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The Flight of the Tethered Satellite System

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The first Tethered Satellite System (TSS-1) Electrodynamics Mission is scheduled for launch aboard the space shuttle ST-46 on July 31, 1992, as a joint mission between the United States and Italy. A 500-kg, 1.6-m-diameter satellite, attached to the shuttle by a thin (.24 cm), conducting, insulated wire (tether), will be reeled upwards from the orbiter payload to a distance of 20 km when the shuttle is at a projected altitude of 300 km.

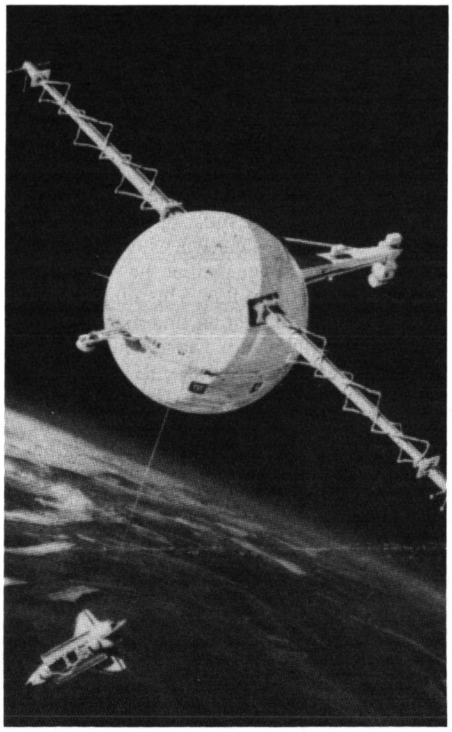
TSS-1 is an extremely ambitious mission with high-risk payoff potential. This is the type of pioneering mission NASA and the United States should be encouraging, with the risk in the achievement of the mission objectives rather than in safety. The mission has been likened to the maiden flight of a new airplane. We expect surprises and hope to set the stage for the next mission, the TSS-reflight.

The TSS-1 mission will score many "firsts" for space experiments in general and shuttle experiments in particular.

- It is the first flight in which the shuttle will be used not only as a launching or observing platform, but actually as part of the experiment. The shuttle is the pivot of the inverted mechanical pendulum and one of the poles of the electrodynamic circuit.
- It is the first mission with an integrated approach to science, with the instrumentation, particular experiments, and mode of operation selected to characterize the dynamic and electric properties of TSS.
- It is the first attempt to resolve the problem postulated in the 1920s by Langmuir that led to the beginnings of plasma physics as a discipline: the determination of the dynamic, current-voltage characteristics for a body charged to high potential, located in a magnetized plasma in the absence of physical boundaries.
- It is unique in combining the potential for resolving a fundamental physics problem (the Langmuir problem), with the exploitation of a technological capability of critical importance to space power and propulsion.
- Finally, it is the first time such a complex, large, gravity-gradient stabilized, electrodynamic tether-system has been flown. The mission has all the uncertainties and excitement of a first experiment that stresses the limits of the system and the interplay of dynamics and electromagnetics.

During TSS-1, when the satellite is in the shuttle cargo bay, the force of gravity will be balanced by the centrifugal force at the orbital velocity of ~8 km/sec. At an outward distance Δ from the orbiter, the centrifugal force will exceed that of gravity and the satellite will feel an effective gravitational acceleration $g_{\text{eff}}=g\cdot\Delta/R_E$, where g is the gravitational constant and R_E is the Earth's radius (~6000 km). The tension on the tether due to this force would be too small to accelerate the satellite away from the tether for separation distances less than 1 km, and the satellite in-line thrusters will be used to achieve the initial separation. Subsequently, the excess centrifugal force, acting as inverse gravity, will induce sufficient tension on the tether to lift the satellite to its projected orbit 20 km away from the shuttle. This configuration is referred to as gravity-gradient-balanced tether equilibrium.

