The First Mission of the Tethered Satellite System

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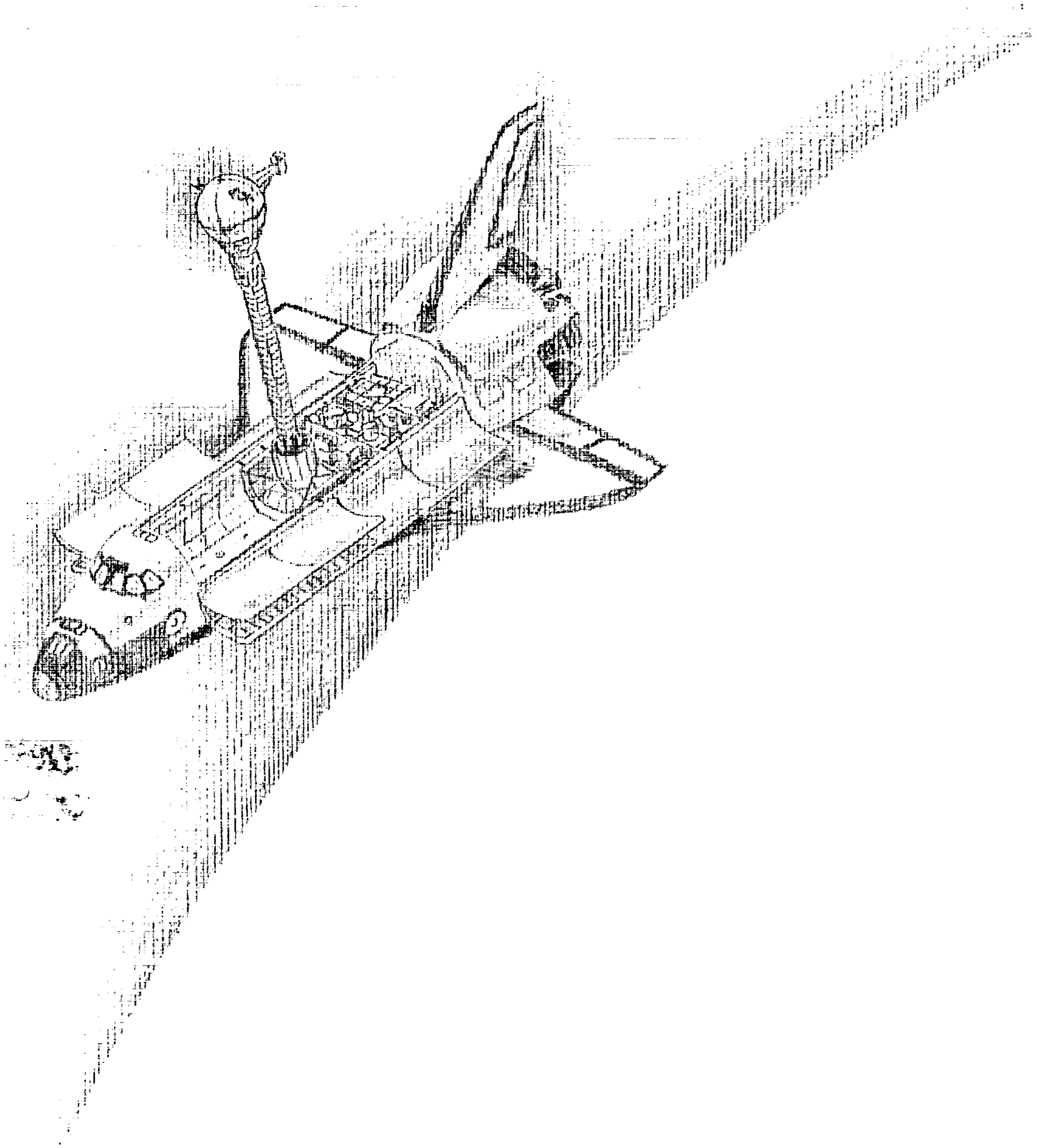
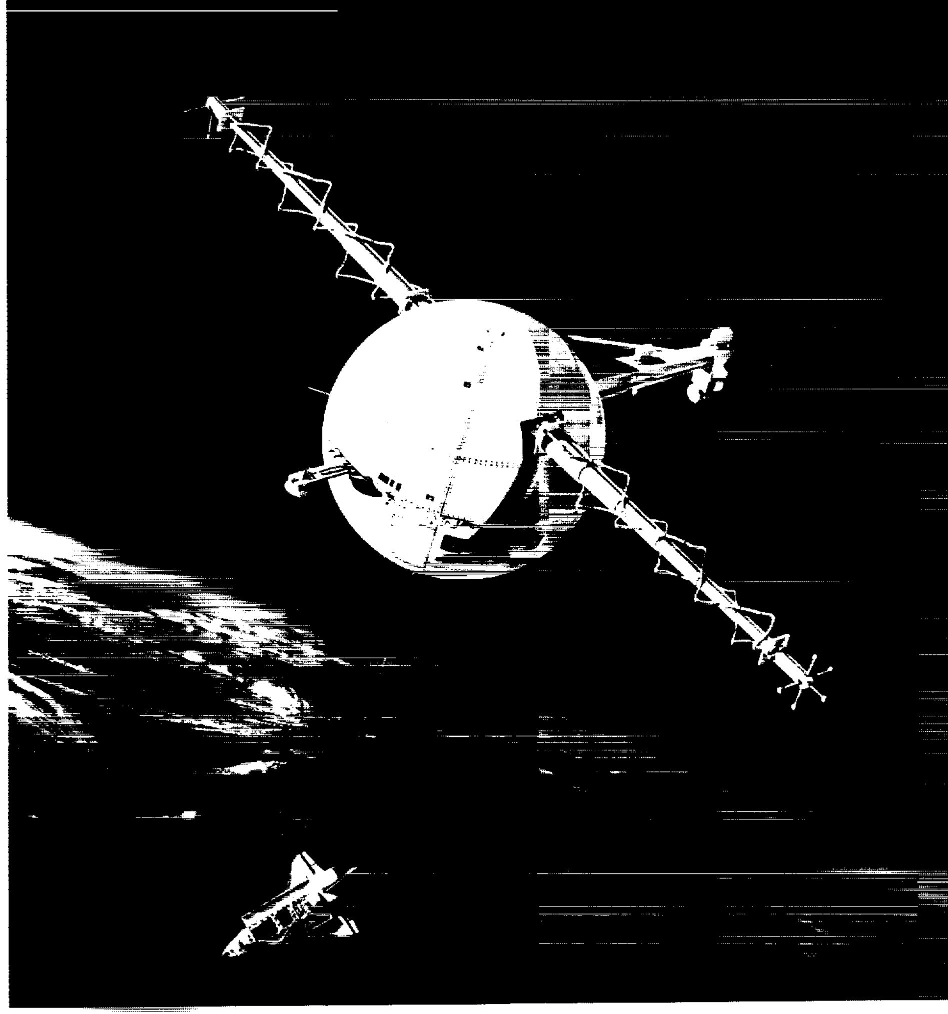


A Line To The Universe

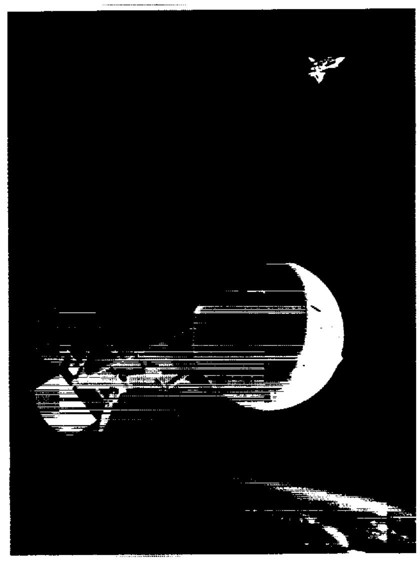
The first Tethered Satellite System (TSS-1) will soon be launched aboard the Space Shuttle. Circling Earth at an altitude of 296 kilometers (km), the reusable tether system will be well within the tenuous, electrically charged layer of the atmosphere known as the ionosphere. There, a satellite attached to the orbiter by a thin conducting cord, or tether, will be reeled from the Shuttle payload bay. This will grant scientists experimental capabilities never before possible.

On this mission, the satellite will be deployed 20 km above the Shuttle. The conducting tether will generate high voltage and electrical currents as it moves through the ionosphere and allow scientists to examine the electrodynamics of a conducting tether system. These studies will not only increase our understanding of physical processes in the near-Earth space environment but will also help provide an explanation for events witnessed elsewhere in the solar system. In addition, the mission will explore the mechanical dynamics of tethered systems, providing information that will improve future missions and possibly lead to a variety of future tether applications.

Tethered spacecraft can be deployed toward or away from Earth. Downward deployment (toward Earth) on future missions could place the satellite in regions of the atmosphere that have been difficult to study because they lie above the range of high-altitude balloons and below the minimum altitude of free-flying satellites. A series of Tethered Satellite System flights, exploring in both directions from the Shuttle, could gather data previously impossible to obtain. Each flight would allow scientists and engineers to conduct new experiments, explore phenomena discovered through previous missions, and develop new uses for tethers in space exploration.

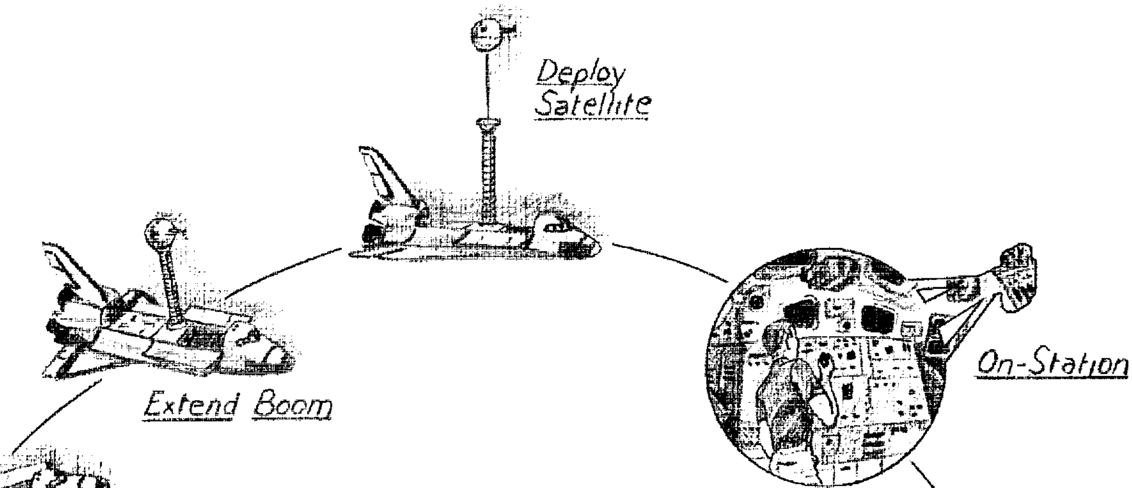


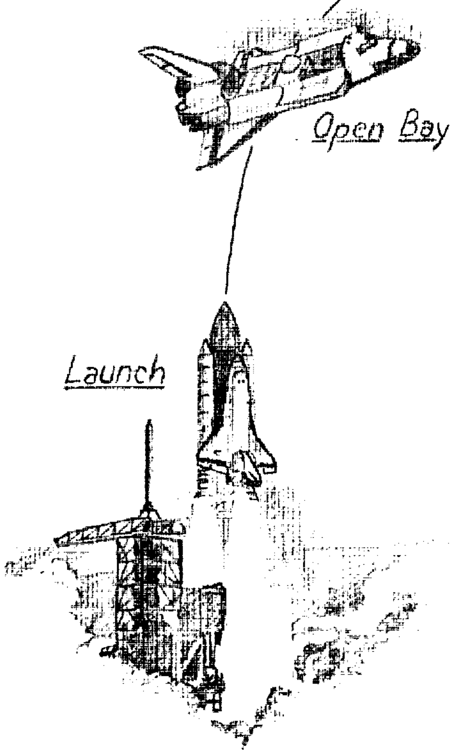
Deployment of the Tethered Satellite System upward from the Shuttle on TSS-1 allows scientists to gather data on performance, while providing an excellent platform for a variety of plasma physics and electrodynamics investigations.

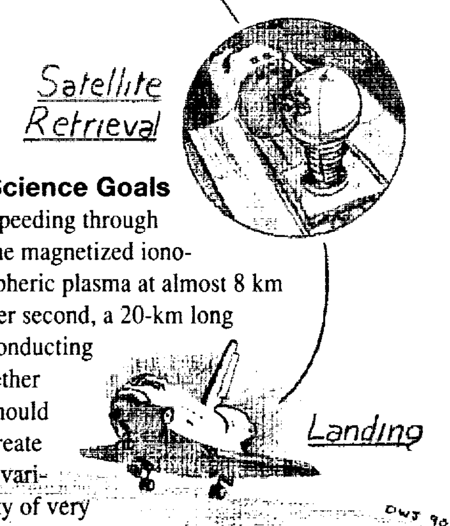


The Tethered Satellite System has the potential to be deployed toward the Earth. On such a future mission, large-scale investigations of previously inaccessible regions of the atmosphere could be performed.

The First Tethered Satellite System Mission







Mission Objectives

The era of space-age tethered operations moves toward reality with the launch of TSS-1. The primary objective of this mission is to demonstrate the technology of long tethered systems in space and to demonstrate, through scientific investigations, that such systems are useful for research.

Engineering Goals

Manipulating a satellite on a tether from the orbiter is a unique engineering challenge. Because gravity, centrifugal force, and atmospheric drag vary with altitude, each of the two bodies in a tethered system, one orbiting above the other, is subject to different influences. Consequently, the primary engineering goal of TSS-1 is to demonstrate that a satellite can be deployed, stabilized, and retrieved on a long tether in space and that an electrically conducting system can be operated successfully. Tether dynamics and control are not intuitive; while reeling out a satellite on a tether is somewhat analogous to flying a kite, the analogy breaks down when the environments in which the systems operate are compared. Unlike a kite in the atmosphere, the tethered satellite is in an electrically charged environment and is controlled by gravity gradient rather than aerodynamic forces. TSS-1 will improve our understanding of tether dynamics and allow scientists and engineers to develop more sophisticated tether control models for future tethered missions.

Science Goals

Speeding through the magnetized ionospheric plasma at almost 8 km per second, a 20-km long conducting tether should create a variety of very interesting plasma-electrodynamic phenomena. These are expected to provide a variety of unique experimental capabilities, including the ability to collect an electrical charge and drive a large current system within the ionosphere, to generate high voltages [on the order of 5 kilovolts (kV)] across the tether at full deployment, to control the satellite potential and the satellite's plasma sheath, and to generate low-frequency electrostatic and electromagnetic waves. It is believed that these capabilities can be used to conduct controlled experimental studies of phenomena and processes that occur naturally in plasmas throughout the solar system, including Earth's magnetosphere.

A necessary first step toward these studies — and the primary science goal of TSS-1 — is to characterize the electrodynamic behavior of the satellite-tether-orbiter system. Of particular interest is the interaction of the system with the charged particles and electric and magnetic fields in the ionosphere, including the nature of the external current loop within the ionosphere and the processes by which current closure occurs at the satellite and the orbiter. This will be investigated by a series of experiments conducted with electron accelerators and tether current-control hardware, along with a set of interdependent diagnostic instruments provided by the TSS-1 investigators.

Organization

The Tethered Satellite System is a joint venture of the United States' National Aeronautics and Space Administration (NASA) and Italy's Agenzia Spaziale Italiana (ASI, the Italian Space Agency). Based on a 1984 Memorandum of Understanding between NASA and ASI, the Italian agency has responsibility for developing the reusable satellite, while NASA has responsibility for developing the deployer system and the tether, integrating the payload, and providing transportation into space. In addition, the U.S. Air Force Phillips Laboratory, by agreement with NASA, is participating in the program by providing an experiment that supports the TSS-1 mission as well as Air Force research interests. The deployer system and the tether were developed by the Martin Marietta Astronautics Group in Denver, Colorado, and the satellite by the Alenia Space Systems Group in Turin, Italy.

Both NASA and ASI are sponsoring experiments to address the goals of the TSS-1 mission. Research guidelines specify that experiments study Tethered Satellite System electrodynamics and plasma interactions. The experiments selected are compatible with the engineering objectives and yield complementary data.

NASA's Marshall Space Flight Center, Huntsville, Alabama, is providing the overall management of the Tethered Satellite System project for NASA Headquarters. Johnson Space Center, Houston, Texas, and Kennedy Space Center, Florida, are also integral parts of the Tethered Satellite System mission. Flight and science operations are controlled from Johnson Space Center, while Kennedy Space Center is responsible for integrating payloads into the orbiter and launching the Shuttle.

An Investigator Working Group, composed of TSS-1 Principal Investigators and Associate Investigators, advises NASA and ASI in the design, development, and operation of TSS-1. This group develops and reviews all science requirements for the mission, recommends mission profiles and experiment sequences, and specifies how data should be acquired, processed, handled, and distributed. The Investigator Working Group also oversees science activities during the flight.

