retrieval).
The former aims at allowing science instrument calibrations and Shuttle proximity environment characterization so that the data gathered during the latter phase can be better understood. The attached phase also serves the purpose of warming up selected TSS elements and checking out the system.

During the detached phase, system dynamics and electrodynamics will be verified from the engineering viewpoint and also studied in greater detail from the scientific one.

The TSS is made up of four major elements: the Tether, the Deployer (TSS-D), the Orbiter-mounted science (on an MPESS saddle) and the Satellite (TSS-S). System, Deployer and Tether engineering, system integration and verification responsibilities were with Martin Marietta Aerospace from the program outset, under contract to NASA.

Satellite design, development, integration and verification was under the responsibility of Aeritalia Space Systems Group (now Alenia Spazio), under contract to the Italian PSN-ASI.

Figure 4 shows an overall view of the TSS inside the Shuttle cargo bay. The spherical TSS-S is shown sitting at the tip of the TSS-D deployer 12 m-long extendible/retractible boom [25].

Figure 5, page 7, shows a stand-alone view of the TSS-D [26] while Figure 6, page 7, provides a stand-alone view of the TSS-S [27].

With reference to the previously explained electrodynamics tether principles of operations, a TSS-equivalent Gamut can be conceived.

It is shown in Figure 7 (see page 8). As the blocks indicate, some of the "equivalent" impedances describe the ambient plasma reaction to the system-generated current flows. These are the subject of several TSS-1 science investigations, while the others are more properly of an engineering character.

The TSS main electrical engineering elements are the subsatellite skin, the tether and the Orbiter-mounted circuitry. The last is made up of switches, resistors and electron generators needed to set the desired maximum current level in the TSS. The actual current flowing through the system is then dictated by how the perturbed ambient plasma behaves near, and at, the TSS-S and the Orbiter surfaces.

As a consequence, the science and engineering aspects of TSS-1 electrodynamics are intertwined, and complete and predictive modelling of system behaviour relies on plasma behaviour simplifications.

The TSS-1 tether is quite complex (see Figure 8, page 9) because it includes, besides the basic load-bearing strength member, the conducting element needed to generate the desired motion-induced e.m.f. [28].

As a consequence, the tether also includes a high-voltage isolating member (15 kV rating) and, in order for the conductor never to bear any mechanical loads, an outer Kevlar strength element.

The tether innermost nomex core serves the purpose of making conductor layout easier, while the outermost nomex jacket is a shield against atomic oxygen action, which is particularly severe at the projected TSS-1 mission altitude.

The tether is stowed on a reel; its deployer end makes contact with the Orbiter-mounted circuitry at a slip ring which accommodates tether twisting during deployment.
Fig. 5 - TSS-D stand-alone view (pallet physical layout, from [25])

Fig. 6 - TSS-S stand-alone view (from [27])
The other tether end makes contact to the TSS-S skin via a feed through high voltage connector and an ammeter; the latter measures the amount of current flowing through the tether (i.e. through the system, excluding tether isolator leaks).

The deployer has been assigned most system (electro)dynamics control tasks. The TSS-S can only loosely support tether dynamics control by means of side thrusters which can be actuated upon external command (i.e. not under close-loop software control).

Tether dynamics control is essentially achieved by means of a one degree of freedom tether tension/velocity control law built into the TSS-D software. A motor and two tether tension control assemblies provide tether (un)reel velocity and tension control actuation to increasing degrees of accuracy. The control software is, however, non-interactive, i.e. the tether velocity/tension control profile is loaded as needed into the TSS-D Motor Control Assembly.

Tether mechanical tension monitor output, however, is not directly fed into the control loop. On the contrary, it is used to assess a possible new profile for subsequent upload.

At the tether free end, the TSS-S supports a variety of plasma physics experiments ranging from electron and ion energy-density measurements (up to several keV) to electric and magnetic field monitoring over a broad frequency spectrum (DC-12 Mhz).

The TSS-S monitors its attitude about three axes to ± 1 deg in real time and can control its attitude and spin rate about the nominal tether axis (yaw) to about ± 3 deg and ± 0.1 RPM, respectively, by means of cold GN2 thrusters.

The TSS-S yaw angle/rate control can also be set to passive, so that the satellite can revolve freely; this serves the purposes of TSS-1 (electro)dynamics investigations requiring dynamically quiet and/or GN2-pollution-free periods.

