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-meter 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 instrumenta-

tion, particular experiments, and mode of operation selected to characterize the dy-

namic 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 tether 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 $\Delta$ from the orbiter, the centrifugal force will exceed that of gravity and the satellite will feel an effective gravitational acceleration

$$E = g - \frac{g}{R^2}$$

where $g$ is the gravitational constant and $R$ is the Earth's radius ($\approx 6000$ 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

$$\Delta \phi = u \times B \cdot L,$$

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 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 inject 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-
gating control of the tether current by elec-
tron 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
0.5 or 1.0 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-generat-
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 IV
characteristics of a sphere charged to high
voltage inside an unmagnetized plasma. This
led to the concept of space-charged limited
flow and the famous Langmuir-Blodget
steady state IV relationship. For TSS the situation is
significantly more complex. First, the iono-
spheric plasma is magnetized, thus breaking
the isotropy of the configuration and prevent-
ing effective electron collection across the
magnetic field (the physics of magnetic insu-
lution). The steady state IV characteristics in
a magnetized plasma were studied theoreti-
cally by Parker and Murphy. Corresponding labora-
tories have been inconclusi-
ve because of the presence of walls. Sec-
ond, 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 length of the['responsive 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 sig-
nificant in altering the current-collecting prop-
erties 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 engi-
neering terms and elucidate the dominant
physical processes.

An important science issue that could
potentially be resolved by the TSS is the clo-
seup 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 prob-
lem of critical importance to space physics
in general and to auroral physics in particu-
lar. Early models of TSS-like configurations
speculated that the currents will flow along
magnetic field lines to the lower ionosphere
in the form of Alven 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 think-
ing stimulated by Stenzel's laboratory experi-
ments at UCLA indicate that the current clo-
sure will be local for TSS-1, through
intersecting, current-carrying whistler waves
rather than Alven waves. Although the ab-
sence of a free flyer with diagnostic instru-
mentation makes direct observations of the
current path impossible, combining meas-
urements of low-frequency magnetic fields,
observations of emissions using the orbiter
camera, and radar diagnostics during the
overflight above Arecibo will improve under-
standing of this important topic.

The global current closure mechanism
already discussed indicates that TSS can act
as a large antenna for ULF (~1 Hz) 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 whis-
tlers, there will be two antiphased current
loops produced in the inverter vicinity and the
radiation effects of ULF whistlers will be unde-
ctable. 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 gun. Whether the iono-
sphere can stably support such a high cur-
rent is to be determined. Preliminary esti-
mates indicate that gas from thruster
operation can sustain currents in excess of 1
amp. The projection is that long tethers will
genereate 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 gener-
ated for spacecraft maneuvering without the
use of propellants. This reversible tether oper-
ation, 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 re-
trieval. Since this is the first such experi-
tment, there are several unknowns. Viewed
superficially, the TSS system resembles an
inverted pendulum; it is actually a regular
pendulum, since the direction of the effec-
tive 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 ten-
sion. The period of the oscillations is typi-
cally on the order of a few minutes. Mode
frequencies and resonances can cause circu-
larization of the transverse oscillations, lead-
ing to an oscillation resembling "skip-rope"
motion. Oscillations can be driven or
damped by movements of the satellite and
shuttle. Furthermore, the JxB 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 dynam-
ics 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 refight of
a first mission, and incorporated it as part
of the original selection plan. For this rea-
son, 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 perfor-
mance.

Scientific Investigations and
Diagnostic Instrumentation

Mission Scientists: Noble Stone, Mike Chan-
dler (Asst.), NASA/MSFC; M. Candidi, J.
Badalamenti (Asst.), ASI, Rome, Italy
DCORE: Core electron gun, vacuum gauge,
accelerometer (shuttle bay) satellite am-
cmeter—C. Bonifazi, ASI, Rome, Italy
SETS: Fast pulse electron gun, retarding po-
tential analyzer, Langmuir probe, fluxgate
magnetometer (shuttle bay)—P. Banks and B.
Gilchrist (Univ. of Michigan), J. Raat
(Utah State)
SPREE: Electrostatic analyzers, measure sor-
biter 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 (IFSl, 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 retractable boom)—F.
Manarini (Second University of Rome,
Italy)
EMET: Generation and ground observation
of low frequency waves—R. Estes (SAO,
Cambridge, MA)
OES: Generation and ground observation of
low frequency waves—G. Taconi (Uni-
versity of Genoa, Italy)
MDN: Investigation of TSS dynamics using
satellite accelerometers and gyro—G.
Gullahorn (SAO, Cambridge, MA)
TEID: Investigation of TSS dynamics using
satellite accelerometers and gyro—S. Ber-
gamaschi (Institute of Applied Mech.,
Padua, Italy)
TMST: Develop overall mission models in-
cluding IV characteristics, current closure,
shath structure, current collection capa-
bility, and wave efficiency generation—A.
Drobot (SAIC, McLean, VA), K. Papadop-
oulos (Univ. of Maryland, College Park)
Hill Takes Action on NOAA Funding

**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**


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

Satellite: Satellite structure and instrumentation—B. Strimm, Mgr. (Alemna 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 level of $38.9 million. The president requested $35.1 million for weather research. The House bill 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 $84.3 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 $22 million called the “ill-conceived polar next-satellite program.” 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 $84.3 million.

While the 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,” he said.

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, he said, was “a no brainer 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 Environmental Satellites) series, the last of which is due to expire soon.

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

**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

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