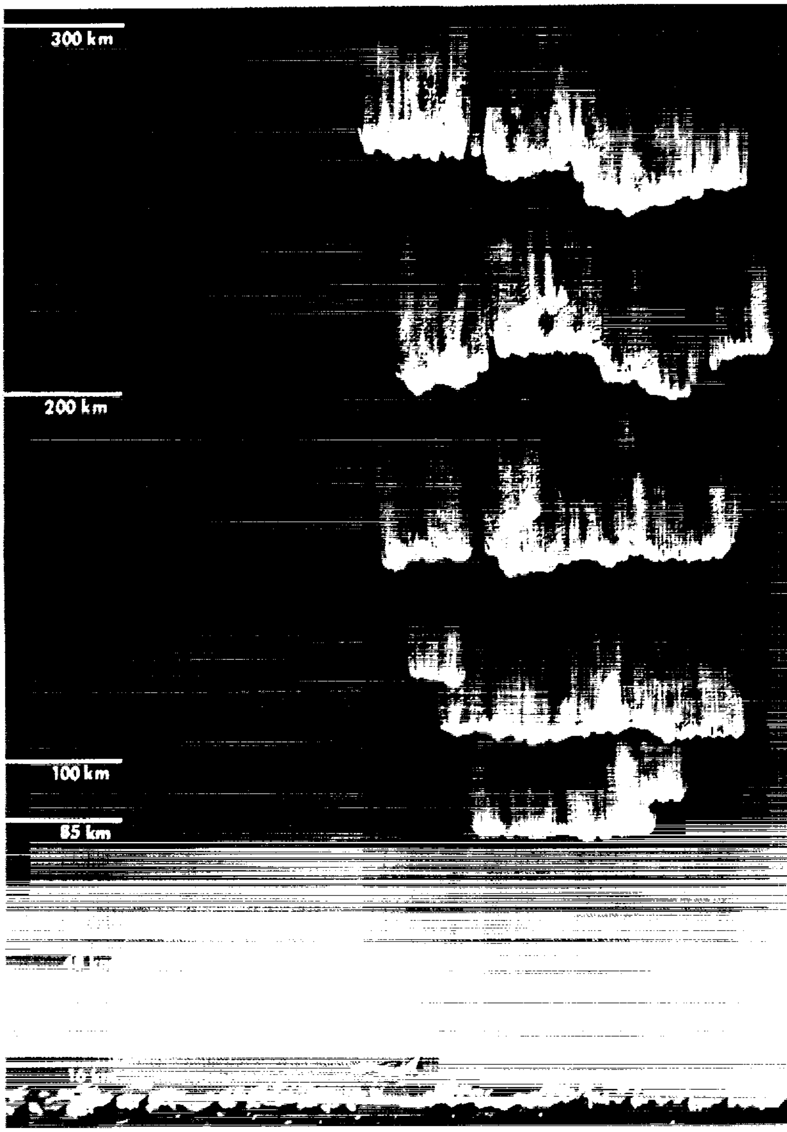
Mission Profile

The Shuttle will carry TSS-1 in its payload bay to a circular orbit where the satellite will be deployed spaceward on a conducting tether. Thus begins an adventure that could revolutionize the architecture of space structures and expand the possibilities for space investigations.

The deployed mission begins when a crew member unlatches the satellite and the deployer boom extends. Then the satellite's tether-aligned thrusters fire, gently lifting it away from the boom and the Shuttle. At a distance of 6 km from the Shuttle, other thrusters will spin the satellite so that it rotates a quarter turn each minute, allowing data to be collected as the satellite sensors rotate through different electric and magnetic fields.

Approximately 6 hours later, the satellite is fully deployed 20 km from the Shuttle. Ten hours of on-station operations begin with the satellite's spin being stopped for an orbit as data on tether system dynamics are collected. After this orbit, thrusters will spin the satellite so that it rotates at slightly less than one full turn each minute. As the Tethered Satellite System stimulates and interacts with the ionosphere, instruments in the satellite and the Shuttle's payload bay measure the response, determine how the Tethered Satellite System collects an electrical current from the ionosphere, study the power generation properties of the entire tether system, and characterize the surrounding environment.

Retrieval operations begin with the reel assembly winding in the tether. The satellite approaches to within 2.4 km of the orbiter, where it stops for 5 hours to gather additional data and stabilize the system for final retrieval. Retrieval resumes and crewmembers take manual control for final approach and docking.



Layers of the Atmosphere

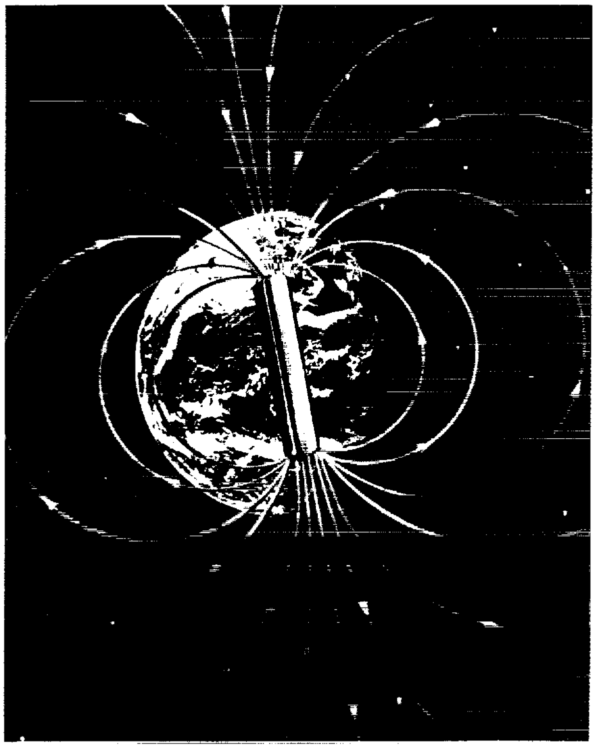
Regions of the Atmosphere

Earth's electrically neutral atmosphere is composed of four primary layers. The lowest layer, the one we live in on Earth's surface, is known as the troposphere and extends as high as 16 km above sea level. Extending from about 16 to 48 km is the stratosphere. Ninety-nine percent of the air in the atmosphere is located in these two regions. Above the stratosphere, from 48 to 85 km is the mesosphere. The uppermost layer is the thermosphere, which extends to approximately 1,000 km.

The upper thermosphere is also characterized by the presence of electrically charged gases, or plasma. This region, which extends from 85 to approximately 1,000 km, is also known as the ionosphere. The boundaries of the ionosphere vary according to solar activity. Overlapping the ionosphere is the magnetosphere, which extends from approximately 80 to 60,000 km on the side towards the Sun, and trails out more than 300,000 km away from the Sun. The magnetosphere is the region of space surrounding Earth in which the geomagnetic field plays a dominant role in the behavior of charged particles.

TSS-1 will allow scientists to study a variety of ionospheric processes. For example, it will generate large-scale electrical current loops in the ionosphere. These current loops may be similar to currents that occur in the polar regions of the atmosphere associated with auroras. Conducting tethers may also provide an alternate source of power for future spacecraft. This mission will help quantify the amount of electrical power that can be produced by conducting tethers.

The lower region of the thermosphere, from approximately 130 to 180 km, has been very difficult to explore. Satellites cannot orbit in this region because they would rapidly fall from orbit and burn up from atmospheric friction. Balloons cannot reach this altitude, and sounding rockets pass through the region too quickly to obtain more than a quick vertical profile of a particular spot. While TSS-1 will be deployed away from Earth, future missions can be deployed downward. These future Tethered Satellite System missions can spend days at these altitudes, gathering valuable data in a previously inaccessible region of our atmosphere.



Just as the bar magnet produces field lines, so too does Earth. You can visualize these field lines by thinking of the Earth as having a bar magnet running from the North to South poles.

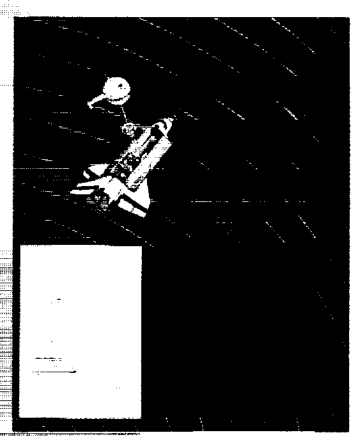
Earth's Magnetic Field and How TSS-1 Will Produce Power

TSS-1 makes use of Earth's magnetic field and electrically charged ionosphere to produce a current through the tether for a variety of experiments. To understand some of the discussions about the mission, a basic knowledge of Earth's magnetic field is helpful.

All magnetic objects produce invisible lines of force, extending between the poles of the object. An easy way to visualize this is to spread iron filings on a sheet of paper and place a bar magnet under the paper. The iron filings will arrange themselves around the magnet and along the magnetic field lines.

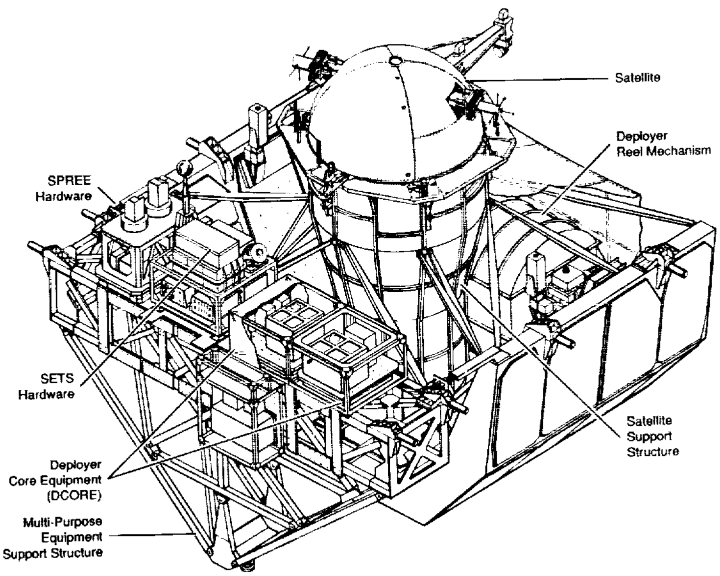
In the simplest terms, Earth can be thought of as a dipole (2-pole) magnet. Magnetic field lines radiate between Earth's north and south magnetic poles, just as they do between the poles of a bar magnet. Charged particles and atmospheric molecules become trapped on these field lines (just as the iron filings are trapped), forming the magnetosphere. Earth's field lines are not as symmetrical as those of the bar magnet. The impact of the solar wind causes the compression of the lines facing sunward, while the field lines facing away from the Sun stream back to form Earth's magnetotail.

The Tethered Satellite System can produce power because a high potential is generated across the tether as a result of its rapid motion across Earth's magnetic field lines. This effect is analogous to the way power is generated by an automobile alternator. The electric potential attracts free electrons to the satellite as it passes through the ionospheric plasma. For a current (a flow of charged particles) to be produced, the circuit must be completed — just as a wire must close the circuit between two poles of a battery before a current can flow. In the case of TSS-1, the circuit must be closed by the conducting ionosphere. The electrons collected by the satellite will flow through the tether to the orbiter, where electron accelerators will return them to the ionosphere. At the altitude of TSS-1, currents normally can only flow along Earth's magnetic field lines. As a result, regions of positive and negative charge created at the ends of the tether stream out along the geomagnetic field lines. These are called field-aligned currents. However, when the currents reach the lower and denser part of the ionosphere, known as the E-region, collisions between the charged and neutral particles will effectively scatter electric charges across the field lines, forming what are known as cross field current branches. These branches play an important role in TSS-1 power production by allowing the circuit to be closed.



TSS Power Production

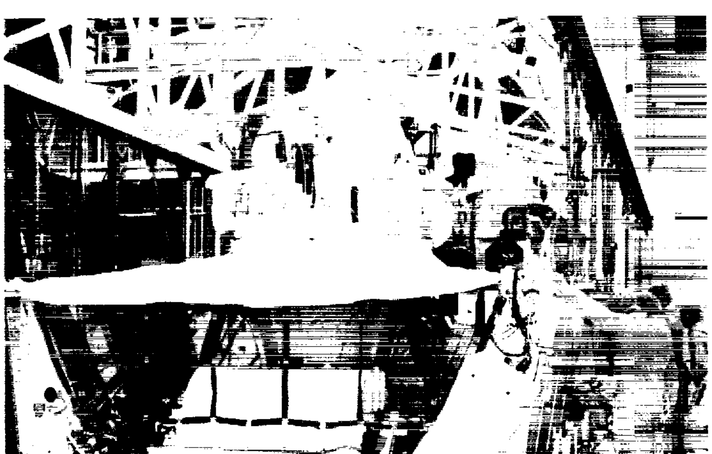
Major Tethered Satellite System Elements



The Tethered Satellite System

The Tethered Satellite System has five major components: the deployer system, the tether, the satellite, the carriers on which the system is mounted, and the science instruments. These specific elements are supported by the standard capabilities of the Space Shuttle orbiter, payload bay mounting equipment, and control and command facilities on the ground.

The Tethered Satellite System is seen here undergoing integration at the Kennedy Space Center.



The TSS-1 hardware is mounted on two carriers in the payload bay. The deployer rides on a Spacelab Enhanced Multiplexer Demultiplexer Pallet (called an EMP), a general-purpose unpressurized platform. The pallet provides both functional and structural support to the deployer, and its enhanced features include temperature control, power distribution, and command and data transmission capabilities. The second carrier is the Multi-Purpose Equipment Support Structure, an inverted A-frame truss located immediately aft of the enhanced pallet. This structure holds deployer core equipment and two of the mission's experiments.

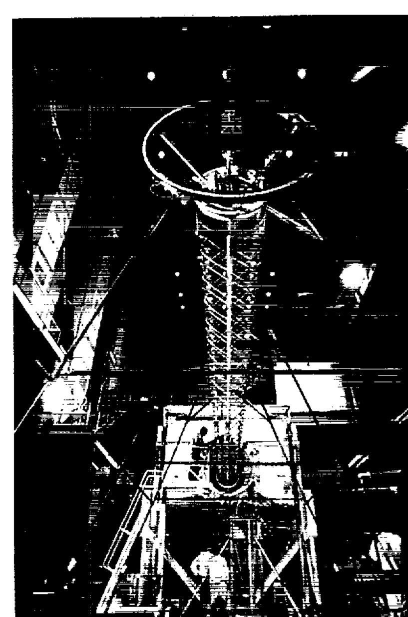
The Deployer System

The deployer system includes the satellite support structure, the deployment boom, the tether reel mechanism, a system that distributes power to the satellite before deployment, and a data acquisition and control assembly.

Umbilical cables woven through the deployment structure provide power and data lines to the satellite before deployment. When the umbilicals are disconnected after checkout, the satellite operates on its internal battery power. If the safety of the orbiter becomes a concern, the tether can be cut and the boom and satellite jettisoned.

When fully extended, the boom is a 12-meter (m) four-sided framework resembling a short broadcasting tower. Like a bolt forced upward by a rotating nut, the boom unfolds and extends slowly out of the turning canister on rollers that follow four tracks. As the canister rotates, fiberglass battens, similar to ones that give strength to sails, are released from their stowed, bent-in-half positions, to act as horizontal crossmembers to hold the longerons, or vertical members, erect. Diagonal tension cables further strengthen the boom, and flat ribbon-like cables provide the connection for electrical functions at the boom tip. During retrieval, the canister rotation is reversed. Tracks guide the rollers back, forcing the battens into their original bent position, and the longerons fold smoothly into the boom canister. The tether reel mechanism, which controls the length, rate, and tension of the tether, is critical to tether control. This assembly consists of the tether reel and the reel motor. It is controlled by

The TSS-1 deployer system has undergone many tests to ensure proper operations during the mission.



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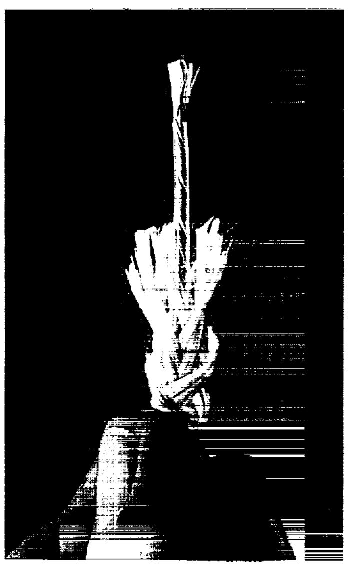
the motor control assembly and a data acquisition and control assembly. The reel mechanism is capable of letting out the tether at 16 km per hour; during the TSS-1 mission, however, the tether will be reeled out at a much slower rate.

The Tether

The tether's length and electrical properties affect all aspects of tethered operations. With its satellite fully deployed, the TSS-1/orbiter combination is 100 times longer than any previous spacecraft, and when the tether's current is pulsed by electron accelerators, it becomes the longest and lowest frequency antenna ever placed in orbit. Also, for the first time, scientists can measure the charges collected by spacecraft with high electrical potentials. All these capabilities are directly related to the structure of the shoe lace-thick tether, a conducting cord designed to anchor a satellite miles above the orbiter.

The TSS-1 tether is 22-km long and is expected to develop a 5,000 volt (V) potential and carry a current of up to 1 ampere (A). Manufactured for Martin-Marietta by the Cortland Cable Company of New York, the tether has a center of Nomex™ that is wrapped with copper wire which acts as the electrical conductor. The layer of wire is insulated with Teflon™, which is then covered with braided Kevlar™ 29 to give strength to the tether. The outer jacket of the tether is braided Nomex™ which protects the tether against the corrosive effects of atomic oxygen and mechanism-induced abrasion.



The different layers of the tether can be seen in this photograph.

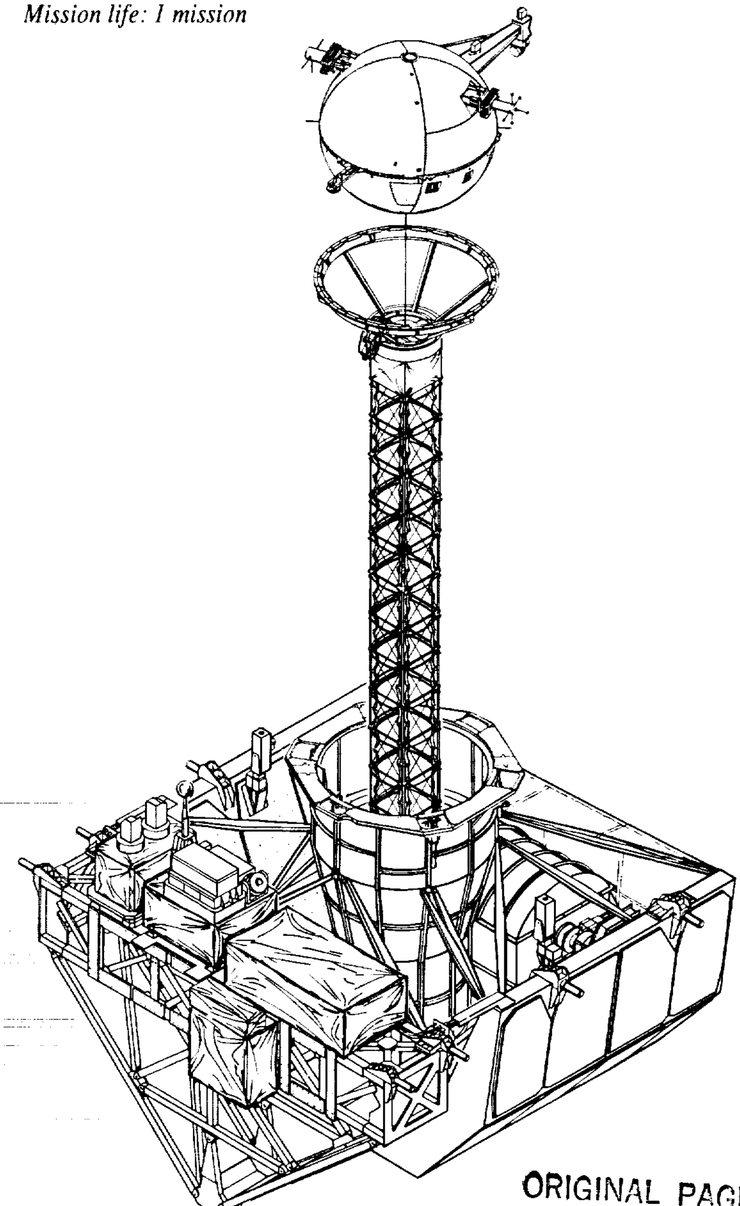
TSS-1 Tether Characteristics

Diameter (outer): 2.54 mm
Deployed length: 20 km
Breakstrength: 1,780 N
Maximum allowable tension: 700 N
Maximum expected load: 53 N
Maximum allowable mass: 8.2 g/m
Temperature range: -100 to +125 °C
Electrical characteristics:
- *current (maximum) – 1 A at 10 kV*
- *dc resistance – 0.12 ohms/m*
- *nominal operating voltage - 5,000 Vdc*

Maximum expected operational current: 500 to 750 mA
Mission life: 1 mission

Deployer System Characteristics

- *Deployer System*
  Total mass: 2,027 kg
  Thermal control: 4 coldplates, Multi-Layer Insulation (MLI), thermal tent covering pallet
  Power: 500 to 1,000 W (average); 1,500 W (peak)
  Data: 16 kbps (telemetry); 2 kbps (command)
- *Tether Reel Assembly*
  Capacity: 22-km conducting tether; 110-km nonconducting tether
- *Boom*
  Extended length: 12 m



The Deployer System

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The Satellite

Before it is deployed, the satellite is located on a satellite support structure where six latches hold it in place. Once removed from this structure, the satellite rests on a Teflon™-coated docking ring at the tip of the deployment boom. A 1-m fixed instrument boom extends out of the satellite's skin at the equator; a short mast opposite the boom carries the S-band antenna. For TSS-1, the satellite will have two deployable/retrievable instrument booms. Aluminum-alloy panels covered with electrically conductive paint form the outer skin of the satellite. These panels contain the connectors for the umbilical cables from the deployer; windows for Sun, Earth, and charged particle sensors; and access doors for installation or replacement of each satellite battery. At the base of the satellite, a bayonet pin attaches the tether to the satellite structure, and a connector routes the tether conductor to an ammeter and then to the satellite's skin.

