SECTION 1.0 TETHER FLIGHTS

1.1 The Tethered Satellite System Program: TSS-1 and TSS-1R Missions

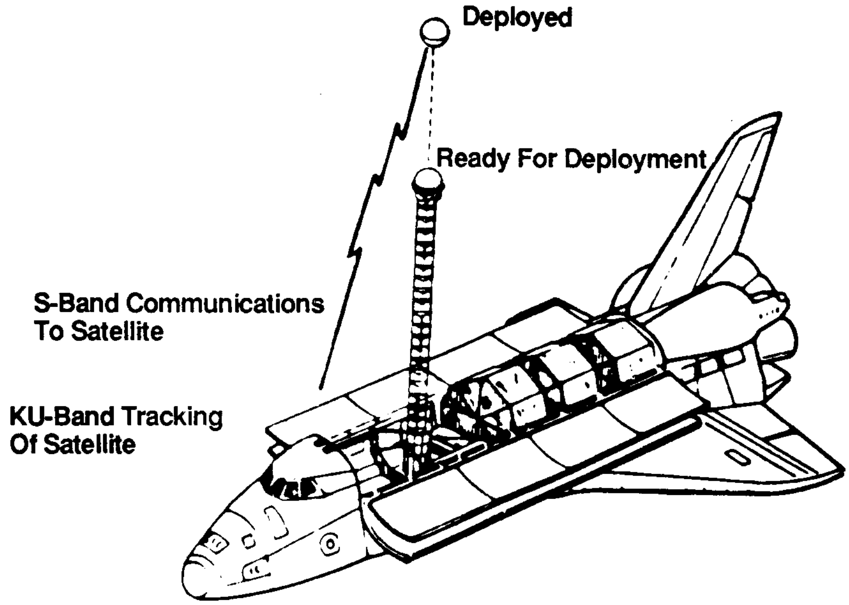

Figure 1.1 TSS-1 Satellite and Tether Attached to 12 Meter Extendible Boom

The Tethered Satellite System (TSS) was proposed to NASA and the Italian Space Agency (ASI) in the early 1970's by Mario Grossi, of the Smithsonian Astrophysical Observatory, and Giuseppe Colombo, of Padua University. A science committee, the Facilities Requirements Definition Team (FRDT), met in 1979 to consider the possible scientific applications for long tethers in space and whether the development of a tethered system was justified. The FRDT report, published in 1980, strongly endorsed a Shuttle-based tether system. A NASA-ASI memorandum of understanding was signed in 1984, in which NASA agreed to develop a deployer system and tether and ASI agreed to develop a special satellite for deployment. A science advisory team provided guidance on science accommodation requirements prior to the formal joint NASA-ASI Announcement of Opportunity for science investigations being issued in April, 1984.

The purpose of the TSS was to provide the capability of deploying a satellite on a long, gravity-gradient stabilized tether from the Space Shuttle where it would provide a research facility for investigations in space physics and plasma-electrodynamics. Nine investigations were selected for definition for the first mission (TSS-1) in July, 1985. In addition, ASI agreed to provide CORE equipment (common to most investigations) that consisted of two electron guns, current and voltage monitors and a pressure gauge mounted on the Orbiter, and a linear accelerometer and an ammeter on the satellite. NASA agreed to add a hand-held low light level TV camera, for night-time observation of the deployed satellite. The U.S. Air Force Phillips Laboratory agreed to provide a set of electrostatic charged particle analyzers, mounted in the Shuttle's payload bay, to determine Orbiter potential.