Moving through the ionosphere, the satellite-tether-shuttle system will intersect the Earth's magnetic field, creating an electromotive force (emf) between the satellite and the shuttle, whose value is given by $\Delta\phi=\mathbf{u}\times\mathbf{B}\cdot\mathbf{L}$, where **u** is the shuttle velocity (8 km/sec), **B** the Earth's magnetic field (~1/3 Gauss), and **L** the tether length. The maximum emf produced by the TSS is about .25 volts per tether meter, or about 5 kV at the 20-km deployment distance. For the eastward-moving shuttle, the satellite will charge positive, while the shuttle will be negative with respect to the ambient ionospheric plasma. The induced emf will lead to collection of electrons at the satellite and electron emission at the orbiter, using one of the two sets of electron guns in the shuttle bay. Investigating how TSS can draw current from the ionosphere, and thus generate power, is a primary objective of the mission.



The Tethered Satellite System (TSS-1) Electrodynamics Mission, attached to the space shuttle. Scheduled for launch on July 31, 1992, TSS-1 targets a fundamental problem in plasma physics, with a major impact on space engineering as well.

The dominant objective of the electrodynamic mission is the development of a cause-and-effect understanding of the capabilities and limitations of electrodynamic tethers to draw current from the ionospheric plasma. In engineering terms, this translates to the determination of the current-voltage (I/V) characteristics of the circuit composed of the TSS and the ionosphere. The tether voltage will be varied by controlling the current, using the electron guns located in the orbiter bay, and monitored by the scientific instruments. One set of electron guns can eject up to 0.75 amp of current. The guns are powered by the tether to which they are connected via a master switch. A voltmeter measures the tether potential with respect to the shuttle structure. A second set of electron guns has its own independent power supply and provides the means for investi-

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gating control of the tether current by electron emission at the shuttle end of the TSS circuit. The emitted electron beam has an energy of 1 keV and its current can be set at .05 or .1 amp. This gun can be pulsed with on/off times of about 100 nanoseconds and used to determine transient characteristics of the circuit.

The circuit properties and power-generating capabilities of the TSS critically depend on the nature and structure of the sheaths surrounding the satellite and the orbiter. In the pioneering experiments that provided the foundations of plasma physics in the 1920s, Langmuir developed the steady state I/V characteristics of a sphere charged to high voltage inside an unmagnetized plasma. This led to the concept of space-charge limited flow and the famous Langmuir-Blodget $I \sim V^{3/2}$ relationship. For TSS the situation is significantly more complex. First, the ionospheric plasma is magnetized, thus breaking the isotropy of the configuration and preventing effective electron collection across the magnetic field (the physics of magnetic insulation). The steady state I/V characteristics in a magnetized plasma were studied theoretically by Parker and Murphy. Corresponding laboratory experiments have been inconclusive because of the presence of walls. Second, the supersonic motion of the satellite perturbs its environment by developing wake and front structures with significant local plasma density and kinetic gradients. Third, variations in the ambient plasma conditions and the angle of attack to the magnetic field as the TSS travels through the ionosphere make the situation a dynamic one, to which applicability of steady-state theories is in doubt. Fourth, the presence of neutral gas in the vicinity of the satellite and the orbiter (outgassing, thruster operation, and water damps) can lead to localized discharges significantly altering the current-collecting properties of the TSS.

While several rigorous and speculative models, both analytic and numerical, have been developed to address the basic physics of current collection, the TSS measurements will be the first to address these issues experimentally. The satellite and the shuttle are equipped with many diagnostic instruments that will characterize the sheaths in engineering terms and elucidate the dominant physical processes.

An important science issue that could potentially be resolved by the TSS is the closure path of the induced current through the ionospheric plasma. Current closure across magnetic-field lines and the development of field-aligned anomalous resistivity is a problem of critical importance to space physics in general and to auroral physics in particular. Early models of TSS-like configurations speculated that the currents will flow along magnetic field lines to the lower ionosphere in the form of Alfven waves, where they will close across the magnetic field due to the high electron-neutral-collision frequency. If this is the case, a series of phantom current loops, each with a circumference over 500 km in extent, will follow the motion of TSS, forming a long solenoid. More recent thinking stimulated by Stenzel's laboratory experiments at UCLA indicate that the current closure will be local for TSS-1, through intersecting, current-carrying whistler waves rather than Alfven waves. Although the absence of a free flyer with diagnostic instrumentation makes direct observations of the current path impossible, combining measurements of low-frequency magnetic fields, observations of emissions using the orbiter camera, and radar diagnostics during the overflight above Arecibo will improve understanding of this important topic.