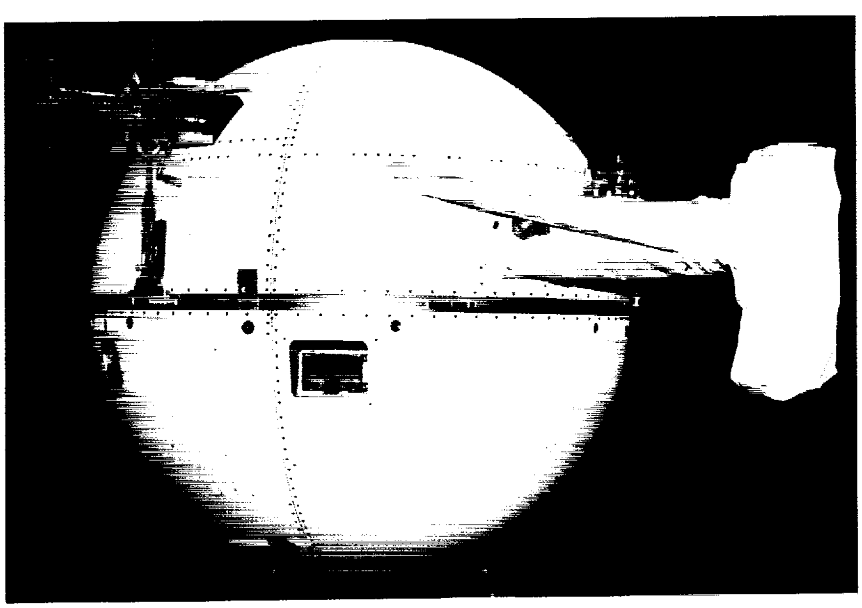
The satellite is divided into two hemispheres: science instruments are located in the Payload Module, or upper half (opposite from the tether), and the support subsystems (power distribution, data handling, telemetry, and navigational equipment) are housed in the Service Module, or lower half. A pressurized tank containing gaseous nitrogen for the cold gas thrusters is located in the center of the satellite. This tank, along with the various thrusters and associated plumbing, form the Auxiliary Propulsion Module. Separating the science instruments and support equipment into three modules that can be integrated into the satellite independently allows the satellite to be refurbished, reconfigured, and readied for subsequent flights.

The components of the Payload Module will change from mission to mission. For TSS-1, the module houses three experiments (Research on Electrodynamic Tether Effects, Research on Orbital Plasma Electrodynamics, and Magnetic Field Experiment for Tethered Satellite System Missions), the satellite core science equipment (a triaxial accelerometer and a current meter), and the deployable/retrievable instrument booms, which have a maximum extension of 2.4 m. The experi-

Satellite Characteristics for TSS-1

Diameter: 1.6 m
Actual mass: 518 kg
Payload mass: 68 kg
Deployable booms: 2
Fixed boom length: 1 m
Thermal control: white conductive paint on outer skin; black paint on internal skin; multilayer insulation blankets covering portions of the internal skin; heaters in payload and service modules and on batteries and sensors
Propellant: cold gas nitrogen
Lifetime: at least 3 missions

The TSS-1 satellite is seen here undergoing final checkout in Italy, before being shipped to the U.S.



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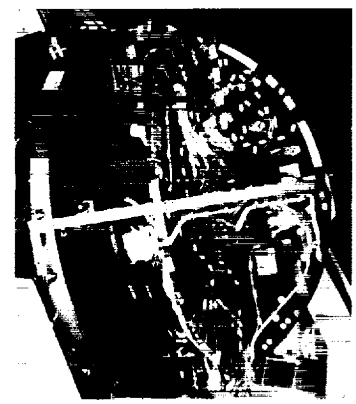
ment electronics are located on the floor and internal side panels of the module. Experiment sensors are mounted on the deployable/retrievable booms, the fixed boom, and the surface of the Payload Module.

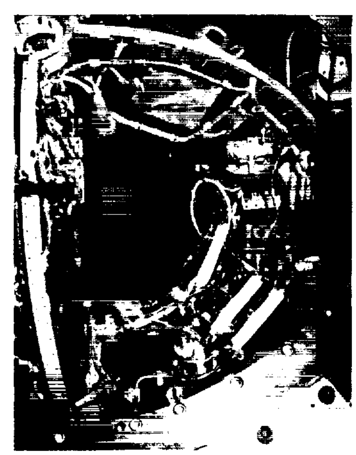
The Auxiliary Propulsion Module, in conjunction with the tether reel and motor, controls the motion of the tethered satellite. This module also initiates, maintains, and controls the satellite spin at up to 0.7 rotations per minute upon command from the Shuttle. Most components, such as the spherical high-pressure gas tank, pipes, valves, and mounting hardware, occupy the equatorial floor of the satellite. A set of thrusters near the tether attachment can provide extra tension on the tether, while a set of thrusters around the equator can be used to reduce or eliminate pendulum-type motions in the satellite. A final set of thrusters, also on the equator but directed off to one side, will be used to spin and despin the satellite.

The Service Module contains all the satellite support subsystems, except the propulsion system. Power distribution, data handling, attitude measurement and control, telemetry and command, thermal control, support structures, and the tether attachment are located at various points on satellite shell sections and the internal panels, permitting easy access to the components.

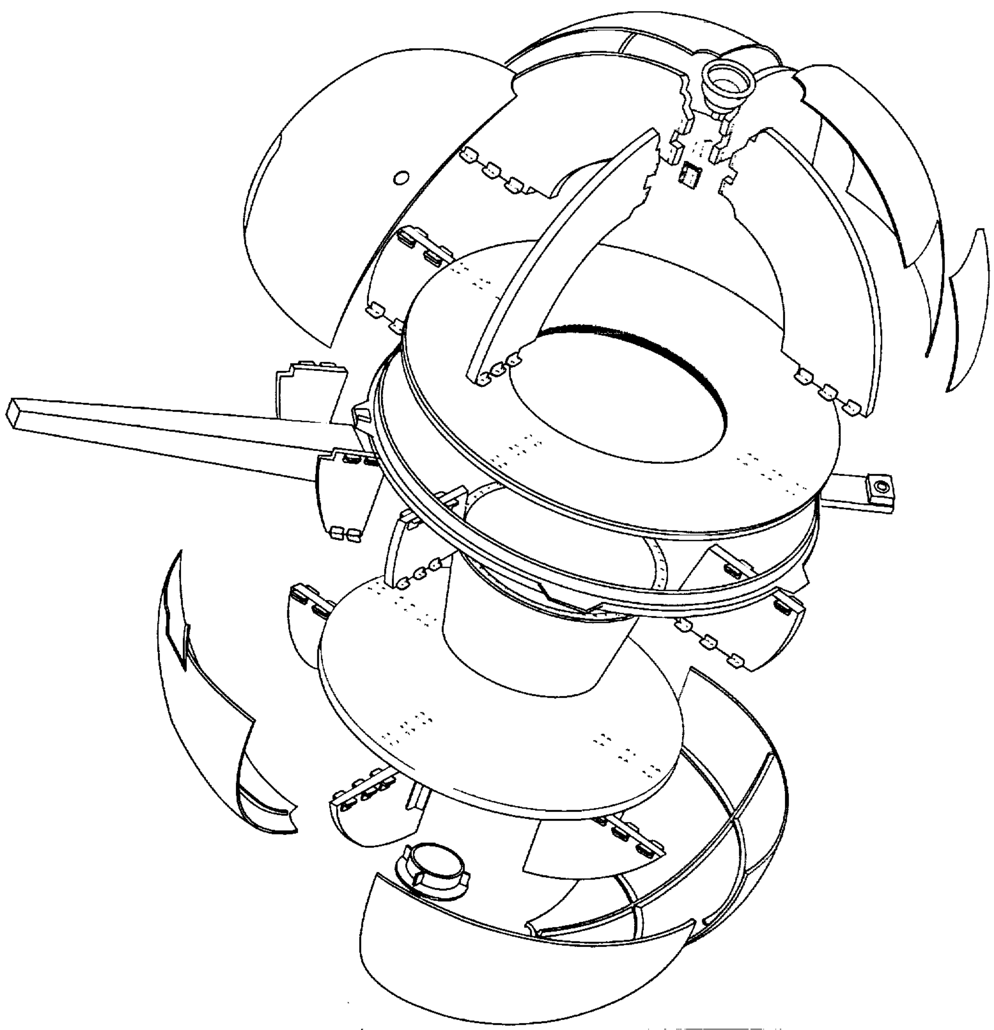
Within the Service Module are the gyros, Sun sensors, and Earth sensors that measure and control satellite attitude. Thermal control is primarily passive, but there are some active heaters. An S-band antenna provides a communications link between the satellite and the orbiter.



In this photograph of the payload module, it is possible to see the internal structure, wiring, and the electronics packages for various experiments.

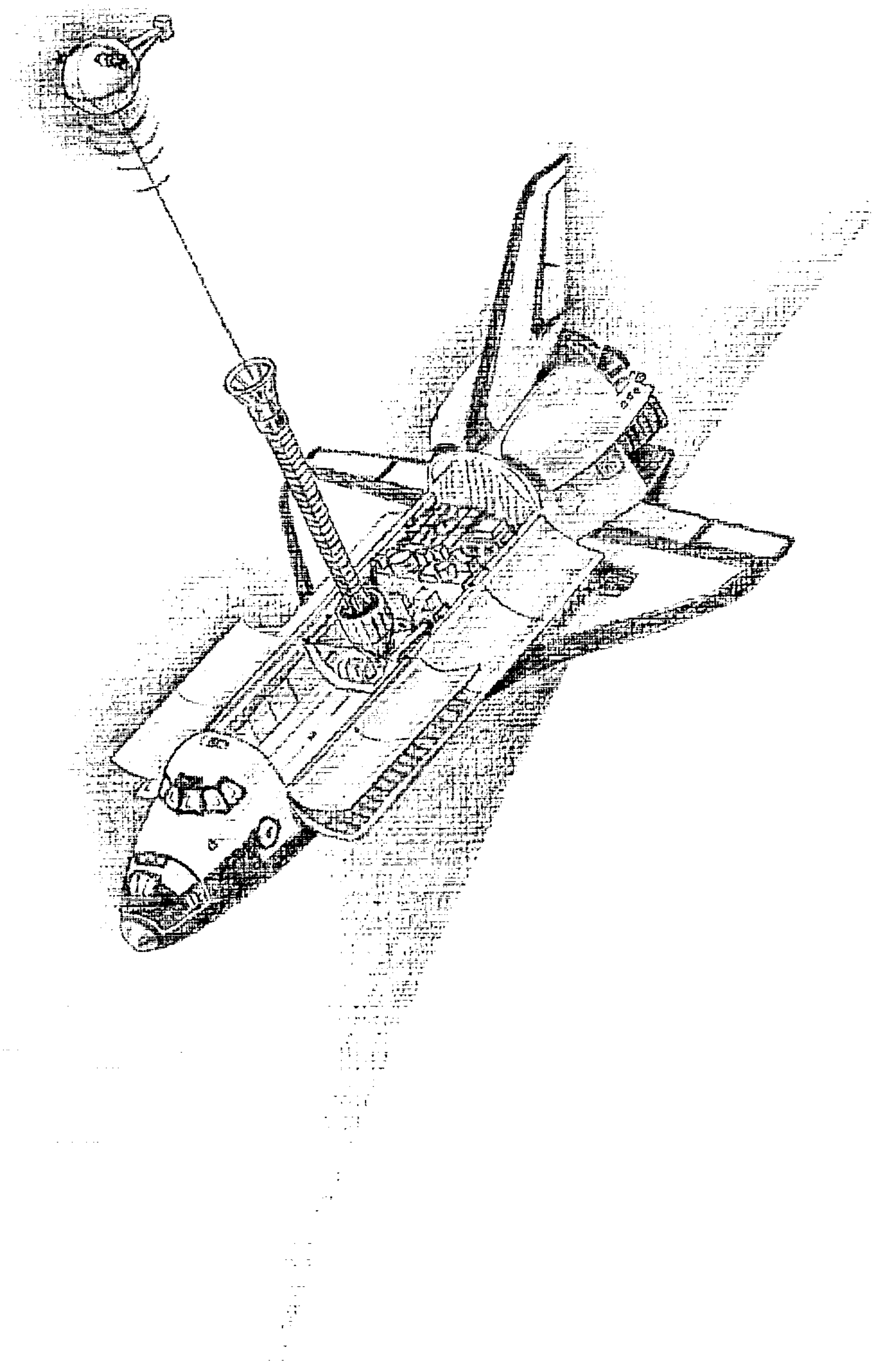


This photograph of the service module shows some of the sensors and instruments located in this half of the satellite. It also shows the tank and piping for the auxiliary propulsion system, the tether attachment point, and in-line thrusters (upper left).



An exploded view of the TSS satellite

Tether Dynamics



While space-based tethers have been studied theoretically since early in the century and later modeled extensively on computers, the TSS-1 investigations of electrical generation and plasma physics in the upper atmosphere will be the first time such a large, electrodynamic tethered system has ever been flown. In many respects, this mission is like the first test flight of a new airplane: the lessons learned will improve both scientific theory and future operations on tether missions.

The use of tethers in space is not new, but the applications have been extremely limited. The application most people remember are the tethers that connected spacewalking astronauts to their spacecraft; these were used until the advent of the Manned Maneuvering Units used on the Shuttle. These applications, however, used very short tethers that were not stabilized by gravitational forces and, therefore, have little relation to the Tethered

Satellite System. The TSS-1 mission will be using a 20-km long tether that will be stabilized by gravitational forces. Since the dynamics of the Tethered Satellite System are complex and can only be tested fully in orbit, it is impossible to predict before the mission exactly how the system will act. While the dynamics have been extensively tested and simulated, it is possible that the actual dynamics will be somewhat different from predictions. In addition to the normal mechanical dynamics there are also the complexities of a widely separated, multi-component system and the forces created by the flow of current through the system.

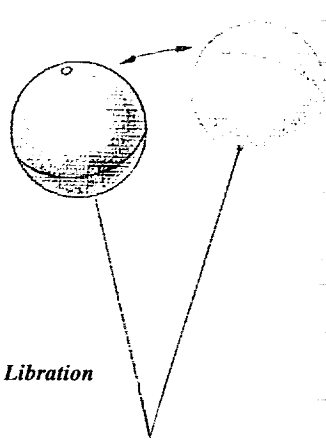
Deployment

A satellite is maintained in its orbit around Earth by a balance between the force of gravity, which pulls it toward Earth, and a centrifugal force, which pushes it away from Earth. The centrifugal force results from the motion of the satellite around its circular orbit. This is the same force that one can experience by swinging a ball around on the end of a string.

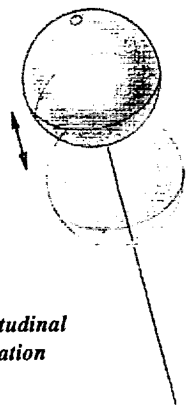
At the orbital altitude for TSS-1, a speed of approximately 7.6 km per second is required to create sufficient centrifugal force to balance gravitational attraction. If the altitude is changed, however, the two opposing forces will no longer be in balance unless the Shuttle's speed is also changed. Going higher requires a slightly greater speed, although it will take longer to complete an orbit because increasing the altitude makes the orbit a larger circle and significantly increases the distance around it. As a result, a higher satellite will move at a slightly higher speed but will take longer to travel around its orbit than a satellite below it. If the two satellites are tied together with a tether, they will be forced to travel at a higher speed than required for its orbit and, therefore, its centrifugal force will be greater than the pull of gravity. If the tether were cut, it would move to a higher orbit where the two forces would, again, be in balance. With the tether in place, however, the net effect of the unbalanced forces is to create tension in the tether. This is the force that causes the Tethered Satellite System satellite to rise above the orbiter as the tether is reeled out. Very close to the orbiter, there is little difference in the two orbits and the tension force is insufficient to overcome friction in the deployer mechanism. Therefore, until the satellite reaches a separation of approximately 1,000 m, the tension is augmented by small tether-aligned thrusters on the satellite. Beyond this point, the tension in the tether is the only force required.

But deployment of the satellite is not quite as smooth as it might seem. While the process is inherently stable, the system can experience libration, or back and forth movement of the tether. If the satellite were stopped suddenly, the gravity gradient would bring the tether back to the vertical orientation. However, the tether would overshoot and go out in the forward direction, and then come back again. The satellite would be moving in much the same back-and-forth movement as a pendulum in a clock but without the friction needed to stop the motion. Indeed, to dampen this pendulous motion, or libration, would require much more time than a typical Shuttle mission.