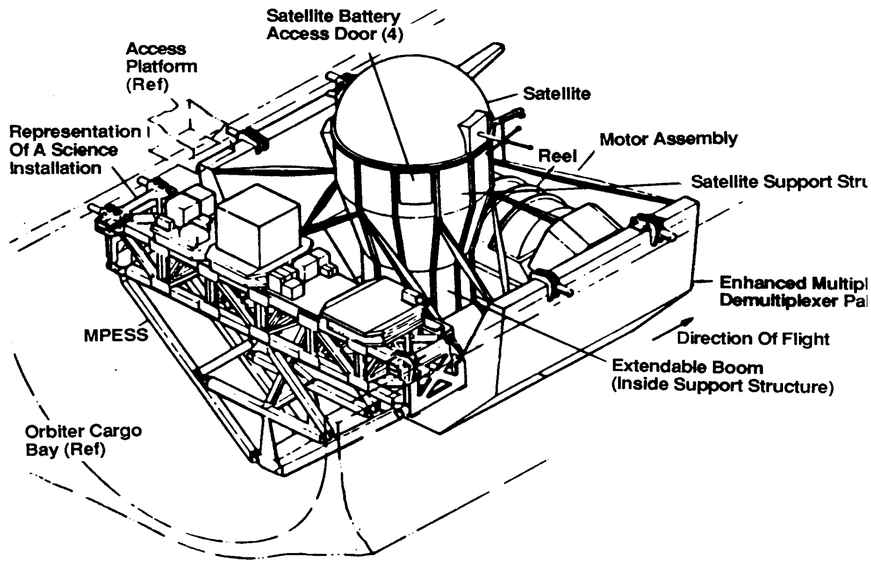

Figure 1.2 TSS-1 Configuration on Orbiter

During TSS-1, which was launched July 31, 1992 on STS-46, the Italian satellite was deployed 268 m directly above the Orbiter where it remained for most of the mission. This provided over 20 hours of stable deployment in the near vicinity of the Orbiter--the region of deployed operations that was of greatest concern prior to the mission. The TSS-1 results conclusively show that the basic concept of long gravity-gradient stabilized tethers is sound and settled several short deployment dynamics issues, reduced safety concerns, and clearly demonstrated the feasibility of deploying the satellite to long distances--which allowed the TSS-1R mission to be focused on science objectives.

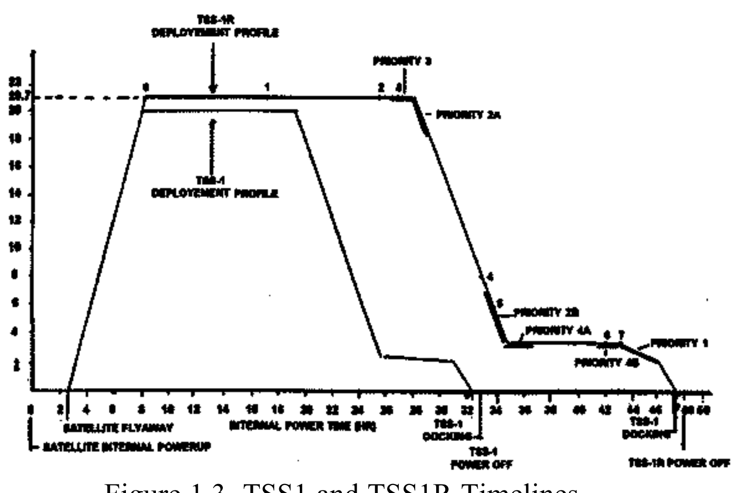

Figure 1.3 TSS1 and TSS1R Timelines

The TSS-1R mission was launched February 22, 1996 on STS-75. During this mission, the satellite was to have been deployed 20.7 km above the Space Shuttle on a conducting tether where it was to remain for more than 20 hours of science experiments, followed by a second stop for an additional seven to nine hours of experiments at a deployed distance of 2.5 km.

The goals of the TSS-1R mission were to demonstrate some of the unique applications of the TSS as a tool for research by conducting exploratory experiments in space plasma physics. It was anticipated that the motion of a long conducting tether through the Earth's magnetic field would create a large motional emf that would bias the satellite to high voltages and drive a current through the tether system. The circuit for the tether current would be closed by a large external loop in the conducting ionospheric plasma where an array of physical phenomena and processes would be generated for controlled studies.

Although the TSS-1R mission was not completed as planned, the Italian satellite was deployed to a distance of 19.7 km--making TSS-1R the largest man-made electrodynamic structure ever placed in orbit. This deployment was sufficient to generate high voltages across the tether and extract large currents from the ionosphere. These voltages and currents, in turn, excited several space plasma phenomena and processes of interest. Active tether science operations had begun at satellite fly-away and continued throughout the deployment phase, which lasted more than 5 hours. As a result, a high-quality data set was gathered and significant science activities had already been accomplished prior to the time the tether broke. These activities included the measurement of the motional emf, satellite potential, Orbiter potential, current in the tether, charged particle distributions, and electric and magnetic fields. Significant findings include:

(1) Currents, collected by the satellite at different voltages during deployment, that exceeded the levels predicted by the best available numerical models by factors of up to three (see figure 1.4).
(2) Energetic electrons, that are not of natural ionospheric origin and whose energy ranged as high as 10 keV, were observed coincident with current flow in the tether. These data suggested possible energization of electrons by wave-particle interactions(see figure 1.5).
(3) A large increase of the tether current, a precipitous drop of the satellite bias voltage, very intense and energetic ion fluxes moving outward from the satellite's high-voltage plasma sheath, and a strong enhancement of the ac electric field in the 200 Hz to 2 kHz range-all observed to be concurrent with a satellite ACS yaw thruster firing. These observations imply a plasma density enhancement by ionization of the neutral gas emitted by the satellite thrusters.