The global current closure mechanism already discussed indicates that TSS can act as a large antenna for ULF (~1Hz) waves through modulation of the tether current at a low frequency. This concept will be tested during the TSS-1 mission by low-frequency-wave ground measurements from stations in Puerto Rico, Australia, the Canary Islands, and Kenya. It should be stressed that if the current closure is local, by intersecting whistlers, there will be two antiphased current loops produced in the tether vicinity and the radiation efficiency at ULF may be undetectable. On the other hand, whistler waves in the kHz range will be produced and should be observed on the field-line footprints.

The TSS-1 is the first step toward utilizing tethers for space power propulsion and as a unique space laboratory. The maximum power that can be demonstrated by TSS-1 is approximately 2.5 kW and is limited by the tether resistance and the maximum current from the electron guns. Whether the ionosphere can stably support such a high current is to be determined. Preliminary estimates indicate that gas from thruster operation can sustain currents in excess of 1 amp. The projection is that long tethers will generate tens of kW of space power. It should be noted that the tether operation is reversible. If the current direction is reversed using on-board power, thrust can be generated for spacecraft maneuvering without the use of propellant. This reversible tether operation, which is a form of energy storage, is an attractive engineering feature for future space applications.

A primary engineering objective of TSS-1 is to demonstrate deployment of the satellite to a distance of 20 km, and subsequent retrieval. Since this is the first such experiment, there are several unknowns. Viewed superficially, the TSS system resembles an inverted pendulum; it is actually a regular pendulum, since the direction of the effective gravity force is upwards. Similar to a pendulum, it is subject to various oscillation modes. The oscillations can be longitudinal, transverse, and pendulous. The oscillation frequencies vary with tether length and tension. The period of the oscillations is typically on the order of a few minutes. Mode couplings and resonances can cause circularization of the transverse oscillations, leading to an oscillation resembling "skip-rope" motion. Oscillations can be driven or damped by movements of the satellite and shuttle. Furthermore, the $\mathbf{J}\times\mathbf{B}$ force on the tether can drive or damp oscillations. When the satellite is retrieved, the excited modes can be amplified and coupled. A series of dynamic experiments planned by the dynamics group will study the oscillations of the TSS system and aim to learn how to control them.

Scientific and other advisory committees realized the importance of the quick reflight of a first mission, and incorporated it as part of the original selection plan. For this reason, satellite recovery has been raised from a secondary to primary mission objective. We look forward to this shuttle mission as a major scientific and engineering milestone in the space sciences and in spacecraft performance.

Scientific Investigations and Diagnostic Instrumentation

Mission Scientists: Nobie Stone, Mike Chandler (Asst.), NASA/MSFC; M. Candidi, J. Sabbagh (Asst.), ASI, Rome, Italy

DCORE: Core electron gun, vacuum gauge, accelerometer (shuttle bay) satellite ammeter—C. Bonifazi, ASI, Rome, Italy

SETS: Fast pulse electron gun, retarding potential analyzer, Langmuir probe, fluxgate magnetometer (shuttle bay)—P. Banks and B. Gilchrist (Univ. of Michigan), J. Raitt (Utah State)

SPREE: Electrostatic analyzers, measure sorbiter potential and particle distributions above 10 ev (shuttle bay)—M. Oberhardt (Phillips Lab/GL, Hanscom Field, MA), D. Hardy (Phillips Lab/GL, Hanscom Field, MA)

TOP: Imaging system, crew operated camera (shuttle)—S. Mende (Lockheed, Palo Alto, CA)

RETE: Electric and magnetic field probes, Langmuir probe (on extendable satellite booms)—M. Dobrowolny (IFSI, Frascati, Italy), C. Harvey (Meudon Observatory, France)