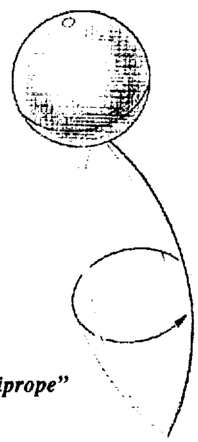
Libration will be controlled by varying the speed at which the tether is reeled. By avoiding sudden stops and decreasing the reel-rate slowly, the rate at which the gravity gradient brings the tether closer to the vertical is also slowed. If the motion is slowed just right, the tether will come to a halt in a stable, vertical position, with no residual libration.



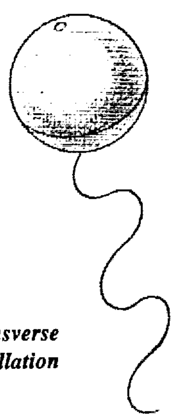
Libration



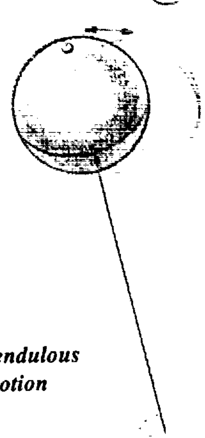
Longitudinal Oscillation



"Skiprope"



Transverse Oscillation



Pendulous Motion

Tether Oscillations

By experimenting with a ball hung on a piece of elastic cord (a paddle ball, for example) it is possible to simulate all the different types of oscillation that are possible on a space-based tether system. The elastic cord, representing the tether, may compress and stretch causing the ball to bounce up and down (referred to as longitudinal oscillation). It may also develop wave-like motions (transverse oscillation), or even move in a circular, or "skiprope" motion. Even if the string itself is not moving much, it is possible to get the ball rocking back and forth about its attachment point (pendulous motion).

Each type of motion occurs with a particular frequency, which depends on the length and tension of the tether. When the frequencies are different, the motions do not interact. However, at some tether lengths, the frequencies of two or more types of oscillation can become very close. At this point, energy can be transferred from one type of motion to another, a phenomenon known as resonance. For instance, the transverse oscillations in the tether may cause the satellite to rock back and forth in pendulous motion.

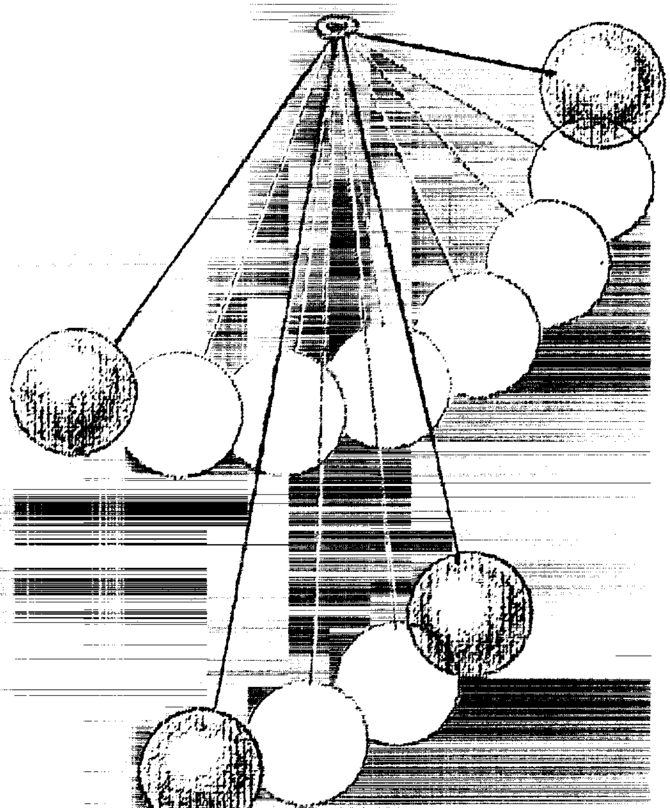
Many different factors may cause oscillations; the movements of the satellite or Shuttle are but two of these. On TSS-1, one potential cause of oscillation will be of particular interest. As the system produces an electrical current, it also produces a magnetic field around the tether. This magnetic field will interact with Earth's magnetic field resulting in a force expected to produce skiprope oscillations.

Because it is necessary to maintain control of the satellite, much study has gone into identifying the different types of possible motions and methods to control them. Dynamicists hope to observe all these types of oscillations during TSS-1 to see how real-world tether behavior compares to the mathematical simulations done over many years. This will increase the knowledge and understanding of tethered systems.

Retrieval

While deployment is an inherently stable process, retrieval of the tethered satellite is inherently unstable. As it comes toward the Shuttle, the satellite is also moving towards Earth's axis of rotation and so moves "east" or ahead of the orbiter. Any libration produced by this movement will tend to grow as the satellite and orbiter get closer to each other, because of the conservation of angular momentum.

Retrieval will, therefore, be very carefully controlled. The retrieval rate is programmed into the deployer system computer to keep the libration angle under control. The gravity gradient will be used to keep the tether taut until the satellite is approximately 200 m from the orbiter, when the satellite's thrusters will be turned on. At this point, the crew will take manual control of the last stages of retrieval. Then, using the tether reel rate, satellite thrusters, and movement of the orbiter itself, the crew will keep the satellite lined up as it is returned to its docking ring on the deployer.



The Conservation of Angular Momentum

Many of the dynamics theories affecting, or being tested on, TSS-1 are quite complex. While the conservation of angular momentum may seem complex, it is quite easy to visualize.

Take a ball attached to the end of a string and move it in a steady motion back and forth, like a pendulum. Once a steady swing has been established, take the thumb and forefinger of your other hand and make a circle around the top of the string. This will not interfere with the swing, so no change will be noticed.

While keeping your swing steady, slowly begin to raise the hand holding the string. As your hand goes higher, the string begins to hit the side of the circle made by your fingers. As this happens the frequency of the balls movement increases. The shorter the string, the faster the ball travels and the further from the vertical it tries to go. As you lower the string back down, the ball will eventually return to its original motion.

The reason for this is that the energy in the system remains the same. As the length of the string grows shorter, the same amount of energy is present. This produces a longer and faster arc.

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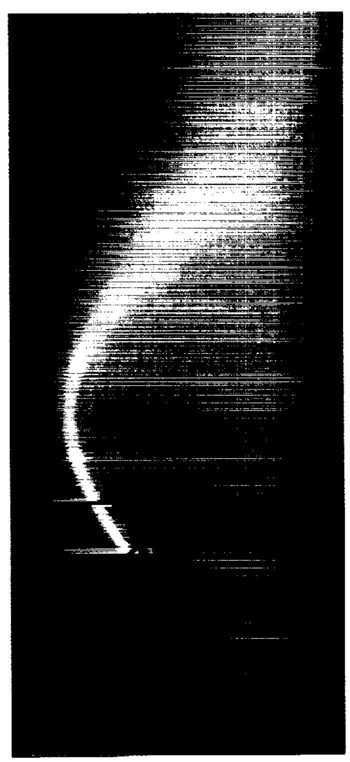
TSS-1 Science Background

To prepare for the mission, numerous tests using scale models of the TSS satellite, such as this one in the Frascati (Italy) Plasma Chamber, were conducted to test instruments, paints, and materials.

The TSS-1 mission will study the electrodynamic properties of a tethered satellite system and its interaction with Earth's ionospheric environment of charged gas and magnetic and electric fields. These studies will help demonstrate the Tethered Satellite System's capabilities as a research facility for investigations in electrodynamics and space plasma physics. Most of the TSS-1 experiments require essentially the same set of measurements, with instrumentation from each investigation providing different parts of the total set. While some instruments measure magnetic fields, others record particle energies and spectra, and others map electric fields. A complete set of data on the plasma and field conditions is required to characterize this environment and Tethered Satellite System perturbations accurately and completely. The TSS-1 science investigations are interdependent; they must share information to achieve their objectives. In fact, these investigations may be considered to be different parts of a single complex experiment.



The spiral path of an electron beam around magnetic field lines can be seen clearly in this photograph taken in a plasma research chamber.

The motion of the Tethered Satellite System through Earth's magnetic field generates a voltage across the conductive tether. As a result, it is able to extract an electrical current from the ionospheric plasma at the satellite and emit that current by means of electron accelerators in the payload bay. Investigators will use the ability to vary this current and control the electrical potential of the satellite to create and study a variety of phenomena and processes. These include electric power generation, wave generation and propagation, neutral gas ionization, and basic physical processes that occur naturally in plasmas surrounding Earth and other planets, moons, and comets. Although some of these phenomena have been studied in laboratories, very small scale-size, chamber wall effects, unnatural plasma distributions, and other problems hamper the ground-based experimenter. For the Tethered Satellite System, Earth's ionosphere is a vast, unbounded laboratory for space plasma experiments that can be conducted in no other way.

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Lightning is a commonly seen form of plasma.

The Fourth State of Matter

There are three classic states of matter: solid, liquid and gas. Then, there is plasma, which some scientists consider to be the fourth state of matter. The plasma state of matter is not related to blood plasma, the most common usage of the word. Rather, the term plasma has been used in physics since the 1920s to represent an ionized gas, and space plasma physics became an important scientific discipline in the early 1950s with the discovery of the Van Allen radiation belts.

Matter changes state as it is exposed to different physical conditions. Ice is a solid with hydrogen (H) and oxygen (O) molecules arranged in regular patterns, but if the ice melts, the H_2O enters a new state: liquid water. As the water molecules are warmed more, they separate further to form a gas, steam. In these classic states, the positive charge of each atomic nucleus equals the total charge of all the electrons orbiting around it so that the net charge is zero. Each entire atom is electrically neutral.

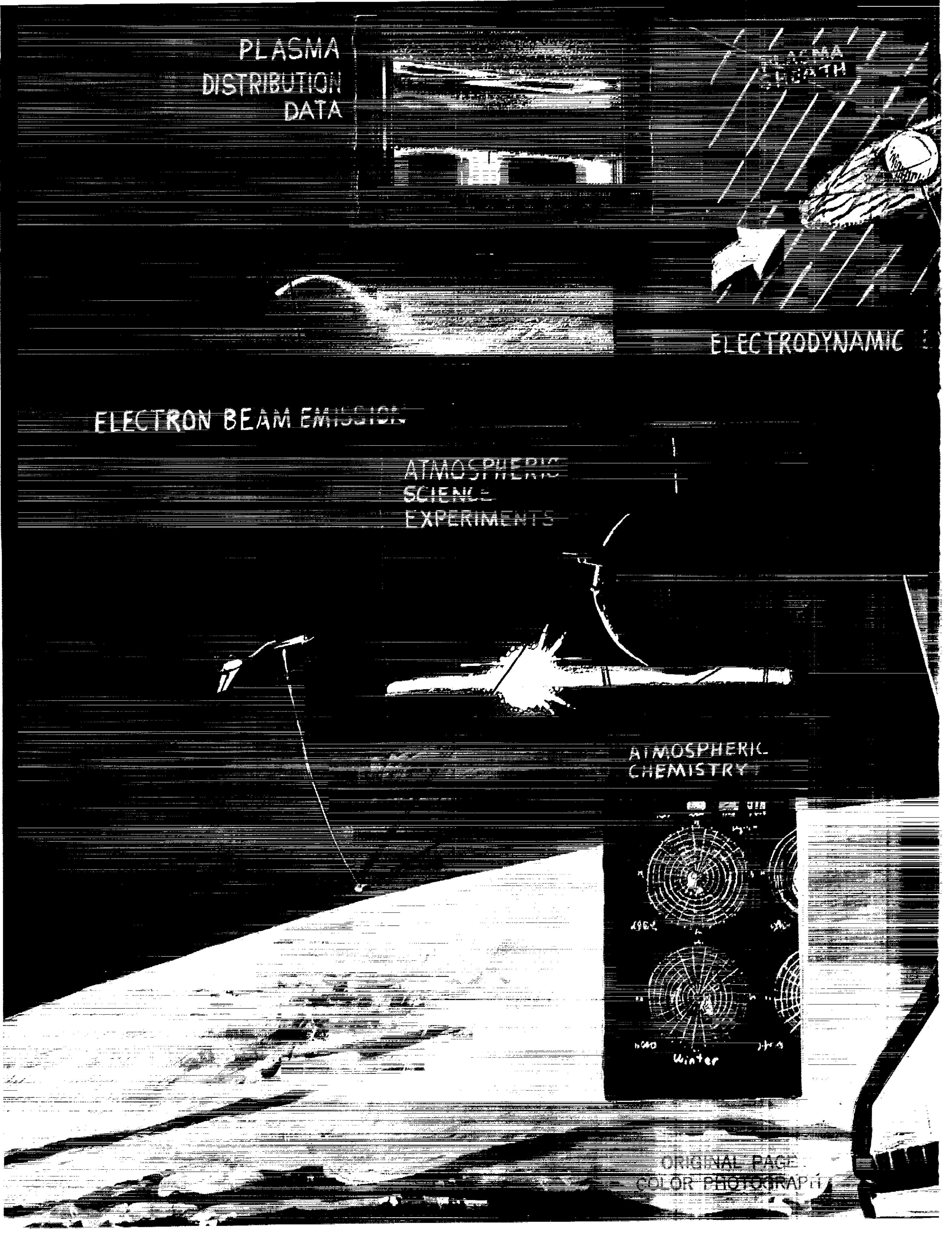
When more heat is applied, the steam may be ionized: an electron will gain enough energy to escape its atom. This atom is left one electron short and now has a net positive charge; it is now called an ion. In a sufficiently heated gas, ionization happens many times, creating crowds of free electrons together with ions. However, not all the atoms are necessarily ionized; some may remain completely intact with no net charge. This ionized gas mixture, consisting of ions, electrons, and neutral atoms is called plasma.

Although plasma includes electrons and ions, and conducts electricity, it is macroscopically neutral: in measurable quantities the number of electrons and ions are everywhere equal. The charged particles are affected by electric and magnetic fields applied to the plasma, and the motions of the particles in the plasma generate fields and electric currents from within. This complex set of interactions makes plasma a unique, fascinating, and complex state of matter.

Plasma is found both in ordinary and exotic places. When an electric current is passed through neon gas, it produces both plasma and light. Lightning is a massive electrical discharge in the atmosphere that creates a jagged column of ionized air, or plasma. Part of a comet's streaming tail is plasma from gas ionized by sunlight and other unknown processes. The Sun is a 1.5-million-kilometer ball of plasma, heated by nuclear fusion.

Scientists study plasma for practical purposes. In an effort to harness fusion energy here on Earth, physicists are studying devices that create and confine very hot plasmas in magnetic fields. In space, plasma processes are largely responsible for shielding Earth from cosmic radiation, and much of the Sun's influence on Earth occurs by energy transfer through the ionized layers of the upper atmosphere.

The Sun, seen here in a Solar Max image of the corona, is a plasma heated by nuclear fusion.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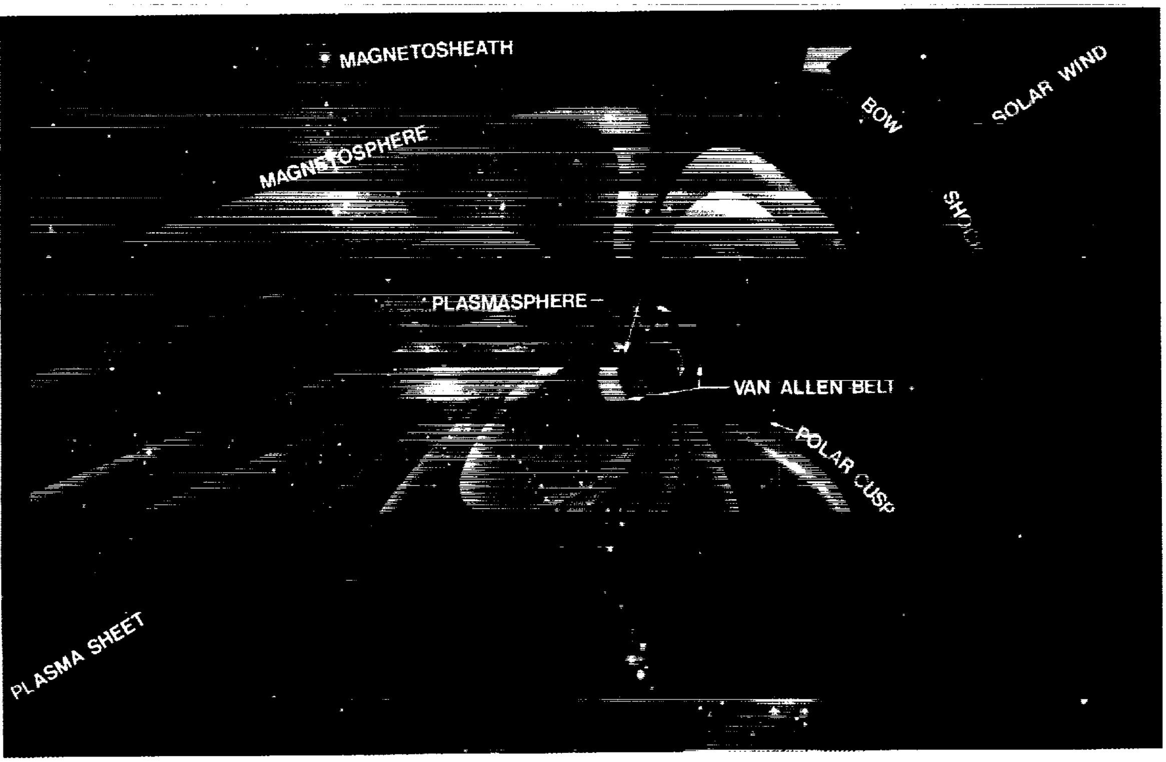
Tethered Satellite System



Earth's Magnetosphere.

The Plasma Universe

More than 99 percent of matter in the Universe exists in the plasma state — that is, as a mixture of ionized and neutral gases. Although nature rarely produces plasma on Earth's surface, it is common elsewhere. The electrically neutral environment to which we are accustomed is a rare exception. Plasma processes are important factors in the behavior of stars, interstellar clouds, comets, the aurora, and even in our upper atmosphere. Our understanding of astrophysical and many geophysical phenomena depends on our knowledge of how matter behaves in the plasma state.

Even before the space era, an unexpected discovery was made through ground-based radio wave observations: a region of plasma that exists above Earth's electrically neutral atmosphere. Plasma begins to dominate Earth's environment in the ionosphere, which extends upwards from about 85 km above the ground. The ionosphere has distinctive layers that differ in composition and density: the F1 layer (around 200 km) and F2 layer (around 300 to 400 km). The plasma in these layers, consisting mainly of electrons and atomic oxygen ions, is sustained by the ionizing action of solar ultraviolet radiation on the neutral atmospheric gas. All ionospheric layers tend to merge at night.