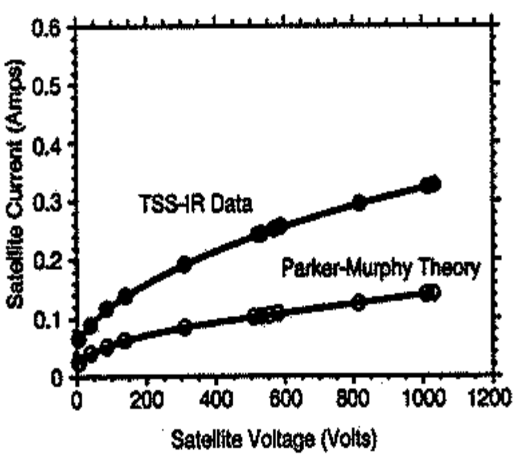

Figure 1.4 Measured TSS-1R and theoretically predicted I-V characteristics

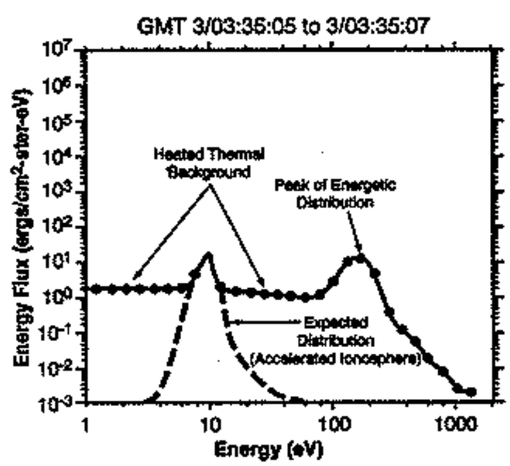

Figure 1.5 Energetic electron Population measured at the satellite’s surface.

It is already apparent, therefore that the data gathered during TSS-1R have the potential to significantly refine the present understanding of the physics of (1) the collection of current and production of electrical power or electrodynamic thrust by high-voltage tethered systems in space, (2) the interaction of spacecraft, and even certain types of celestial bodies, with their local space plasmas, and (3) neutral gas releases in space plasmas and their effect on both of the above processes.