ROPE: Differential ion and flux probe, soft particle electron spectrometer (on satellite and fixed boom)—N. Stone, K. Wright (NASA/MSFC), D. Winningham (SWRI, San Antonio, TX)

TMAG: Triaxial fluxgate magnetometers, measure magnetic field in satellite region (tip and middle of rectractable boom)—F. Manarini (Second University of Rome, Italy)

EMET: Generation and ground observation of low frequency waves—R. Estes (SAO, Cambridge, MA)

OESEE: Generation and ground observation of low frequency waves—G. Taconi (University of Genoa, Italy)

IMDN: Investigation of TSS dynamics using satellite accelerometers and gyros—G. Gullahorn (SAO, Cambridge, MA)

TEID: Investigation of TSS dynamics using satellite accelerometers and gyros—S. Bergamaschi (Institute of Applied Mech., Padua, Italy)

TMST: Develop overall mission models including I/V characteristics, current closure, sheath structure, current collection capability, and wave efficiency generation—A. Drobot (SAIC, McLean, VA), K. Papadopoulos (Univ. of Maryland, College Park)

TSS Management

Program Managers: T. Stuart, NASA HQ, Code M; J. F. Manarini, ASI, Rome, Italy

TSS-1 Science Program Manager: R. Howard, NASA HQ, Code SE

Mission Manager, TSS-1 Project Manager: W. Nunley, NASA/MSFC

Flight Director: C. Shaw, NASA/JSFC

System Components for TSS

Shuttle: Mission Platform—Orbiter Crew: L. J. Shriver (USAF), A. M. Allen (USMC), M. S. Ivins (NASA); Science Crew: J. A. Hoffman (NASA), F. R. Chang-Diaz (NASA), C. Nicollier (ESA), F. Malerba (ASI), U. Guidoni (ASI)

Deployer: Equipment for release, deployment control, and retrieval of the tethered satellite—R. Schwindt, Mgr. (Martin Marietta Astronautics Group, Denver, CO)

Satellite: Satellite structure and instrumentation—B. Strim, Mgr. (Alenia Space Group, Turin, Italy)

Hill Takes Action on NOAA Funding

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Action was taken recently in both the House and Senate on fiscal year 1993 appropriation bills that fund the National Oceanic and Atmospheric Administration.

The House Commerce, Justice, and State, the Judiciary and Related Agencies Subcommittee voted on its funding bill on June 30. The Senate, the Commerce, Justice, and State, the Judiciary and Related Agencies Appropriations Subcommittee marked up its bill on July 22.

The House bill proposed that Climate and Global Change receive $43.9 million, a decrease from this year's level of $46.9 million. The president requested $78.2 million for this program. For the Coastal Ocean program, spending is set at $12 million, a decrease from the president's request of $17 million, but up from the fiscal 1992 level of $11.5 million. Weather research, which includes PROFS/Advanced Forecasting Applications, the wind profiler, and federal and state weather modernization grants, would receive $37.6 million, a decrease from the 1992 $38.9 million level. The president requested $35.1 million for weather research. The House would fund Solar-Terrestrial Services and Research at $5 million, a slight increase from 1992, but down from the president's proposed level of $5.6 million.

Funding was restored to both VENTS, NOAA's ocean vent exploration program, and NURP, NOAA's Undersea Research Program. VENTS would receive $2.4 million, a slight decrease from the 1992 level of $2.6 million, while NURP would receive $15.9 million, an increase from the 1992 level of $15.2 million. The president eliminated both programs in his budget request.

Spending for operations and research in the National Weather Service, which is undergoing a modernization, would increase from the 1992 level of $311.5 million to $341.6 million. The president requested $371 million for the modernization. NEXRAD (next generation radar) would receive $79.3 million in the House bill. Spending for 1992 was $83.4 million, and the president requested $84.5 million.

Funding for National Environmental and Satellite, Data, and Information Service (NESDIS), which manages NOAA's environmental data and the weather satellites, was set at $349.2 million, a drop of $88.7 million from the president's request. Spending for 1992 was $338.4 million.