Ionospheric plasma is very tenuous. In the F2 layer, where the plasma is the most dense, there are rarely more than 1 million electron-ion pairs in a cubic centimeter (cc), or thimbleful, of space. In comparison, the neutral gas density for the same region is typically 1 billion particles per cc, while neutral gas density at Earth's surface is approximately 100 billion billion particles per cc. Never the less, the ionosphere effectively reflects most radio waves back to Earth, and it is this process that led to its discovery.

With the advent of man-made satellites, it became possible to measure the characteristics of the space environment near Earth directly — and it was discovered that Earth's ionized atmosphere extends much higher than originally thought. The region between the ionospheric E-layer (approximately 140 km) and the boundary between Earth's magnetic field and interplanetary magnetic fields (approximately 64,000 km on the sunward side), known as the magnetopause, contains minute quantities of Earth's ionized atmosphere. The behavior of the gas in this region is controlled by the geomagnetic field, and the region is, therefore, referred to as the magnetosphere. On the night side of Earth, the magnetopause trails away from the Sun forming the magnetotail, which has been found to extend more than 384,000 km, the distance from Earth to the moon, forming a shape similar to a comet's tail.

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Plasma is strongly influenced by magnetic and electric forces, and in turn, plasma particles affect the distribution of magnetic and electric fields. Beyond the magnetopause, energetic plasma from the Sun, called the solar wind, rushes past Earth at speeds ranging from 300- to 1,000-km per second. While most of this solar wind goes around Earth, some of it penetrates the magnetosphere. The interaction between the solar wind and the magnetospheric plasma acts like an electric generator [called the magnetospheric MagnetoHydroDynamic (MHD) generator], creating electric fields deep inside the magnetopause. These fields in turn give rise to a general circulation of the plasma, or a current system, and accelerate some electrons and ions to higher energies.

The visible manifestation of the high-energy electrons are seen in the aurora, the colorful Northern and Southern Lights that appear at 90 to 160 km above Earth. The auroral colors are determined by the nature of the atoms that are struck by magnetospheric electrons and the energies of the collisions: the night sky is painted with the reds and greens of oxygen and hydrogen and the purples and pinks of nitrogen. A typical 3-hour aurora, covering a million square kilometers, discharges approximately 100 million kilowatt hours of electric energy into Earth's immediate environment.

By characterizing the magnetic and plasma environments in our own neighborhood, we are able to recognize and understand plasma processes in the rest of the Universe. Already, auroras have been spotted on Jupiter, and the same types of phenomena appear to occur in the magnetospheres of Saturn and Uranus.

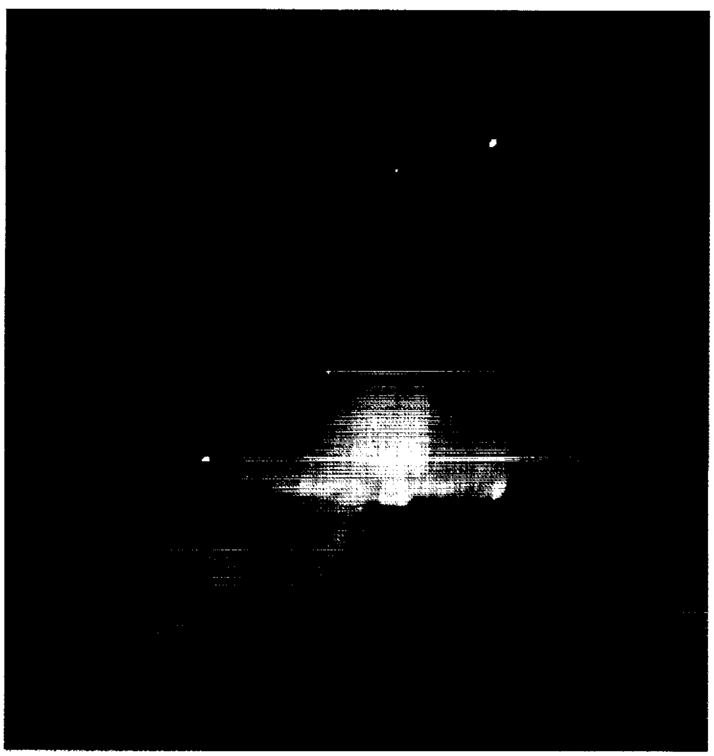
Many high-energy X-rays and gamma rays detected by astronomical observations come from magnetized plasmas near stars, galaxies, and other objects. A visual image of our Universe reveals only the superficial appearances, but plasma studies will show us the invisible structure of space and the processes that may have formed the solar system from dust and plasma.

Mission Science Objectives

One of the most important TSS-1 science objectives is to measure the plasma and field environment of the electrodynamic tether system. These measurements will be obtained over a wide range of conditions, since the ionospheric density varies naturally along an orbit from day to night and with the inclination of the geomagnetic field, causing the voltage across the tether to change by a factor of two or more during a complete orbit. This results in increases and decreases in the maximum current the Tethered Satellite System can collect.

In addition to natural variations, the Shuttle alters the space plasma when it dumps water, fires thrusters, or changes attitudes. In fact, some scientists have compared the Shuttle to a comet enclosed by a halo of water vapor and other ions that interact with the natural plasma. The environment near the Shuttle will be thoroughly characterized before, during, and after the satellite is deployed. In this way, investigators can separate natural variations and disturbances caused by the Shuttle from interactions between the Tethered Satellite System and the plasma.

While the Shuttle and tether are monitored by instruments in the payload bay, instruments on the satellite simultaneously measure the space plasma and fields around the satellite. The physical processes in the region around the satellite determine how many particles it collects and, hence, the magnitude of the current in the tether.



Colorful auroral displays, such as this view of the Aurora Australis photographed from the Shuttle, are the result of collisions between electrons and magnetospheric plasma. A typical 3-hour display can discharge 100 million kilowatt hours of electric energy into Earth's immediate environment.

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The ideal goal for each experiment would be to cover all ranges of electromotive force and plasma conditions experienced by the Tethered Satellite System during both the day and night portions of an orbit at all tether lengths. Since TSS-1 is the test flight of a new, reusable system, most measurements during the mission will be made at a single tether deployment distance.

Wakes and Sheaths

Some special features are likely to develop in the vicinity of the satellite as it actively perturbs the space plasma. Traveling at high speed (around 27,200 km per hour), the satellite affects the density, temperature, and electrical properties of the surrounding plasma. A plasma sheath containing an electric field develops around the satellite, while a wake, in some respects resembling the wake left by a boat in water, trails behind.

Sizable voltage drops are predicted to occur across the plasma sheath surrounding the positively biased satellite. The physics of a high-voltage sheath of this type is largely unknown, and its effects on the current flowing to the satellite and on the ambient neutral and charged particles are uncertain.

As the electrons accelerated by the electrically biased satellite collide with the neutral particles in the vicinity of the satellite, some of these particles may be ionized, releasing more electrons that will then be attracted to the positive surface of the satellite and may add significantly to the current collected by the tether system. This process should be enhanced when the satellite thrusters release more neutral gas, which can become ionized in the sheath.

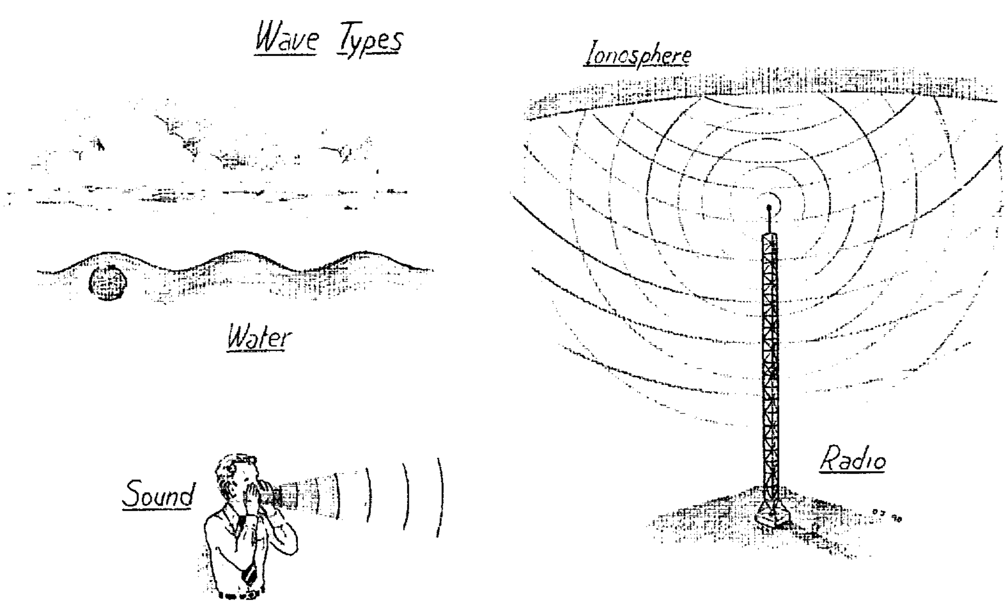
The plasma sheath around the satellite is predicted to be unstable and to change in size and shape with variations in ionospheric density, magnetic field alignment, and the voltage developed across the tether. As the sheath changes, it may produce instabilities in the plasma that result in an unsteady tether current and voltage. Electron heating in the sheath would also affect the plasma processes taking place near the satellite. For example, the character of the satellite's plasma sheath and wake will be affected, and the type and amplitude of waves excited may change. These changes can in turn affect the current and voltage of the tether.

In addition to mapping the sheath and wake, investigators will attempt to change the sheath's structure and study the resulting processes. Laboratory investigations have shown that the satellite potential can be set to determine the dominant mechanism involved in the plasma sheath and the near- and mid-wake regions. For example, if the satellite is maintained at a few tens of volts negative, a plasma sheath will exist, and the electric field within the sheath will focus ions into the wake. If the satellite is maintained at the ambient plasma potential, however, no plasma sheath develops and the plasma rapidly expands from denser regions to fill the void. If the satellite is maintained a few tens of volts positive, it will repel the ambient ions while attracting electrons. Higher positive voltages will expel ions, ionize neutral particles, and possibly generate instabilities in the plasma near the satellite. In the majority of TSS-1 operations, the satellite will vary from electrically neutral to positively charged. Wake-filling processes are of interest because they can affect the tether current and voltage and because the same processes affect the environments, and, therefore, the measurements made from all spacecraft. These processes may also occur in the environments of some natural celestial bodies — such as the Moon or asteroids.

Antennas and Waves

Waves are large-scale coordinated disturbances. While the medium in which a wave travels does not necessarily move as a whole in the direction of the wave, the wave creates small-scale motion in the medium. This motion varies with the type of wave: a wave on the surface of a lake moves molecules in small circles, and sound waves move air molecules back and forth. Just as a water wave lifts swimmers up and sets them down as it passes, plasma waves can shift a net electrical charge in a plasma from one ionospheric region to another.

Waves of every kind carry energy and momentum obtained from their source, which may be transferred to objects they impact: ocean waves transform the shore, sound waves crack glass, and electromagnetic (infrared and ultraviolet) waves heat Earth. Similarly, plasma and electromagnetic waves transfer energy between electrons, ions, and neutral particles. Scientists are very interested in how energy is exchanged between ionospheric and atmospheric layers, and waves (and wave- particle



interactions) are partially responsible for this transfer.

One TSS-1 goal is to study how waves are generated naturally in the ionosphere. The ionosphere supports a variety of plasma waves from many sources, including whistle-like noises triggered by magnetic storms and lightning, which can be heard on a radio. In a plasma, the particles vibrate and oscillate in unison, and the plasma waves, when converted to sound by a radio receiver, form a symphony of sound. TSS-1 instruments on the satellite and in the payload bay can measure the generation and propagation of naturally occurring plasma waves.

A plasma may also emit and absorb light, radio, and other electromagnetic waves created by shifting electric and magnetic fields. Radio signals of the right frequency are able to pass through the ionosphere and travel up into the magnetosphere, where they grow and trigger a noisy chorus of signals at different frequencies. By injecting known amounts of radio waves into the space plasma, scientists can study the composition, distribution, and motion of the plasma. Since the speed and pattern of waves are influenced by the medium in which they travel, the way in which the ionosphere affects radio wave propagation can tell us much about the ionospheric plasma.

The TSS-1 tether will be the longest antenna ever placed in orbit. It can either be used passively, for receiving radio waves from other sources, or actively, as a transmitting antenna. To transmit, the current passing through the tether may be modulated by pulsing it on and off at the required frequency. The longer the tether, the lower the frequency at which it can radiate waves efficiently. This unique ability to produce low-frequency waves makes a number of active experiments possible.

Currents in Space

Currents are created in the polar regions of the magnetosphere by the magnetospheric MagnetoHydroDynamic generator. The generator is driven by the motion of the plasma at the boundary of the magnetosphere. These auroral current systems are aligned with Earth's magnetic field in the magnetosphere but have cross-field branches in the lower ionosphere. This is very similar to the type of current system that may be generated in the ionosphere by the Tethered Satellite System.

When the field-aligned branches of the auroral currents exceed the capacity of the plasma to carry a charge, a drop in electrical potential occurs. This may take the form of electric double layers — plasma structures in which two layers of excess electric charge, one positive and the other negative — exist in close proximity. Between the two, there is an electric field that can accelerate charged particles. Plasma theory and laboratory experiments have shown that double layers can form when currents are driven along magnetic fields in a plasma. There is some evidence that weak double layers exist naturally in the ionosphere, but because they are so thin, they are difficult, if not impossible, to observe directly. Their effects on charged particle distributions can be measured, however, and Tethered Satellite System instruments should be able to detect the presence and motion of double layers by measuring electrons beamed from below the satellite and energetic ions created by the collapse of double layers near the satellite.

Simulating Phenomena of the Plasma Universe

Immersed in the ionospheric plasma, the Tethered Satellite System will allow scientists to study many space plasma phenomena first hand. The electrodynamics of the satellite system involve a number of phenomena, such as wakes, sheaths, and currents, that will be carefully studied throughout the mission. Once the basic phenomena of the Tethered Satellite System are characterized, some experimental parameters, such as satellite potential and tether current, can be varied to model important basic processes that occur naturally in our magnetosphere, solar system, and beyond.

Because of the difficulty, expense, and time required to send probes to other parts of the solar system, scientists want to

A tethered satellite research facility can be used to duplicate electrodynamic phenomena observed elsewhere, such as the interaction of Jupiter and Io, the small orange moon in the upper left.

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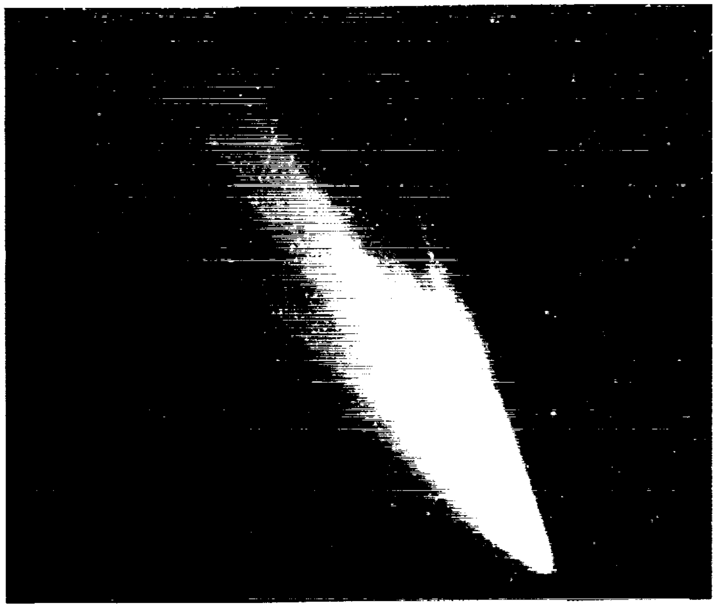


TSS-1 may help scientists better understand both the processes occurring in comets as they travel and how they were formed.

model plasma environments around other celestial objects accurately. Observations to date reveal that plasma may interact with the surface of a body (the Moon or artificial satellites), with the gaseous atmosphere of the object (comets or Venus), or with the intrinsic magnetic field of the body (Earth or Jupiter). These interactions affect both the space plasma and the electrodynamic characteristics of the body. Shock waves occur in front of planets, waves are generated and interact with charged particles, and wakes and sheaths may form. Not enough on-site data has been collected to understand these processes fully, and laboratories are not large enough to model the vast size of the processes created by the movement of planets through space. The Tethered Satellite System, however, may bridge the gap between these two extremes, allowing scientists to investigate actively such large-scale plasma phenomena.

Jupiter and Io

Scientists have detected intense, naturally occurring, radio-frequency emissions from Jupiter. These emissions may last more than an hour at a time and consist of bursts of extremely intense 1- to 2-second pulses. The radiated energy from a single pulse may be as great as 100 thousand million joules, the equivalent of the energy released from 25 tons of dynamite.

These emissions have been correlated with the motion of Jupiter's moon, Io. Unlike Earth's moon, Io orbits deep inside the Jovian magnetosphere, where it moves at hypersonic speeds through the magnetic field and magnetospheric plasma. Volcanic activity on Io ejects gases, forming an atmosphere, which is ionized to form a region similar to Earth's ionosphere. As Io sweeps through the Jovian magnetic field, a potential of approximately 400,000 volts is created across its conducting atmosphere, and massive currents on the order of 5 million amperes flow along the field lines between Io and Jupiter into the lower Jovian ionosphere.

The current that will be created by the tether's motion through Earth's ionosphere is predicted by some scientists to be similar to the current system generated by the motion of Io. In this scaled-down model of the Jovian system, the Tethered Satellite System serves as the conducting moon, and Earth with its ionosphere and magnetic fields mimics Jupiter. Parameters to be measured include field-aligned currents, turbulence, radio frequency emissions, and wave-particle interactions.

Comets

Comets are essentially balls of ice and dust that streak through the solar system. When they approach the Sun, the intense radiation converts some of the ice to gas which ionizes very rapidly — apparently as a result of several processes. The solar wind and the interplanetary magnetic field force the ionized gas to stream behind the comet, forming the familiar cometary tail. It is thought that one of the ionization processes results from the rapid motion of the neutral cometary gas through the interplanetary medium. This ionization mechanism is known as "critical velocity ionization."