Unlike TSS-1 dynamics, TSS-1 electrodynamics is entirely controlled, with the afore-mentioned limitations, by the Orbiter-mounted equipment belonging to the TSS-1 science complement. This consists of switches, resistors and two electron generators. The electron generators serve the purpose of "getting rid" of the negative electric charge coming from the tether as a result of the e.m.f..

Thus, they supplement positive charge collection by the Orbiter engine bells which, however, cannot sustain the current levels anticipated for the TSS-1 (up to 0.75 A). As the electron generators can emit collimated, energetic electron beams into the plasma surrounding the Shuttle, they also serve the purpose of studying the plasma sheath around it and the beam-plasma interactions in presence of the geomagnetic field.

Although the TSS-1 science complement is partially accommodated inside the Orbiter cargo bay, partially on board the TSS-S, it constitutes a single, integrated diagnostic package, and the two separate sets are required to operate in a carefully coordinated and synchronous fashion.

No direct deployer-satellite communication link exists, however, because the deployer only acts as a bend-pipe for data and command transfer from and to the TSS-S. Thus, operations taking place at the two tether ends cannot be directly synchronized; this requires commands to be issued in parallel, or with the same time tag, to both elements from an external source, namely the Orbiter and/or ground crew.

Achieving such a degree of integration between the two remotely accommodated sensor sets has required considerable planning efforts and a remarkable number of iterations at both the engineering and the scientific level.

The astronaut role in support to TSS-1 science experiments has grown accordingly. This has resulted in an experiment timeline satisfying many of the TSS-1 science objectives, compatibly with its engineering verification character.
Over the years, TSS-1 hardware and software integration at higher and higher levels has been going on to assure that all the equipment would be operating correctly to support the mission goals.

Among the most challenging tasks, tether dynamics modelling, command and data path verification and tether design and manufacturing are worth some comments.

Verifying that system dynamics were correctly modelled to an extent enabling confidence in the adopted control strategy proved quite an effort, particularly after the so called "skiprope" tether motion was identified. This occurred late in the program and relates to the interaction between pulsed electric current in the tether and the geomagnetic field.

The skiprope problem was overcome through modelling, operational arrangement review and equipment capability upgrades at a stage when most equipment was ready for delivery to NASA KSC for pre-launch processing.

The complex interplay between the TSS-S and the TSS-D equipment needed to assure mission success required extensive testing of command and data paths and formatting and rehearsal of operating procedures.

Tether fabrication, test and repair also constituted a challenge, particularly from a manufacturing viewpoint. It was, however, smoothly overcome [28] despite the tether's complex structure.

The experience acquired in the different areas outlined above provides some confidence for the future transition of Tether Systems from the verification stage to the more advanced application phase. It is worth pointing out that the TSS-1 actually constituted a development effort aimed at providing a cost-optimized tether concept feasibility verification.

---

**Fig. 8 - The TSS-1 Tether Structure (from [6])**

---

<table>
<thead>
<tr>
<th>Item</th>
<th>Cumulative Dia (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core</td>
<td>0.51</td>
</tr>
<tr>
<td>Conductor</td>
<td>0.86</td>
</tr>
<tr>
<td>Insulation</td>
<td>1.47</td>
</tr>
<tr>
<td>Strength Member</td>
<td>2.85</td>
</tr>
<tr>
<td>Protective Jacket</td>
<td>3.64</td>
</tr>
</tbody>
</table>

- **Core**: 0.51 mm (12 strands, 200 denier Nomex)
- **Conductor**: 0.86 mm (10 strands, 34 AWG (24 AWG equiv.) Bare, electrolytic tough pitch, annealed copper wire, blackened around core.
- **Insulation**: 1.47 mm (PEF, 0.2 mm wall thickness, 10 kV voltage breakdown testing)
- **Strength Member**: 2.85 mm (12 strands, 1000 denier braided Kevlar, 1700 lb tensile strength rating)
- **Protective Jacket**: 3.64 mm (8 strands, 1200 denier braided Nomex)
Its very origin and its size placed it in a manned environment which further restricted design innovations. Thus, the program has generated a rugged, reliable system focused on the verification of several basic properties.

As such, it will open the way to more sophisticated and more precisely aimed programs. These are most likely to focus on more extensive and detailed modeling in preparation for more sophisticated dynamics control techniques.

Likewise, more advanced technology and less rugged design is likely to be employed once the basic verification data are made available by the TSS-1.

They will include deployer-to-satellite direct communication links to synchronize operations at the two tether ends, electronics upgrades and composite structures.