NOAA's fleet modernization of its research vessels would receive the requested $2 million, which was a sharp drop from the 1992 level of $33 million.

While Senate action does not usually proceed until House action is complete, subcommittee chairman Ernest Hollings (D-S.C.) felt it necessary to get the Senate process moving quickly this year. "I intend to move this bill forward, and with any luck, bring back a conference report before the Republican convention [in August]," he said. The House action was delayed for over a month because of necessary reductions under this year's low budget allocations, he explained. During the Senate mark up, Hollings noted that "This has been a tough year. . . . A lot of domestic agencies will be provided funding below the fiscal 1992 enacted level."

Hollings said that he rejected the "fair share" approach and instead assigned priorities to five areas under this broad Senate appropriations bill. Maintaining and modernizing the National Weather Service in support of its mission to protect the life and safety of Americans ranked third among justice, trade, and economic issues.

The Senate bill proposes $401.8 million for the operation and staffing of the NWS, an increase of $54.6 million from fiscal 1992. More funding will enable the NWS to maintain stations across the country at current operations and staffing, said Hollings. The bill also proposes $177 million for acquisition of NEXRAD "tornado detecting" Doppler radar, facilities, and other technologies needed to upgrade the NWS's capabilities of issuing warnings and to protect Americans from severe weather.

The spending bill would cut $62.6 million from what Hollings called the "ill-conceived polar next-satellite program." The five geostationary satellites of GOES-NEXT were to replace the GOES (Geostationary Operational Environment Satellites) series, the last of which is due to expire soon.

The NOAA fleet modernization program would receive $37 million, an increase of $35 million from fiscal 1992. This includes $22 million to convert a Navy oceanographic ship for use by NOAA.—*Susan Bush*

Watkins Offers View of Future DOE Mission

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The fifth plenary meeting of the Secretary of Energy Advisory Board (SEAB) was held in Washington on July 10. Opening comments by Admiral James Watkins, Secretary of the Department of Energy, provided insights into his vision of the agency's future direction.

These are exciting times, Watkins said, declaring that the "evil empire has disappeared." He hailed Boris Yeltsin's recent declaration to Congress that communism is dead. Watkins spoke of the opportunities of the "new world order," but also said that DOE is facing a management challenge of great proportions.

Among these challenges will be cleaning up 40 years of environmental problems at weapons production facilities, turning "swords into plowshares," and defining a role for DOE in a new strategy for national economic competitiveness. Watkins discussed at some length the role DOE could play in America's economic future.

After an extensive task force presentation calling for a new DOE unit to perform economic analysis and modeling relating to energy, Watkins spoke somewhat emotionally about the difficulties he will encounter in attempting to carry this out. DOE will be criticized, he said, for excessive headquarters growth and will be told that this is not any of DOE's business. This will, Watkins said, require "a lot of push," both in Congress and within the executive branch.

Watkins is frustrated with Congress. He cited problems in getting a final version of the massive energy bill, HR776, passed by the House and Senate. Even more frustrating to him are the delays in opening up the New Mexico nuclear waste facility. Watkins charged critics of this facility with distorting science, misleading the public, and retarding national economic progress. He conceded, though, that DOE has had a credibility problem, saying that the agency has to make up for 10 lost years of eroded public confidence.

"The jewels in our crown" are the national labs, Watkins said, praising them for having the "finest technology in the world." On-going efforts to provide industry with some of the technical knowledge of the labs are paying dividends, he declared, calling for increased efforts in this area. Comparing these efforts to the Manhattan Project, he spoke of this being DOE's challenge for the next 10 years. Yet these efforts have been frustrated, he said, by a Congress that has not yet given its approval for the reprogramming of $160 million for domestic purposes.

It is somewhat telling that during the entire day-long presentation, only one mention was made of the recent House vote to terminate the superconducting super collider. Watkins, toward the end of the meeting, wondered what facility or instrument might be eliminated next.—*Richard M. Jones, American Institute of Physics*