This effect, hypothesized by Nobel Prize winning Swedish plasma physicist Hannes Alfvén and subsequently observed in laboratories, may explain the rapid ionization in comets and may also help explain how comets and planets formed in the solar system. According to Alfvén's theory, the gravitational field of the ionized core of a primordial dust cloud attracted the surrounding dust and gas, and as the atoms fell toward the core, they became ionized and subject to the effects of the core's magnetic field. Alfvén hypothesized that when the falling neutral gas reached a certain "critical" velocity, massive ionization occurred, and the gas was trapped, suspended in space some distance from the core by its magnetic field. This velocity was assumed to be related to the energy required to ionize the gas. Since the energy required to ionize different elements varies, clouds of gases would become trapped at various distances from the evolving Sun based on the composition of the cloud. The ionized particles were concentrated in the plane of the solar equator, eventually coalescing into planetary bodies.

Scientists, therefore, want to study how a high-speed cloud of neutral gas interacts with a magnetized plasma. The motion of the Tethered Satellite System through the geomagnetic field offers this opportunity. It provides the essential ability to control spacecraft potential, combined with the ability to release controlled amounts of neutral gas from the satellite thrusters. In particular, the system can be used to establish the conditions necessary for the ignition of critical velocity ionization. Local measurements can be made to study the creation and growth of plasma instabilities, the heating of electrons, the conditions at which critical velocity ionization becomes self-sustaining in space, and its effect on the ambient ionospheric medium.

TSS-1 Science Investigations

TSS-1 is comprised of 12 investigations. Seven investigations address the science goals of the TSS-1 mission, using equipment that either stimulates or monitors the tether system and its environment. Two investigators will use ground-based instruments to measure electromagnetic emissions from the Tethered Satellite System as it passes overhead, and three investigators were selected to provide theoretical support in the areas of dynamics and electrodynamics.

Indicates instrument(s) located in orbiter
Indicates instrument(s) located on ground
Indicates instrument(s) located on deployer
Indicates instrument(s) located on satellite

TSS Deployer Core Equipment and Satellite Core Equipment (DCORE/SCORE)
Carlo Bonifazi, Principal Investigator
Agenzia Spaziale Italiana

The Tethered Satellite System Core Equipment will demonstrate the capability of a tether system to produce electrical energy and allow studies to be made of the electrodynamic interaction with the ionosphere. It does this by controlling the current flowing through the tether between the satellite and the orbiter, and by making a number of basic electrical and physical measurements of the Tethered Satellite System.

Deployer Core Equipment consists of several instruments and sensors on a pallet aft of the deployer in the cargo bay. A master switch connects the tether conductor to science equipment in the orbiter; a power distribution and electronic control unit provides basic power, command, and data interfaces for all deployer core equipment except the master switch; and
a volt meter measures the tether potential with respect to the orbiter structure. The Core Electron accelerator has two electron beam emitters that can eject up to 500 milliamperes of current from the system. Two other instruments complement the electron accelerator's operations: a vacuum gauge to measure ambient gas pressure and prevent operation if pressure conditions might cause arcing and a device to electrically connect either generator head to the tether.

Satellite Core Equipment consists of a linear three-axis accelerometer and an ammeter. The accelerometer (along with the satellite's gyroscope) will measure satellite dynamics, while the ammeter will provide a slow sampling monitor of the current collected on the skin of the TSS-1 satellite.

Research on Orbital Plasma Electrodynamics (ROPE)
Nobie Stone, Principal Investigator
NASA Marshall Space Flight Center

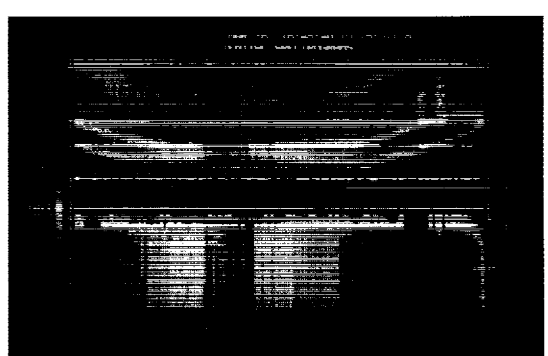
This investigation is designed to study the behavior of the ambient ionospheric charged particle populations and of ionized neutral particles around the TSS-1 satellite under a variety of conditions. Since the collection of free electrons from the surrounding plasma produces current in the tether, knowledge of the behavior of charged particles is essential to understanding the physics of tether current production.

From its location on the 1-m fixed boom, the Differential Ion Flux Probe measures the energy, temperature, density, and direction of ambient ions that flow around the satellite and neutral particles that have been ionized in the satellite's plasma sheath and accelerated radially outward. In this instrument, an electrostatic deflection system, which determines the charged particle direction of motion over a range of 100 degrees, routes particles to a retarding potential analyzer, which determines the energy of the ion stream, measuring particle energies from 0- to 100-electronvolts (eV). The directional discrimination of the Differential Ion Flux Probe will allow scientists to differentiate between the ionospheric ions flowing around the satellite from ions that are created in the satellite's plasma sheath and accelerated outward by the sheath's electric field.

The Soft Particle Energy Spectrometer instrument is a collection of five electrostatic analyzers that measure electron and ion energies from 1- to 10,000-eV. Three analyzer modules provide measurements at different locations on the surface of the satellite's hemispherical payload module. These sensors determine the potential of the satellite and the distribution of charged particles flowing to its surface. Two other Soft Particle Energy Spectrometer sensors, mounted with the Differential Ion Flux Probe on the end of the boom, measure ions and electrons flowing both inward and outward from the satellite. These measurements can be used to calculate the local potential of the plasma sheath.

The sensor package on the boom is electrically isolated from the satellite and its potential is controlled by the floating power supply. For satellite potentials up to 500 volts, the sensor package will be maintained near the local plasma potential to allow unambiguous measurements to be obtained. The potential of the sensor package can also be swept, allowing the package itself to serve as a diagnostic probe.

The DCORE equipment can be seen in the two boxes below and to the right of the satellite in this photograph taken during payload integration at the Kennedy Space Center.



The ROPE experiment will gather data around the TSS-1 satellite similar to these spectrograms obtained during a previous space plasma experiment.

ORIGINAL PAGE
COLOR PHOTOGRAPH

Research on Electrodynamic Tether Effects (RETE)

Marino Dobrowolny, Principal Investigator
Consiglio Nazionale delle Ricerche/Instituto Fisica Spazio Interplanetario

The behavior of electrostatic waves and plasma in the region around a tethered satellite affects the ability of that satellite to collect ions or electrons and, consequently, the ability of the tether to conduct an electric current. This investigation provides a profile of the electrical potential in the plasma sheath and identifies waves excited by this potential in the region around the satellite. Probes, placed directly into the plasma in the vicinity of the satellite, map alternating (ac) and direct current (dc) electric and ac magnetic fields produced as the current in the tether is changed by instabilities in the plasma sheath or as the Fast-Pulse Electron accelerator or Core Electron accelerator are fired in the payload bay.

The instruments are mounted in two canisters at the end of a pair of 2.4-m extendible booms. As the satellite spins, the booms are extended and sensors measure electric and magnetic fields, particle density, and temperature at various angles and distances in the equatorial plane of the satellite. To produce a profile of the plasma sheath, measurements of dc potential and electron characteristics are made both while the boom is fully extended and as it is being extended or retracted. The same measurements, taken at only one distance from the spinning satellite, produce a map of the angular structure of the sheath.

One boom carries a wave sensor canister, which contains a three-axis alternating current electric field meter and a two-axis search coil ac magnetometer to identify electric fields and electrostatic waves and characterize the intensity of surrounding magnetic fields. Highly sensitive radio receivers and electric field preamplifiers within the canister complement the operations of the probes.

On the opposite boom, a plasma package determines electron density, plasma potential and low-frequency fluctuations in electric fields around the satellite. A Langmuir probe with two metallic sensors samples the plasma current; from this measurement, plasma density, electron temperature, and plasma potential may be determined. This potential is then compared to that of the satellite. Two other probes measure low-frequency electric fields.

Magnetic Field Experiment for TSS Missions (TEMAG)

Franco Mariani, Principal Investigator
Second University of Rome

The primary goal of this investigation is to map the magnetic fields around the satellite. If the magnetic disturbances produced by satellite interference, attitude changes, and the tether current can be removed from measurements of the ambient magnetic fields, then the Tethered Satellite System will prove an appropriate tool for magnetic field studies.

Two triaxial fluxgate magnetometers, very accurate devices designed to measure magnetic field fluctuations, are located on the fixed boom. One sensor at the tip of the boom and another at midboom characterize ionospheric conditions at two distances from the satellite, determining the magnetic signature produced as the satellite moves rapidly through the ionosphere. Combining measurements from the two magnetometers allows realtime estimates to be made of the magnetic fields produced by the presence of satellite batteries, power systems, gyros, motors, relays, and permanent magnets. The environment at the tip of the boom should be less affected by the spacecraft subsystems. After the mission, the variable effects of switching satellite subsystems on and off, of thruster firings, and of other operations that introduce magnetic disturbances will be modeled on the ground in an attempt to remove these spurious signals from the data.

The two magnetometers will make magnetic field vector readings 16 times per second to obtain the geographic and temporal resolution needed to locate short-lived or thin magnetic structures, and twice per second to allow discrimination between satellite-induced magnetic noise, the magnetic signals produced by the tether current, and the ambient environment. The magnetometers will alternate these rates: while the one on the tip of the boom operates 16 times per second, the midpoint magnetometer will operate twice per second, and vice versa. Data gathering begins as soon as possible after the satellite is switched on in the payload bay and continues as long as possible during satellite retrieval.

Shuttle Electrodynamic Tether System (SETS)

Peter Banks, Principal Investigator
University of Michigan

This investigation is designed to study the ability of the tethered satellite to collect electrons by determining the current and voltage of the tethered system and measuring the resistance to current flow in the tether itself. The experiment also explores how tether current can be controlled by the emission of electrons at the orbiter end of the system and characterizes the charge that the orbiter acquires as the tether system produces power, broadcasts low-frequency radio waves, and creates instabilities in the surrounding plasma.

The hardware is located on the Multi-Purpose Equipment Support Structure near the center of the payload bay and adjacent to the deployer pallet. A Spherical Retarding Potential Analyzer, mounted on a stem at one corner of the support structure, records ion current density, temperature, and energy and determines the potential of the orbiter. The potential of the surrounding plasma and charged particle density and temperature are measured by a Spherical Langmuir Probe, also mounted on the tower. At the center of the support structure, the Charge and Current Probe measures the return current to the orbiter, recording large and rapid changes in orbiter potential, such as those produced when electrons are conducted from the tether to the orbiter frame or when an electron beam is emitted.

A Fast-Pulse Electron accelerator emits electron beams of 50 and 100 milliamperes (mA) at 1 kiloelectronvolt (keV), stimulating wave activity over a wide range of frequencies. These beams discharge the orbiter and produce electrical changes in the system and can be pulsed with on/off times ranging from 105 to 106 nanoseconds. The Fast-Pulse Electron accelerator is located as close to the Core Electron accelerator as possible and aligned so that the beams of both instruments are adjacent and parallel.

For the Fast-Pulse Electron accelerator beam to be aimed with precision for several experiments, a three-axis fluxgate magnetometer will measure the magnetic fields in the payload bay. These measurements will map the magnetic field lines in the payload bay, which is crucial since electron beams spiral in response to these fields. Using this information, the electron beam can be aimed at various targets, including orbiter surfaces to study the fluorescing that occurs.

Shuttle Potential and Return Electron Experiment (SPREE)

Marylin Oberhardt, Associate Investigator
Department of the Air Force, Phillips Laboratory

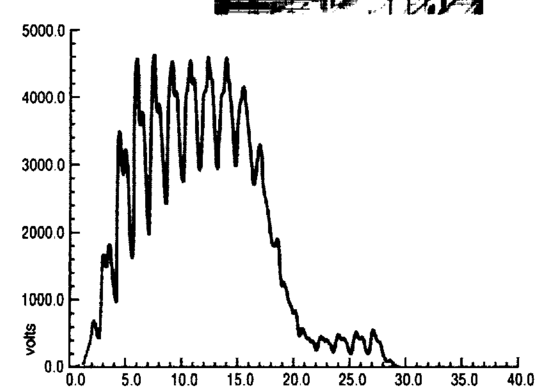
The SPREE will measure the charged particle populations around the orbiter for ambient space conditions and during active TSS-1 operations. SPREE supports the TSS-1 electrodynamic mission by determining the level of orbiter charging with respect to the ambient space plasma, by characterizing the particles returning to the orbiter as a result of TSS-1 electron beam operation and by investigating local wave particle interactions produced by TSS-1 operations.

SPREE is mounted on the portside of the Mission Peculiar Experiment Support Structure (MPESS). The sensors for SPREE are two pairs of Electrostatic Analyzers, each pair mounted on a Rotary Table Motor Drive. The sensors measure the flux of all electrons and ions in the orbiter at the SPREE location. The energy range is sampled either once or eight times per second. The sensors measure the electrons and ions simultaneously over an angular field-of-view of 100 degrees x 10 degrees. This field-of-view combined with the motion of the rotary tables allows SPREE measurements over all angles out of the payload bay.

The Data Processing Unit (DPU) performs all SPREE command and control functions and handles all data and power interfaces to the orbiter. In addition, the DPU processes SPREE data for use by the crew and the ground support team. A portion of the SPREE data is downlinked real-time and the full data set is stored on two SPREE Flight Data Recorders (FDR). Each FDR holds up to 2 Gigabytes of data for post flight analysis.

The SPREE hardware is located on the left side of the Mission Peculiar Equipment Support Structure in this view of the tether payload.

The SETS hardware can be seen in the center of this photograph of the Tether System.



This graph is a premission prediction of the voltage generated across the tether over time. The SETS and DCORE experiments will make detailed measurements of tether generated potential.

Tether Optical Phenomena Experiment (TOP)

Stephen Mende, Associate Investigator
Lockheed

Using a hand-held camera system aboard the orbiter with image intensifiers and special filters, this investigation will provide visual data that may allow scientists to answer a variety of questions concerning tether dynamics and optical effects generated by TSS-1. In particular, this experiment will examine the high voltage plasma sheath surrounding the satellite, by which the electron accelerators return current to the plasma.

In place of the image-intensified conventional photographic experiment package, that has flown on nine previous Shuttle missions, a charge-coupled device electronic system will replace the film back. This new system combines the image intensifier and the charge-coupled device in the same package. The advantage of charge-coupled devices over film is that they allow realtime observation of the image, unlike film, which has to be processed after the mission. It also provides higher resolution in low-light situations than conventional video cameras.

The imaging system will operate in four configurations: filtered, interferometer, spectrographic, and filtered with telephoto lens. The basic system consists of a 55 mm F/1.2 or 135 mm F/2.0 lens attached to the charge-coupled device equipment. Various slide mounted filters, an airspaced Fabry Perot interferometer, and spectrographic equipment will be attached to the equipment so that the crew can perform various observations.

For a current to be developed by the Tethered Satellite System, electron accelerators have to return electrons to the plasma surrounding the orbiter. The interaction between these electron beams and the plasma is not well understood. By using the charge-coupled device to make visual, spectrographic, and interferometer measurements, this process, and how it affects both the spacecraft and the plasma, can be better understood.

Thruster gases may also play a critical role in Tethered Satellite System operations. By observing optical emissions during the build-up of the system-induced electromotive force and during gas discharges, scientists can gain a better understanding of the interaction between a charged spacecraft and the plasma environment and how the current system closes at the poles of the voltage source.

Investigation of Electromagnetic Emissions for Electrodynamic Tether (EMET)

Robert Estes, Principal Investigator
Smithsonian Astrophysical Observatory

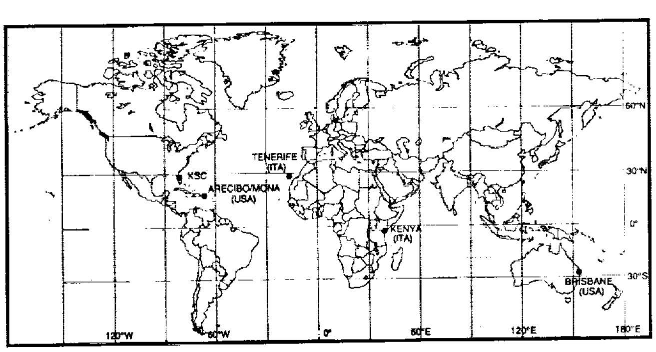
Observations at the Earth's Surface of Electromagnetic Emissions by TSS (OESEE)

Giorgio Tacconi, Principal Investigator
University of Genoa

One goal of these investigations is to determine the extent that waves generated by the tether interact with trapped particles and precipitate them. Wave-particle interactions are thought to occur in the Van Allen radiation belts where waves transmitted from Earth jar regions of energetic plasma and cause particles to rain into the lower atmosphere. Although poorly understood, wave-induced precipitation is important because it may affect activity in the atmosphere closer to Earth. Various wave phenomena that need to be evaluated are: discrete emissions, lightning-generated whistlers, and sustained waves such as plasma hiss. Wave receivers on the satellite detect and measure the characteristics of the waves, and particle detectors sense wave-particle interactions, including those that resemble natural interactions in radiation belts. Ground stations may also be able to detect faint optical emissions produced as waves disturb particles and enhance ionization.

Another goal is to determine how well the Tethered Satellite System can broadcast from space. Ground-based transmissions, especially below 15 kHz, suffer from inefficiency. Most of the power supplied to the antenna, large portions of which are buried, is absorbed by the ground. Because of the large antenna size and consequent high cost, very few ground-based transmitters operate at frequencies below 10 kHz. Since the Tethered Satellite System operates in the ionosphere, it should radiate waves more efficiently. For frequencies less than 15 kHz, the radiated signals from a 1-kW space transmitter may equal that from a 100-kW ground transmitter.

Waves generated by the tether will move in a complex pattern within the ionosphere and into the magnetosphere. Magnetometers at several locations in the chain of worldwide geomagnetic observatories and extremely low-frequency receivers at the Arecibo Radio Telescope facility, Puerto Rico, will try to measure the emissions produced and track the direction of the waves when electron accelerators in the orbiter payload bay pulse the tether current over specific land reference points. An Italian ocean surface and ocean bottom observational facility also provides remote measurements of TSS-1 emissions. These instruments measure emissions in the frequency range from dc to about 3 kHz.



(Far Left) Ground stations around the world will attempt to detect and measure the different types of electromagnetic waves generated by the TSS.

The Arecibo Radio Observatory will be the focus of Caribbean operations during TSS-1.