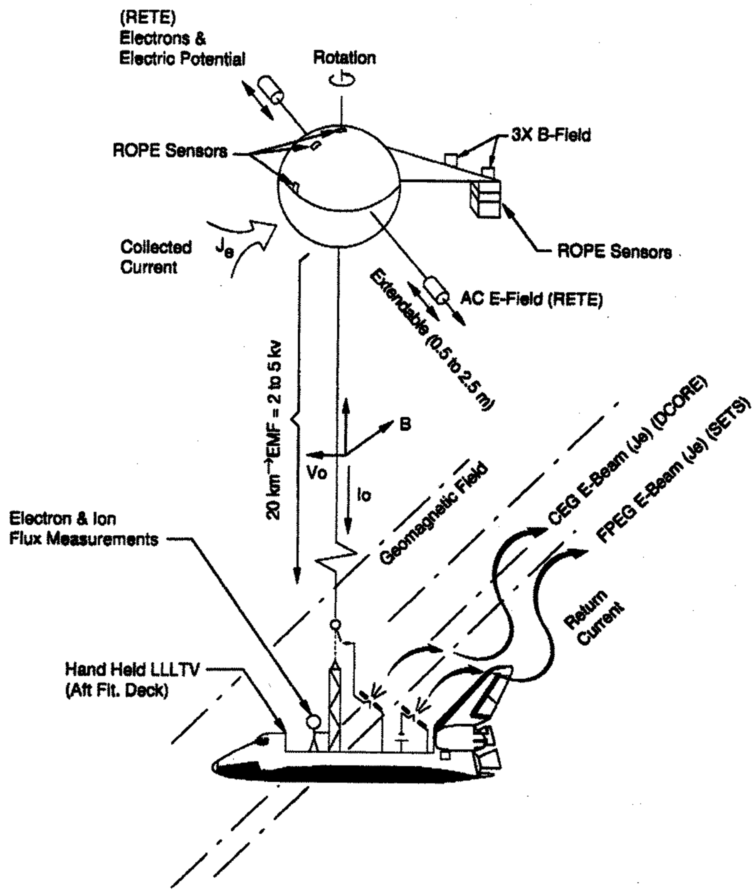

Figure 1.6 TSS Functional Schematic

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

TSS-1R Science Investigators

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 tethered system to produce electrical energy and will allow studies of the electrodynamic interaction of the tethered system with the ionosphere. The TSS Core Equipment controls the current flowing through the tether between the satellite and the orbiter and makes a number of basic electrical and physical measurements of the Tethered Satellite System.

Deployer Core Equipment consists of several instruments and sensors on the starboard side of the MPESS in the payload bay. A master switch connects the tether conductor to science equipment in the orbiter payload bay; 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 voltmeter measures the tether potential with respect to the orbiter structure. The Core Electron Accelerator has two electron-beam emitters that can eject up to 750 milliamperes of current from the system. Two other instruments complement the electron accelerator's operations: a vacuum gauge to measure ambient gas pressure and to prevent operation if pressure conditions could cause arcing and a device to connect either generator head to the tether electrically.

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-1R 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-1R 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 satellite's fixed boom, the Differential Ion Flux Probe measures the energy, temperature, density, and direction of ambient ions that flow around the satellite, as well as neutral particles that have been ionized in the satellite's plasma sheath and accelerated outward radially. 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 electron volts (eV). The directional discrimination of the Differential Ion Flux Probe will allow scientists to differentiate between the ionospheric ions flowing around the satellite and the 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 V, the sensor package will be maintained near the local plasma potential to allow unambiguous measurements to be obtained. The potential of the sensor package also can be swept, allowing the package itself to serve as a diagnostic probe.

Research on Electrodynamic Tether Effects (RETE)

Marino Dobrowolny, Principal Investigator
Agenzia Spaziale Italiana

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 current (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 or Core Electron Accelerator is 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 earth.

One boom carries a wave sensor canister, which contains a three-axis ac electric field meter and a two-axis search coil ac magnetometer to identify electric fields and electrostatic waves and to 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 the TEMAG 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, 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 mid-boom characterize ionospheric conditions at two distances from the satellite, determining the magnetic signature that is produced as the satellite moves rapidly through the ionosphere. Combining measurements from the two magnetometers allows real-time 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 than that at mid-boom. 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 by investigators 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. The readings will be made two times 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)

Brian Gilchrist, Principal Investigator,
University of Michigan

This investigation is designed to study the current-voltage characteristics of the orbiter-tether-satellite system and the fundamental controlling parameters in the Earth's ionosphere. This is accomplished through control of the tether system electrical load impedance and the emission of electrons at the orbiter end of the system. The experiment also explores the use of space tethers as science tools. Orbiter charging processes are measured using electron emissions plus the tethered satellite as a remote electrical reference. Plasma waves generated by electron beams are measured by receives at the satellite. Ionospheric spatial structure is investigated by simultaneous in-situ measurements at both the orbiter and satellite. Also, electrodynamic tether low-frequency radio wave reception, emission, and transient response are investigated.

The hardware is located on the MPESS near the center of the payload bay and adjacent to the deployer pallet. A Tether Current-Voltage Monitor measures tether current and voltage, while controlling tether circuit load resistance. The Fast-Pulse Electron Accelerator emits an electron beam of 100 or 200 milliamperes at an energy of 1000 electron volts. The beam can be pulsed with on/off times ranging from 400 nanoseconds to 107 seconds. The beam balances the tether current and is used to control the level of charging of the Space Shuttle orbiter. In addition, the beam is used as an active stimulus of the plasma near the orbiter in support of several scientific objectives.

The Spherical Retarding Potential Analyzer, mounted on a stem at one corner of the support structure, records plasma ion density and energy distribution in the payload bay. Similarly, a Langmuir Probe measures electron plasma temperature and density and is mounted on the tower also. 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 that are produced when electrons are conducted from the tether to the orbiter frame or when an electron beam is emitted. A three-axis fluxgate magnetometer measures the magnetic field, allowing the magnetic field lines in the payload bay to be mapped, which is crucial since electron beams and the flow of plasma spiral in response to these fields. Using this information, scientists can aim the electron beam at various targets, including orbiter surfaces, to study the fluorescing that occurs.