The overall TSS-1 can thus be seen as the basic engineering and scientific experiment on the way to the extensive and focused application of the tether concept to different engineering and research branches.

4. CONCLUSIONS

A few conclusive remarks are worth adding to help provide a final picture of where the tether world is going and how.

As illustrated in Chapter 2, Tether System basics are by now fairly well understood and many applications have been proposed, which cover virtually all the technical and scientific areas.

Furthermore, as described in Chapter 3, a major Tether System, the TSS, is undergoing final checkout at NASA KSC for launch on board the U.S. Space Shuttle; the TSS will verify the tether concept basic feasibility in preparation for its future application science and engineering purposes.

Although the TSS is the only major program in the field of Tether Systems, other preparatory activities are under way while waiting for the TSS-1 verification mission results. These consist of studies carried out by various contractors, including Alenia, under the supervision of NASA, ESA/ESTEC, the German DLR and ASI.

The main parallel activities have to do with TSS-1 follow-on preparation; they include a proposal for a TSS-1 Reflight (TSS-1R), emphasizing science experiments over engineering verification.

Also part of the TSS-1 follow-ons is the study of a possible TSS Atmospheric Verification Mission (TSS-AVM) [22]; this would be a pathfinder mission in preparation for the TSS-2 atmospheric mission.

It would lower a tethered subsatellite into the upper atmosphere (down to 120 km or lower) to gather engineering data about atmosphere density and composition and about tether and subsatellite thermal design.

The TSS-2 mission would then be more properly science-oriented relative to the TSS-AVM, much the same way as the TSS-1R would be as compared to the TSS-1.

The main focus of most activities is on dynamics and control modeling and on technology; the purpose of most of them is identifying improvements to the TSS-1 which help adapting its design to the different mission needs and improving its overall performance [29].

Studies aiming at a better system-level definition of mission and design requirements, of technology needs and critical areas have also been, and still are, under way for some specific applications. Alenia is contributing to most of these studies, too, under contract to all the involved Agencies.

Particularly relevant among these for their potential return in terms of scientific and engineering data are those applications which aim at low altitude, long duration mappings of the Earth's (or another planet's) features.

Tether Systems for tether-assisted de-orbit and re-entry, for Space Station center of gravity management, for microgravity experiments, for electric power generation/propulsion and for orbit transfer are also examples of these application-specific activities.

As a consequence, this paper can point out at the liveliness of the tether community which, while awaiting the TSS-1 verification mission data, is getting ready to pursue further applications of the tether concept.

REFERENCES

[2] M.D. Grossi - Experimenting with a long wire antenna at ULF from the PPEL, SAO technical note to NOAA Aeronomy Laboratory, June 1973
[10] TSS Facility Requirement Definition Team - Final Report, Utah State University, 1980
[18] Injection orbitale par interaction d'un cable long conducteur avec le plasma jovien, CICLOPE project, CNES report, 1986
[26] The Roles of Tethers on Space Station, NASA TM-86519, 1985
[28] M.D. Grossi - Tether history and historiography, in [14]

ACRONYMS

ASI Agenzia Spaziale Italiana (formerly PSN)
CNES Centre National d'Etudes Spatiales
DLR Deutsche Luft- und Raumfahrttechnik
DRB Deployable-Retrievable Booms
EM ElectroMagnetic
EMC ElectroMagnetic Cleanliness
e.m.f. electro-motive force
EMP Equipment Multipurpose Pallet
ESA European Space Agency
ESTEC European Space Technology Enhancement Center
GN2 Gaseous Nitrogen (molecular, i.e. cold)
IABG IndustrieAnlagen-BetriebGesellschaft
JSC Johnson Space Center
KSC Kennedy Space Center
MMA(G) Martin Marietta Aerospace (Group)
M.o.U. Memorandum of Understanding
MPFESS Multi Purpose Equipment Support Structure
MSFC Marshall Space Flight Center
nT nano (billionth of) Tesla
OAST Office of Aeronautics and Space Technology
PSN Piano Spaziale Nazionale (now ASI)
RPM Revolutions Per Minute
SAO Smithsonian Astrophysics Observatory
SATP Science and Application Tethered Platform
TSS Tethered Satellite System
TSS-AVM TSS Atmospheric Verification Mission
TSS-D TSS Deployer
TSS-S TSS Satellite
TSS-1 TSS first (electrodynamic) mission
TSS-2 TSS second (atmospheric) mission
TSS-3 TSS third (expanded electrodynamic) mission
TSS-1R TSS-1 mission Reflight
ULF Ultra Low Frequency