The Investigation and Measurement of Dynamic Noise in the TSS (IMDN)

Gordon Gullahorn, Principal Investigator
Smithsonian Astrophysical Observatory

Theoretical and Experimental Investigation of TSS Dynamics (TEID)

Silvio Bergamaschi, Principal Investigator
Institute of Applied Mechanics

TSS-1 will be the longest structure ever flown in space, and its dynamic behavior will involve oscillations over a wide range of frequencies. Although the major dynamic characteristics are readily predicted, future applications of long tethers demand verification of the theoretical models. Moreover, higher frequency — essentially random — oscillations are more difficult to predict. This seemingly random behavior is called "dynamic noise" by analogy to radio static, and an understanding of its nature is needed for possible future uses of tethered platforms for microgravity facilities and for studying variation in the small scale structure of Earth's gravitational and magnetic fields, caused by variations in the composition and structure of Earth's crust. These gravitational variations may be related to mineral sources.

These two investigations will analyze data from a variety of instruments to investigate Tethered Satellite System dynamics. Primary instruments will be accelerometers and gyros on board the satellite; tether tension and length measurements and magnetic field measurements will also be used. The dynamics will be observed realtime at the Science Operations Center and subjected to detailed postflight analysis. Basic models and simulations will be verified (and extended or corrected as needed); these can then be used confidently in the design of future tethered missions, both of Tethered Satellite System and of other designs. The dynamic noise inherent to the system will be analyzed to determine the suitability of tethered systems to serve as platforms for sensitive observations of the geomagnetic and gravitational fields, and if required, to develop possible damping methods.

Theory and Modeling in Support of Tethered Satellite Applications (TMST)

Adam Drobot, Principal Investigator
Science Applications International Corporation

This investigation will develop numerical models of the tether system's overall current and voltage characteristics, of the plasma sheaths that surround the satellite and the orbiter, and of the system's response to the operation of the electron accelerators. Also of interest are the plasma waves generated as the tether current is modulated. All data collected on the mission will be combined to refine these models.

Two- and three-dimensional mathematical models of the electrodynamics of the tether system will be developed to provide an understanding of the behavior of the electric and magnetic fields, and the charged particles, surrounding the satellite. These studies are expected to model the plasma sheath surrounding the satellite under a variety of conditions. This includes those in which the motion of the tether and neutral gas emissions from thrusters are not considered, those that incorporate the effects of tether motion, and those that factor in the gas emissions.

The sheath surrounding the orbiter has several unique features that are related to the ability of the electron accelerators to control the orbiter's potential. Models of the orbiter's sheath when small currents are flowing in the tether will consider the potential of the orbiter to be negative; for large currents, models will be developed assuming a positive orbiter potential. In this way, the sheath structures and impedance characteristics of the orbiter/plasma interface can be studied.

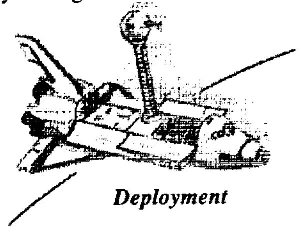
The response of plasma to the electromotive force produced by the motion of the tether system through the geomagnetic field is another focus of this investigation. Using data from other studies, kinetic plasma processes will be analyzed or numerically simulated by computer to model the reaction of the ionosphere to the passage of TSS-1.

This investigation also models the relationship between the efficiency of wave generation and the amount of current flowing through the tether to examine how the tether antenna couples to the ionosphere, and how ultra- and very-low-frequency waves propagate through the ionosphere. These models will complement the information gathered by TSS-1 instruments with emissions recorded at ground stations.

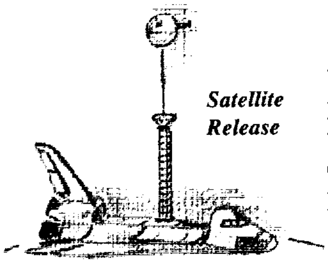
The TMST experiment has developed numerical models of the TSS current and voltage characteristics. Graphic displays of data during the mission will be similar to this premission prediction that examined a case where the satellite was biased to 200 volts.

Mission Scenario

Twenty-four hours before deployment, a crew member at a console in the aft flight deck activates the Tethered Satellite System, to check the different systems. The satellite systems are checked electronically through two cables, called umbilicals, which provide electrical power and link the satellite and orbiter instruments. Portions of the pallet-mounted science payload gather data during different orbital phases and attitudes to establish basic operating characteristics and obtain general measurements of the Shuttle's electrical and optical environment. Engineers and scientists compare these baseline data with measurements made later in the mission to determine the effects of the system on the surrounding plasma.



Deployment



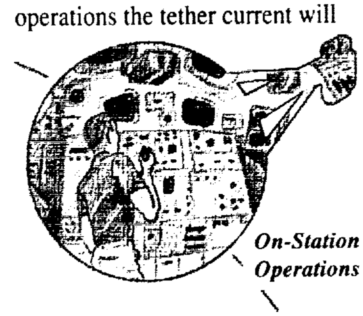
Satellite Release

When these operations are complete, satellite internal power is switched on, and a crew member releases the latches and the first umbilical cable. The 12-m satellite deployment boom slowly extends from its housing, lifting the satellite out of the payload bay. Once the boom is extended, a second umbilical is used for a last-minute checkout of the satellite's support systems at the boom tip and disconnected. The satellite is then sent on its way as its thrusters fire, gently lifting it away from the docking ring.

Using a tether reel assembly, the crew reels the satellite out slowly and carefully, as they and ground controllers monitor status and develop a sense for tether control. A sensor at the tip of the deployment boom continuously measures tether tension, while a second sensor at the base of the boom measures the speed of the tether. This information is fed to the deployer computer that controls the reel assembly. Once it passes 6 km, the satellite is spun at 0.25 rpm so that sensing instruments in the satellite and the orbiter can measure the response of the system as it travels through the electrical and magnetic fields in the ionosphere.

Six hours pass as the satellite steadily and gradually approaches Station 1, its fully deployed position 20 km from the Shuttle. Ten hours of operations begin with the satellite's rotation being stopped so that investigations can be performed on tether dynamics over the course of an orbit. After these investigations, gas-jet thrusters spin the satellite, so it rotates 0.7 revolutions each minute. The Deployable/Retrievable Booms extend to their first stopping point to measure the satellite's particle and field environment. The booms remain at this first point for an entire orbit, and then move further out to a second stopping point to repeat the process. The third and final measuring point is at full extension.

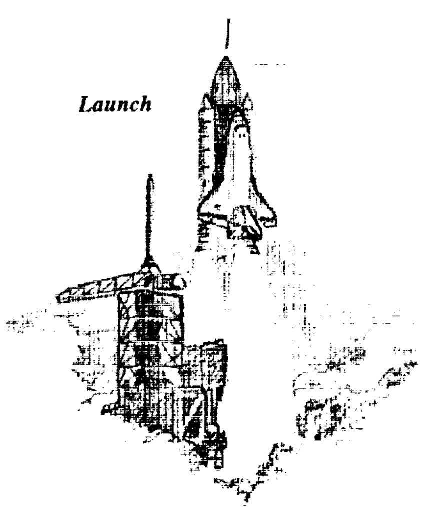
Instruments in the satellite and the payload bay stimulate the ionosphere, measure the resulting response, determine the power generation properties of the entire tether system, and characterize the surrounding environment at three electrodynamic configurations. Direct current operations will permit the study of the most fundamental state of the electrodynamic Tethered Satellite System, allowing the tether current to determine its own behavior. During current-voltage operations the tether current will be stepped rapidly through several different levels to let the relationship between the tether current and the magnitude of the tether's motional electromotive force to be studied. Alternating current operations will permit the investigation of low-frequency radio and plasma waves excited by modulating the tether current. In addition, several variations of these configurations will be used for particular experiments and the overflight of ground stations looking for Tethered Satellite System-induced radio emissions. Approximately halfway through these operations, the satellite's rotation is reversed so that the tether will not be twisted when retrieval begins. However, the tether can be retrieved twisted if necessary.



On-Station Operations

After Station 1 operations, retrieval operations begin with the reel assembly winding in the tether. The satellite, under computer control, approaches to within 2.4 km of the orbiter, a position known as Station 2, where it stops for 5 hours to dampen dynamic perturbations and gather additional engineering and science data. Many of the same experiments conducted at

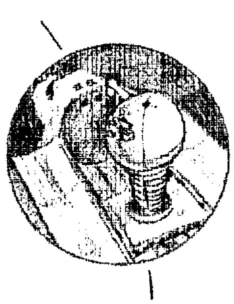
Launch



Station 1 will be repeated, including the boom measurements at three different distances from the satellite. While stopped, any oscillations that have developed in the system will be damped to an acceptable level.

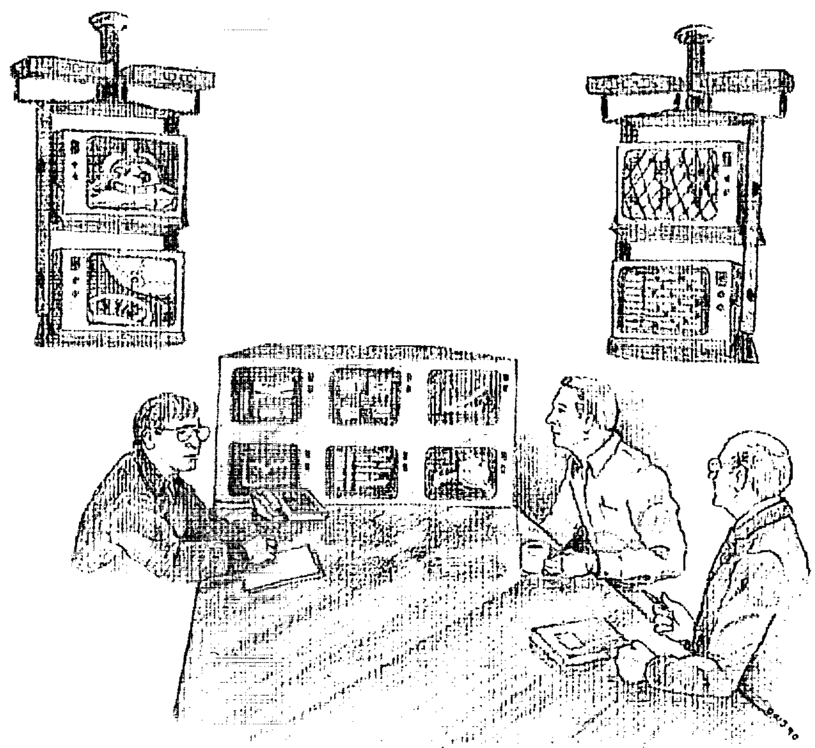
Retrieval resumes so that the final stages of retrieval and docking take place in daylight. When the satellite is 200 m from the orbiter, crewmembers take over tether control. Using radar, closed-circuit television images, computer displays, and looking out the orbiter's windows to monitor the satellite's position and speed, crewmembers gradually ease the satellite back into the docking ring on the boom by controlling the tether reel take-up rate and firing the Shuttle's maneuvering thrusters. After docking, the deployer boom is retracted into its canister, and the satellite relatched to the satellite support structure. The mission timeline provides for post-retrieval operations at this time, allowing scientists to make further measurements with the satellite instruments. Once these operations are complete, satellite electrical power is turned off.

Retrieval



Science instruments mounted in the cargo bay may continue to take readings of the Shuttle environment after docking. When these final measurements are completed, the instruments are turned off, and the Tethered Satellite System enters a quiet state until the Shuttle returns to Earth.

During the TSS-1 mission, principal investigators and their support teams will monitor and direct science activities from the Science Operations Center located at Johnson Space Center. In the operations center, they will be able to evaluate the quality of data obtained, replan science activities as needed, and direct adjustments to the instruments. After the flight, the Science Operations Center will support data distribution and analysis. Deployer and satellite systems will be monitored by the Payload Operations Control Center at Johnson Space Center.



Investigators in the Science Operations Center

The TSS-1 Crew

With a number of experiments sharing equipment, the crew of TSS-1 will work closely with the principal investigators to monitor results, initiate changes, and control satellite operations. The crew member controlling this process will have to rapidly analyze and synthesize data from such sources as radar, computer displays, and direct visual observation.

The crew for the first Tethered Satellite System mission brings to it a variety of experience which allow them to readily meet these challenges. The TSS-1 crew has trained extensively for the mission and will work closely with the principal investigators during the mission.

The Science Crew

Three scientists—Jeffrey A. Hoffman, Franklin R. Chang-Diaz, and Claude Nicollier—will be the mission specialists for TSS-1. Mission specialists are career astronauts who have been trained to operate orbiter hardware, as well as specific mission experiments.

Jeffrey A. Hoffman, the Payload Commander, will be on his third mission. He was selected by NASA in January 1978 and became a mission specialist in August 1979. He graduated from Amherst College in 1966 with a B.A. degree in astronomy (summa cum laude), earned a Ph.D. in 1971 from Harvard University in astrophysics, and in 1988 earned an M.S. degree in materials science from Rice University. He made the first Space Transportation System contingency spacewalk in 1985 in an attempt to rescue a malfunctioning satellite. His research interest lies in high-energy astrophysics and his second spaceflight was the Astro-1 ultraviolet and X-ray observatory mission.

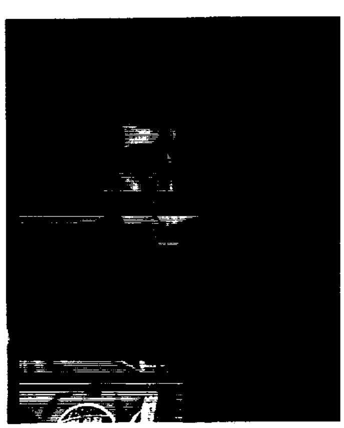
Franklin R. Chang-Diaz was selected in May 1980 as an astronaut candidate and became a mission specialist in August 1981. He earned his B.S. degree in mechanical engineering in 1973 from the University of Connecticut and his Ph.D. in applied plasma physics in 1977 from the Massachusetts Institute of Technology. He has been heavily involved with the United States controlled fusion program and has helped design new concepts in rocket propulsion based on high-temperature plasmas. His previous spaceflights were STS 61-C in January 1986 and STS 34 in October 1989.

Claude Nicollier is a research scientist selected in July 1978 by the European Space Agency (ESA) to be one of three Europeans to train as payload specialists for the Spacelab 1 mission. Under an agreement between ESA and NASA, he joined the NASA astronaut candidates selected in July 1980 for astronaut training as a mission specialist. He earned a B.S. degree in physics from the University of Lausanne, Switzerland, in 1970 and an M.S. degree in astrophysics in 1975 from the University of Geneva. He has helped develop retrieval techniques for the Tethered Satellite System, taken part in infrared astronomy programs, is a certified test pilot, and is a captain in the Swiss Air Force. This will be his first space mission.

Two Italian scientists—Franco Malerba and Umberto Guidoni—will be the prime and alternate payload specialists for the mission. Payload specialists are astronauts provided by a payload sponsor, who have been trained to perform specific science duties.

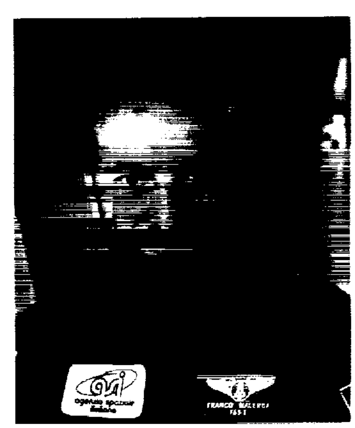
Franco Malerba earned his B.S. in electronics engineering in 1970 (cum laude) and his Ph.D. in physics, specializing in biophysics, in 1974 from the University of Genoa, Italy. He was selected as one of the European payload specialist candidates for the first Spacelab mission and served as a staff member at the European Space Agency Technical Center Space

Dr. Jeffrey A. Hoffman



Dr. Franklin R. Chang-Diaz

Capt. Claude Nicollier



Dr. Franco Malerba

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Science Department, where he participated in a space plasma experiment that flew on Spacelab 1. He has performed research in membrane biophysics at the U.S. National Institutes of Health and the Italian National Research Council (CNR) and served as a consultant to Digital Equipment Corporation, Europe, for more than a decade. He has also performed research on signal detection methodologies for sonar data systems. Dr. Malerba will be the first Italian national in space.

Umberto Guidoni is a co-investigator on the Research on Electrodynamic Tether Effects experiment and was appointed the Project Scientist for it in 1989. In this capacity, he was responsible for integration of the experiment into the TSS-1 satellite. He earned his Ph.D in astrophysics from the University of Rome, Italy, in 1978. He has served as a staff scientist in the solar energy division of ENEA (National Council for Renewable Energy) and became senior researcher at the CNR Space Physics Institute in 1984. He received a CNEN (the Italian Nuclear Energy National Committee) post-doctoral fellowship for 1979-80 in the thermonuclear fusion field.

Dr. Umberto Guidoni

The Orbiter Crew

The commander, pilot, and flight engineer complete the TSS-1 crew. Veteran NASA astronaut Loren J. Shriver serves as the mission commander, Andrew M. Allen serves as the pilot, and Marsha S. Ivins as the flight engineer. The mission commander has responsibility for all operations during the flight, while the pilot and flight engineer assist in these efforts.

Col. Loren J. Shriver (USAF), the Mission Commander, will be on his third mission. He graduated from the U.S. Air Force Academy in 1967 with a B.S. in aeronautical engineering and earned an M.S. in astronautical engineering from Purdue in 1968. Selected as an astronaut candidate in January 1978 and completing training as a pilot in August 1979, Shriver served as pilot on STS-51C, a Department of Defense Mission, and as mission commander on STS-31 for the deployment of the Hubble Space Telescope.

Major Andrew M. Allen (USMC), the Pilot, will be on his first mission. He was selected as an astronaut candidate in June 1987 and qualified as a pilot in August 1988. He graduated from Villanova University in 1977 with a B.S. in mechanical engineering and graduated from the Marine Weapons and Tactics Instructor Course, the U.S. Navy Test Pilot School and the Naval Fighter Weapons School (Top Gun). He has logged more than 3,000 flight hours in some 30 different aircraft.