Shuttle Potential and Return Electron Experiment (SPREE)

David Hardy, Principal Investigator
Department of the Air Force, Phillips Laboratory

SPREE will measure the charged particle populations around the orbiter for ambient space conditions and during active TSS-1R operations. SPREE supports the TSS-1R 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-1R electron beam operation, and by investigating local wave particle interactions produced by TSS-1R operations.

SPREE is mounted on the port side of the 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 energy range from 10 eV to 10 keV that impact 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 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 in real time, and the full data set is stored on two SPREE Flight Data Recorders (FDRs). Each FDR holds up to 2 gigabytes of data for postflight analysis.

Tether Optical Phenomena Experiment (TOP)

Stephen Mende, Associate Investigator
Lockheed

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

In pace of the image-intensified conventional photographic experiment package that has flown on nine previous Shuttle missions, a charge-coupled device electronic system will be used instead of film. 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 real-time observation of the image, unlike film, which has to be processed after the mission. The system also provides higher resolution in low-light situations than do conventional video cameras.

The imaging system will operate in four configurations: filtered, interferometric, 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 air-spaced Fabry Perot interferometer, and spectrographic equipment will be attached to the equipment so that the crew can perform various observations.

In one mode of operation, the current developed in the Tethered Satellite System is closed by using electron accelerators to return electrons to the plasma surrounding the orbiter. The interaction between these electron beams and the plasma is not well understood. Scientists expect to gain a better understanding of this process and how it affects both the spacecraft and the plasma by using the charge-coupled device to make visual, spectrographic, and interferometer measurements. Thruster gasses also may play a critical role in Tethered Satellite System operations. By observing optical emissions during the buildup of the system-induced electromotive force (emf) and during gas discharges, scientists can understand better the interaction between a charged spacecraft and the plasma environment and will increase their knowledge of how the current system closes at the poles of the voltage source.

Investigation of Electromagnetic Emissions by the Electrodynamic Tether (EMET)

Robert Estes, Principal Investigator
Smithsonian Astrophysical Observatory (SAO)

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 to which waves that are 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 be able to detect faint emissions produced as waves disturb particles and enhance ionization. Furthermore, the current is carried away from the tethered system through the ionosphere by electromagnetic waves. Also, investigators want to know what type of wave predominates in this process and whether the tether-ionosphere current closure occurs near the system or hundreds of kilometers away. Ground-based measurements may be able to shed light on this question.

Another goal is to determine how well the Tethered Satellite System can broadcast from space. Ground-based transmissions, especially those below 15 kHz, suffer from inefficiency. Since large portions of ground-based antennas are buried, most of the power supplied to the antenna 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 lower 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. EMET and OESE science teams will operate ground stations equipped with magnetometers at remote sites along the TSS ground track. The EMET sites on Mona Island (Puerto Rico) and Bribie Island (Australia) are capable of measuring frequencies from near dc to 40 kHz. The OESEE sites in the Canary islands and Kenya utilize Superconducting Quantum Interference Devices (SQUIDs) and coil magnetometers to monitor frequencies below 100 Hz. Researchers at these sites will try to measure the emissions produced by the TSS and will track the direction of waves that are generated when electron accelerators in the orbiter payload pulse the tether current as the orbiter passes overhead. The incoherent scattering radar and antenna at the Arecibo Radio Telescope facility will attempt to observe the ionospheric perturbations produced by the TSS system.

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-1R 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 oscillations, which are essentially random, are more difficult to predict. This behavior, called "dynamic noise," is analogous to radio static. An understanding of its nature is needed if tethered platforms are to be used for microgravity facilities and for studying fluctuations in the small-scale structure of Earth's gravitational and magnetic fields. These gravitational fluctuations are caused by variations in the composition and structure of Earth's crust and may be related to mineral sources.

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

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

Adam Drobot, Principal Investigator
Science Applications International Corporation (SAIC)

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 (through which the satellite travels) under a variety of conditions. This includes those in which the motion of the tether and neutral gas emissions from the 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 the TMST 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-1R.

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-low-frequency (ULF) and very-low frequency (VLF) wave propagate through the ionosphere. These models will complement the information gathered by TSS-1R instruments at ground stations.

The Subsatellite element (TSS-S) of the Tethered Satellite System (TSS)

Figure 1.7 TSS-S during TSS-1R Mission

The TSS-S is a Shuttle-tethered instrumented platform supporting dynamic and electrodynamic investigations; it thus avails the unique opportunity offered by the tether complex. The TSS-S has flown twice, first in August, 1992, then in February, 1996 and its performance has exceeded expectations both times.
As shown in figure 1.7, the Satellite has a roughly spherical shape with an outer diameter of 1.6 m; it features two fixed and two deployable/retractible booms. One of the fixed booms (with struts) is one meter long and it is meant for scientific instrument accommodation at its tip and midpoint (2.5 kg overall), while the other fixed boom supports the subsatellite's RF communications antenna. The two deployable/retractible booms (DRBs) are designed to take science instrument packages weighing up to 1.5 kg per boom up to 2.35 m away from the satellite shell in 14 mm steps.

As shown in fig. 1.8, the satellite is functionally divided into three "modules", namely the Service Module (SM), the Auxiliary Propulsion Module (APM) and the Payload Module (PM). The SM is the hemisphere located on the tether' side and it accommodates all subsystems but for the power and command-data handling units interfacing with the experiments; these, together with the science experiment equipment, are housed inside the PM, i.e. the hemisphere opposite to the tether. The SM and PM are separated by, and join at, the APM, which is made up by the equatorial plane, the propellant tank and all the valves, piping and propellant management equipment. The TSS Satellite has an overall mass of about 521 kg, out of which up to 66 kg made up by science instruments and 61 kg by the gaseous nitrogen propellant (GN2) for satellite attitude and rate control and for tether tension augmentation to support early TSS-S deployment and to keep the tether taut during proximity operations, when the gravity-gradient-originated tension is too weak to guarantee that the tether does not become slack. Yaw thrusters are provided at the Satellite's equatorial plane for yaw attitude and yaw rate control; each yaw thruster has two nozzles and provides 0.5 Nm pure torque about the "vertical" axis using about 1.7 g/s of on-board propellant. Yaw attitude control accuracy is about 1 deg of the desired angle while yaw rate control is accurate to +/- 0.1 RPM for rates in the range - 0.7 to + 0.7 RPM. The reference yaw angle and rate as well as the associated control deadbands can be selected by telecommand.

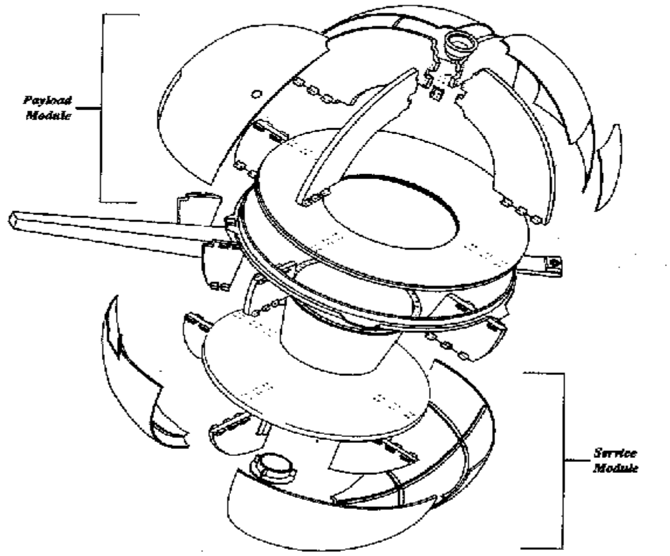

Figure 1.8 TSS-S Exploded view

Thrusters are also present close to the equatorial plane to control pitch and roll oscillation rates; in-plane and out-of-plane thrusters control the pitch and roll rates, respectively; they provide a 0.8 Nm torque about the relevant axis. The in-plane (pitch control) thrusters also generate pure forces along the x (roll) and z (yaw) axes, about 0.7 and 1 N in magnitude, respectively. Likewise, the out-of-plane (pitch control) thrusters give rise to pure force components along the y (pitch) and z axes, about 1.9 and 1 N in magnitude, respectively. In-plane and out-of-plane thrusters use about 4.4 and 3.8 g/s of GN2 each, respectively, and can be actuated one at a time only. They can operate under external command or under control from the TSS-S on board software in the so-called Auto Rate Damping (ARD) mode. The TSS-S's tether-aligned thrusters, in-line 1 and 2, each providing 2 N pure thrust along the z axis, use about 3.2 g/s when active and can be actuated upon external command either individually or together. They are meant for tether tension augmentation and support TSS-S separation from the Orbiter during early deployment and close-in approach to the Orbiter during final retrieval.