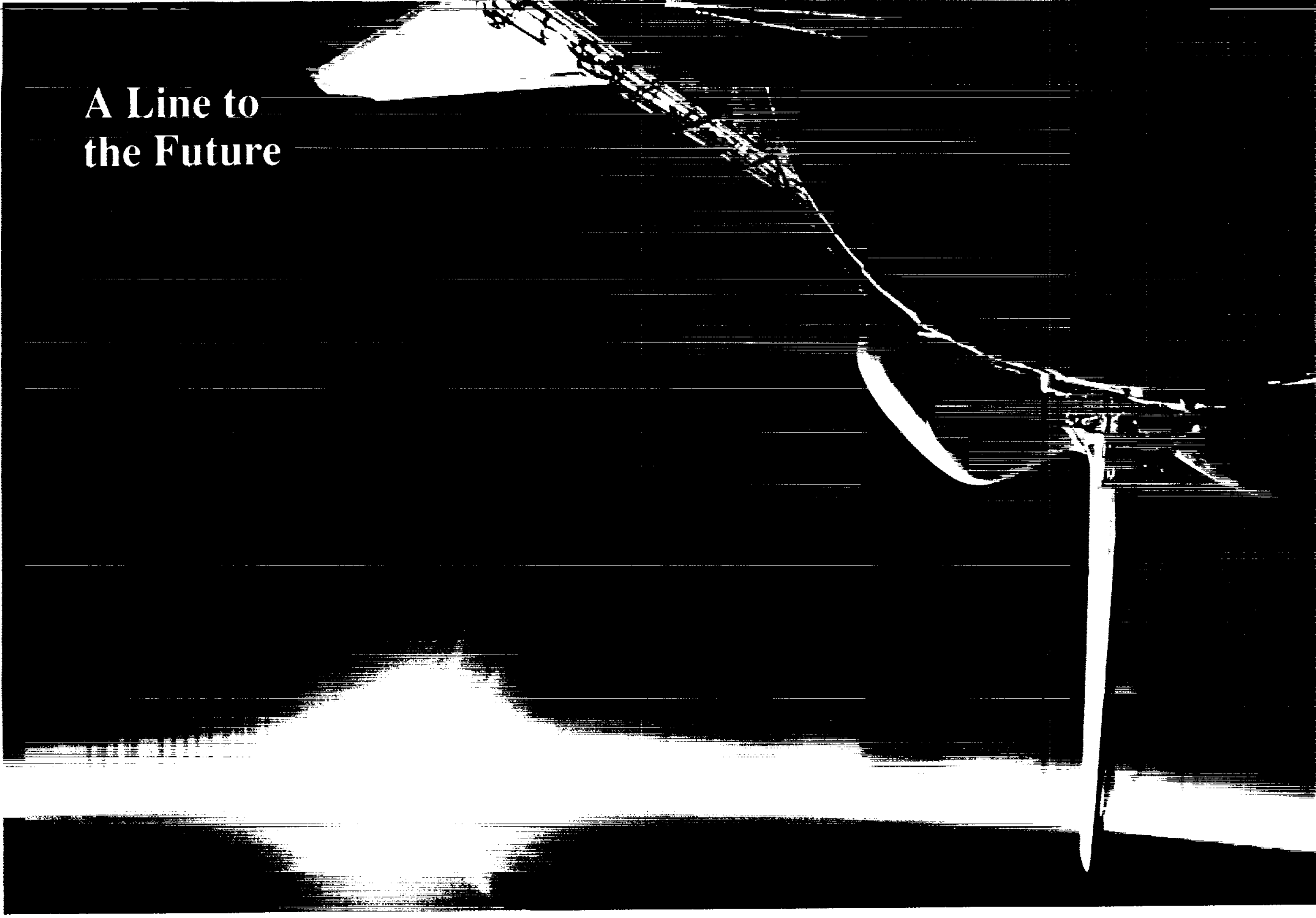
Marsha S. Ivins, the flight engineer, will be on her second mission. She was selected as an astronaut candidate in May 1984, qualified as a mission specialist in June 1985 and served as a mission specialist on STS-32, which retrieved the Long Duration Exposure Facility. She graduated from the University of Colorado in 1973 with a B.S. in aerospace engineering and holds a multi-engine Airline Transport Pilot License, a single engine airplane, land, sea and commercial licenses, and instrument, multi-engine and glider flight instructor ratings. She has logged more than 4,500 hours in civilian and NASA aircraft.

Col. Loren J. Shriver

Maj. Andrew M. Allen

Marsha S. Ivins

A Line to the Future



A tether cuts across magnetic fields in low-Earth orbit, converting some of the spacecraft's orbital energy into electrical power. Another tether is a giant antenna, transmitting electromagnetic waves that carry messages to Earth. An instrumented, aerodynamic model is being towed by a tether through the only wind tunnel that can provide exact high-altitude hypersonic flight conditions — the upper atmosphere. At a space station, a robot craft on its way to capture a satellite is released from a tether and propelled into a higher orbit, and later, the Shuttle is released on a tether from a remote docking port and lowered to the right altitude for return to Earth; no fuel is expended for either maneuver. Still farther away, a tethered probe retrieves samples from the dusty, red Martian landscape and returns them to the parent spacecraft for analysis.

Tethers may make these scenarios possible. Many ideas for using tethers in space are being advanced, but before the scenarios become realities, the concepts behind them must be proven. Several steps are being taken to bring the ideas to fruition. The TSS-1 mission is crucial for demonstrating that satellites on very long tethers can be successfully deployed and retrieved in space. It may also determine whether conducting tethers can generate high electrical potentials and drive currents, possibly leading to the production of power for future spacecraft. Successful Tethered Satellite System flights may lead to the following possible uses for tethers.

Generating Electrical Power

A tether system could supply power to an orbiting spacecraft, supplementing solar arrays and batteries or serving as a backup emergency power system. The longer the tether, the higher the electrical voltage it will produce. The 20-km long tether used in the TSS-1 mission will generate up to approximately 5,000 volts, while a 96-km long tether could generate as much as 15,000 volts. The total amount of power produced by the system will depend on conditions in the ionosphere and the capabilities of the satellite to collect electrons. One of the questions TSS-1 may help to answer is how much current can be extracted from the ionosphere.

Spacecraft Propulsion

Active Spacecraft Propulsion

After TSS-1 characterizes the electrodynamic properties of conductive tethers, future missions may be used to demonstrate tether propulsion. If the direction of the current in the tether is reversed, the force caused by its interaction with Earth's magnetic field changes from drag to propulsion. If an onboard power supply, such as a solar array, pumps electricity into the tether, the current direction is reversed, making the tether into an electric motor. The electrical energy flowing into the tether is transformed into motional energy for the spacecraft, causing it to gain altitude; thus, the spacecraft's orbit is boosted without using precious fuel.

Passive Spacecraft Propulsion
Non-conducting tethers can also propel spacecraft. A tether transfer system could place objects to higher or lower orbits without excessive use of rocket engines and fuel consumption. For example, if a satellite tethered above a space station is released, it gains momentum and moves into a higher orbit while the station's orbit is lowered. Conversely, if the Shuttle is lowered from a space station on a tether and released, it loses altitude and the station is boosted into a higher orbit.

A tethered elevator could be used for many transportation needs: moving payloads up and down between a space station and remote laboratories or platforms; taking laboratories to different gravity levels along a tether; and returning materials to Earth for analysis.

Broadcasting from Space

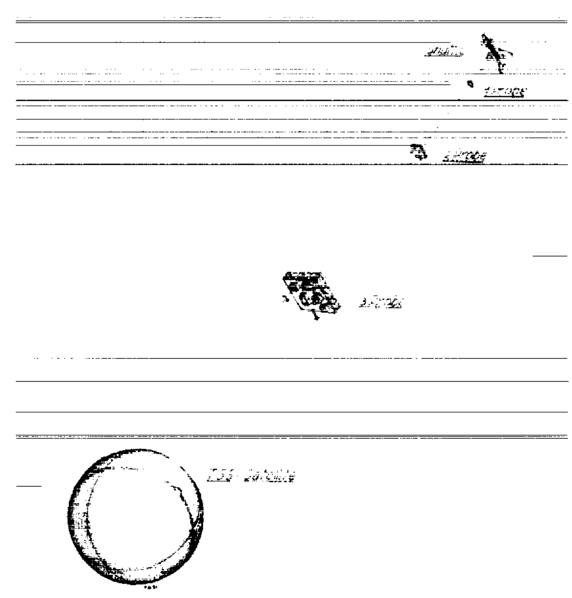
Wave generation and propagation are the focus of some TSS-1 experiments. Travelling through the ionospheric plasma, the current-carrying tether radiates electromagnetic waves from its whole length, and especially from its two ends. By modulating the current (turning it on and off at desired frequencies in the same manner that a radio station operates), it may be possible to use the waves for communications. A 20- to 100-km long tether deployed from the Space Shuttle could produce ultra-low-frequency (ULF) waves from 3 to 30 hertz (Hz); extremely-low- frequency (ELF) waves from 30 to 300 Hz; and very-low-frequency (VLF) waves from 300 to 3,000 Hz. Ground-based antennas, especially below 15,000 Hz, are extremely inefficient as most of the power pushed into them goes into heating the ground. Broadcasting from space in these bands could not only prove to be much more efficient but also extend the radio frequencies available.

Studying the Atmosphere

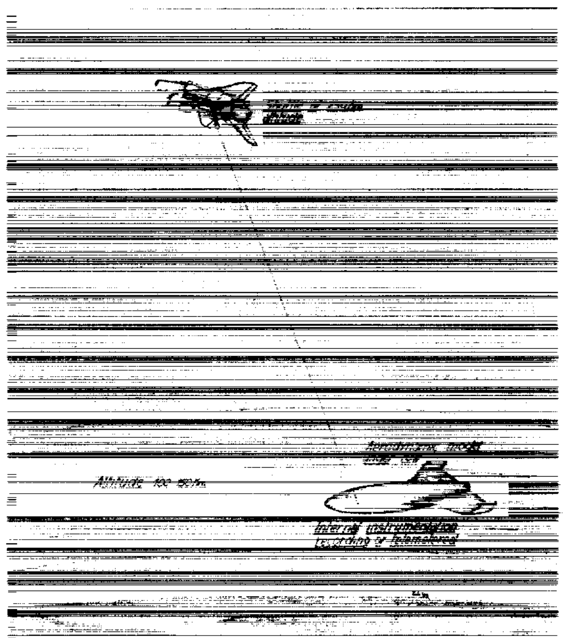
In an atmospheric mission, the Shuttle payload bay would face Earth, and the satellite could be lowered to a fringe area of the atmosphere about 130 km above Earth's surface on tethers up to 100 km long. Sounding rockets have provided vertical profiles of this atmospheric region in a few isolated spots, but it has not been studied on a global basis because atmospheric drag prevents satellites from orbiting below approximately 180 km.

With the Tethered Satellite System, the region down to 130 km can be surveyed for days at a time because the large inertial mass of the orbiter overcomes the satellite's relatively small drag. Satellite instruments immersed in the atmosphere can measure chemical constituents, map global current systems and magnetic and electric fields, track winds, and monitor pollution and ozone depletion. Measurements from this previously inaccessible region will improve models of atmospheric chemistry and dynamics.

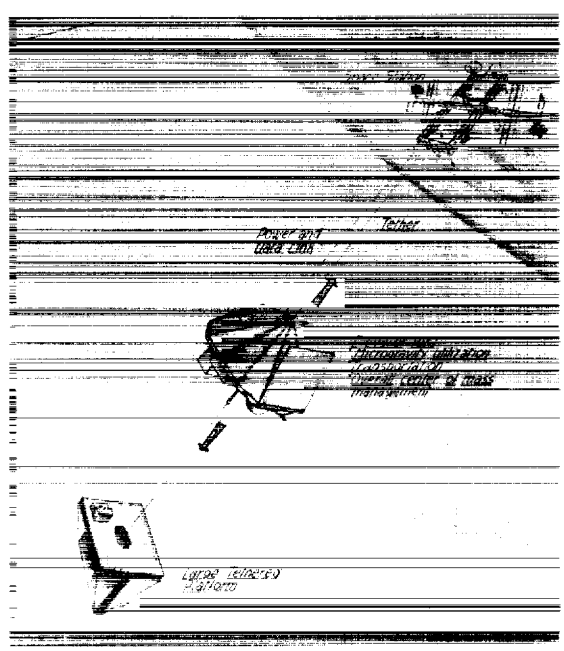
The TSS-1 hardware can be reconfigured for follow-on atmospheric missions. The satellite can be outfitted with additional insulation to control heating, atmospheric instruments, and aerodynamic stabilizers so that most instruments can face forward. Five times longer than on TSS-1, the tether would be nonconducting. More advanced missions may string probes downward to different points along a tether to collect data simultaneously at different altitudes.



Movable platforms on an atmospheric tether could allow scientists to gather extensive, global data about the upper atmosphere simultaneously at a variety of altitudes, possibly leading to an understanding of phenomena such as the ozone hole over the South Pole.



Wind tunnels can only partially simulate flight conditions in the upper atmosphere. By using tethers to place instrumented models in this region, engineers could gather true performance data on proposed designs for aerospace craft.



A movable laboratory on a tether could be positioned at the exact level of gravity required by an experimenter.

Using the Atmosphere as a Wind Tunnel

Wind tunnels on Earth are used to test the effects of aerodynamic flow around objects, including the thermal stability of structures and materials. Tethers can give engineers access to the largest, open, continuous wind tunnel — the atmosphere. A tether anchored to the Space Shuttle can lower an instrumented aerodynamic model 100- to 150-km into the outer atmosphere. Here, it can be exposed to ranges of conditions that are impossible to reproduce in wind tunnels: heat transfer, drag, strong air flows, and turbulence. Data gathered from these tests can be used to improve spacecraft reentry and develop aerobraking techniques that take advantage of the atmosphere to slow a spacecraft's speed. A Shuttle tethered aerothermodynamic research facility is being studied for demonstration on a future mission.

Tether-Controlled Microgravity

When a tethered satellite is deployed from a spacecraft, the center of mass for the total system shifts to a point between the two objects. At some point near this center of mass, an object attached to the tether will experience no relative acceleration, or zero-gravity. By changing the object's position on the tether, different accelerations, or gravities, can be obtained. A portable laboratory that can crawl to different positions along the tether can be exposed to various levels of microgravity; experiments exploring the effects of gravity on materials and biological samples will benefit from such a facility. Conversely, a tethered ballast could be used to "tune" a space station microgravity lab. By changing the length of the tether, the lab's center of gravity could be changed to account for such things as the use of consumables, area movement, and other factors affecting microgravity conditions.

Tethers could also be used to simulate gravity in space. By attaching a tether between two objects, such as a living module and an automated processing facility, and then rotating the two around a common point at the center of the tether, the "artificial gravity" of centrifugal force can be created.

Quick Reference To Experiments

Acronym	Title	Investigator/Organization	Page No.
EMET	Investigation of Electromagnetic Emissions by the Electrodynamic Tether	R. Estes, PI/SAO	p. 26
IMDN	Investigation and Measurement of Dynamic Noise in the TSS	G. Gullahorn, PI/SAO	p. 27
OESEE	Observations at the Earth's Surface of Electromagnetic Emissions by TSS	G. Tacconi, PI/U. of Genoa	p. 26
RETE	Research on Electrodynamic Tether Effects	M. Dobrowolny, PI/CNR	p. 24
ROPE	Research on Orbital Plasma Electrodynamics	N. Stone, PI/MSFC	p. 23
SETS	Shuttle Electrodynamic Tether System	P. Banks, PI/U. of Michigan	p. 25
SPREE	Shuttle Potential and Electron Return Experiment	M. Oberhardt, AI/Phillips Laboratory	p. 25
TEiD	Theoretical and Experimental Investigation of TSS Dynamics	S. Bergamaschi, PI/Inst. of Applied Mechanics	p. 27
TEMAG	Magnetic Field Experiment for TSS Missions	F. Mariani, PI/U. of Rome	p. 24
TMST	Theory and Modelling in Support of Tether	A. Drobot, PI/SAIC	p. 27
TOP	Tether Optical Phenomena Experiment	S. Mende, AI/Lockheed	p. 26
DCORE	Deployer Core Equipment	C. Bonifazi, PI/ASI	p. 23
SCORE	Satellite Core Equipment	C. Bonifazi, PI/ASI	p. 23

Further Reading

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Suggested Terms for Database Searches

Advanced Planetary Exploration
Advanced Propulsion; Advanced Launch Systems
Alfvén
Beanstalk
Electrodynamic Interactions
Electrodynamic Tethers
Funiculars
Orbiter Monitor Transfer
Skyhook
Solar Sails
Tether(s): History, Constellations, and Space

Glossary of Abbreviations and Acronyms

A: Amperes
ac: Alternating Current
Ah: Ampere hours
AI: Associate Investigator
AMPS: Atmospheres and Magnetospheres and Plasmas (NASA working group)
bps: Bits per second
CEA: Core Electron Accelerator
cm: Centimeters
CNR: Consiglio Nazionale delle Ricerche — Italian National Research Council
dc: Direct Current
DCORE: Deployer Core Equipment
deg: Degrees
deg C: Degrees Centigrade
deg/sec: Degrees per second
ELF: Extremely Low Frequency
EMET: Investigation of Electromagnetic Emissions by the Electrodynamic Tether
eV: Electron Volt
FPEA: Fast Pulse Electron Accelerator
g: Gravity
Hz: Hertz
IMDN: Investigation and Measurement of Dynamic Noise in the TSS
IWG: Investigator Working Group
JSC: Johnson Space Center
K: Degree Kelvin
kbps: Kilobits per second
keV: Thousand (Kilo) Electron Volts
kg: Kilogram
kHz: Kilohertz
KSC: Kennedy Space Center
kV: Kilovolt
kW: Kilowatt
m: Meter
mA: Milliamperes
MHz: Megahertz
MOU: Memorandum Of Understanding
MPESS: Multi-Purpose Equipment Support Structure
MSFC: Marshall Space Flight Center
NASA: National Aeronautics and Space Administration
nT: Nanotesla
OESEE: Observations at the Earth's Surface of Electromagnetic Emissions by TSS
PI: Principal Investigator
POCC: Payload Operations Control Center
PSN: Piano Spaziale Nazionale — Italian National Space Plan
RETE: Research on Electrodynamic Tether Effects
ROPE: Research on Orbital Plasma Electrodynamics
SAO: Smithsonian Astrophysical Observatory (Cambridge, Massachusetts)
SCORE: Satellite Core Equipment
SETS: Shuttle Electrodynamic Tether System
SPREE: Shuttle Potential and Return Electron Experiment
STS: Space Transportation System (Numeric designation indicates specific mission)
T: Tesla (unit of measure for magnetic flux density)
TAG: Three-axis Accelerometer Gyro
TEMAG: Magnetic Field Experiment for TSS Missions
TEID: Theoretical and Experimental Investigation on TSS Dynamics
TMST: Theory and Modeling in Support of Tether
TOP: Tether Optical Phenomena Experiment
TSS: Tethered Satellite System
TSS-1: First Tethered Satellite System Mission. TSS deployed spaceward and electrodynamic tests conducted
ULF: Ultra Low Frequency
VLF: Very Low Frequency
W: Watt

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