The Satellite is provided with a complete set of attitude detrmination sensors, i.e. 4 rate-integrating gyroscopes, two bolometer-based optical Earth sensors (ES) and four Digital Sun Sensors (FDSS). Satellite attitude determination is carried out on board he satellite with a +/- 1 deg accuracy whenever the satellite is in attitude hold mode; the on-board attitude determination algorythm is based on gyroscope output and makes use of ES output for gyro drift compensation. Ground-based algorythms have been developed by Alenia Spazio to more accurately reconstruct the Satellite attitude history, even while in spin and passive mode, to support post-flight science data analyses; under normal operating conditions and data availability, they can provide TSS-S attitude history reconstruction to better than 1'.

The TSS Satellite element also carries on board a set of four Ag-Zn batteries to support the deployed mission; they can provide up to 10.6 kWh, depending on their discharge profile and thermal conditions, as ascertained by both ground testing and flight experience. Out of the total, science experiments are allocated about 2.5 kWh overall, with a 100 W maximum overall power level. Twelve individually switched and fused power lines are provided for use by the TSS-S science experiments, 4 with 5 A rating and 8 with 1.5 A rating, at 30 +/- 6 V input voltage.

The TSS-S provides a 16 kbps continuous telemetry stream, out of which about 4 kbps subsystem housekeeping, 10.25 kbps science instrument telemetry (housekeeping and science data) and about 1.75 kbps service (sunchronisation) words. Discrete, analog and 16-bit serial monitors can be acquired from the science instruments and inserted into the telemetry stream; analog monitors are A/D converted to 8-bit words. The TSS-S supports a 2 kbps maximum telecommand bitrate; the corresponding telecommand rate depends on whether the telecommands require processing by the Satellite on-board software, and can reach the maximum value of about 20 commands/s in case no processing is required.Science experiments can be provided relay-driving, discrete commands as well as 16-bit serial digital commands; no OBDH processing is provided on science experiments commands but routing to the end user. The TSS-S has a 40-slot Time Tagged Command Buffer (TTB), where commands can be stored for execution at a later time. Out of these, up to 30 can be allocated to the science experiments; TTB time tag resolution is about 32 sec, i.e. time tags can differ by 32 sec as a minimum, but commands with the same time tag are executed within 128 msec of each other in a FIFO order.

Besides engineering resources and capabilities, the experiments on board the TSS-S are provided with a magnetic cleanliness program which ensures that DC magnetic field generated by the satellite does not exceed about 20 nT at the fixed boom tip, with a very high stability (a few nT). Additionally, the TSS-S outer shell is coated with a 100-120 micron-thick conductive paint layer applied directly on the shell bare metal (Al); the paint helps keeping the resistance opposed by the skin to the electric current flow to a few tens of Ohms, the exact value depending on paint thickness and applied voltage. Ground testing and flight data have proved both the magnetic cleanliness level and the TSS-S overall conductivity to match or exceed the science requirements.

The TSS-S is equipped with two "standard" science support equipment items, namely the Satellite Ammeter (SA) and the Satellite Linear Accelerometer (SLA). The SA is a four scale (±5, ±0.5, ±0.1, ±0.02 A), auto-ranging instrument capable of providing measurements of the electric current flowing in the tether with a 7-bit accuracy over each range; SA data are provided 16 times a second in the satellite telemetry stream. The instrument, however, also has a 1 kHz bandwidth analog output, allowing other satellite experiments to directly sample current impulse waveforms. The SLA is a three-axis accelerometer with inductive-mechanical (coil-spring) control loop and capacitive pick-off; the instrument provides three mutually orthogonal acceleration measurements in the range -60 - +20 milli-g (z axis) and -20 - +20 milli-g (x, y axes), each available 16 times a second inside the satellite telemetry, with accuracies ranging from 100 micro-g (z axis) to 10 micro-g (x, y axes). The instrument measurement bandwidth is 4.5 Hz.

The experience acquired with the two performed flights has allowed very accurate characterisation of all TSS-S performance characteristics and has provided Alenia Spazio with expertise and S/W tools which allow the Company to provide in-depth and extensive support to both dynamics and electrodynamics analyses as well as to mission analysis, preparation and support.

<u>Contacts for the TSS Project:</u>

- M. Calabrese, R. Carovillano, T. Stuart - NASA Hqts.
- C. Bonifazi, M.Dobrowolny - ASI
- F.Giani, B.Strim, - Alenia
- N.Stone, R. McBrayer - NASA/MSFC
- TSS Investigator Working Group

1.2 The Small Expendable Deployer System (SEDS): SEDS-1 and SEDS-2 Missions

The SEDS project started as a Small Business Innovative Research contract awarded to Joe Carroll by NASA MSFC. SEDS hardware proved to be able to succesfully deploy a 20 km tether in space. Both flights of SEDS-1 (March 29, 1993) and SEDS-2 (March 9, 1994) flew as secondary payloads on Delta II launches of GPS satellites. After the third stage separation the end-mass was deployed from the second stage. SEDS-1 demonstrated the capability of deorbiting a 25 kg payload from LEO. SEDS-2, on the other end, demonstrated the use of a closed loop control law to deploy a tethered payload along the local vertical.

SEDS' hardware, as shown in figure 1.9, consists of a deployer, brake/cutter and electronics box. All the components that are in contact with the tether, except for the brake post, are coated with teflon. The deployer consists of baseplate, core, tether and canister. The tether is wound around the core. In addition there are three Light Emitting Diodes (LED). Two of the LED's are used to count the turns of deployed tether, while the third is used to check when the tether is almost completely unwound. The canister provides a protective cover for the tether and restrains it during deployment. The tether material is SPECTRA-1000.

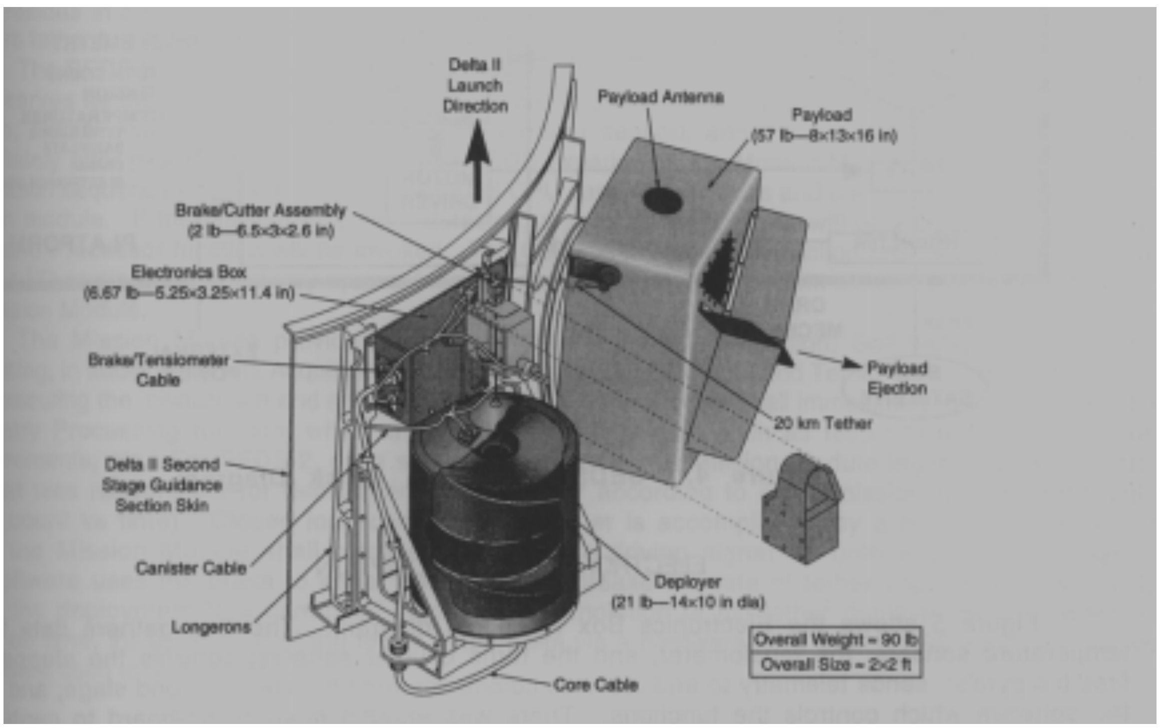

Figure 1.9 SEDS and Endmass on the Delta Second Stage

The brake/cutter components are: brake post, stepper motor, tensiometer, temperature sensor, pyro cutter, exit guide. The tether post is coated with hard anodize. The stepper motor is used to wrap or unwrap the tether to vary the deployment tension and the resulting deployment velocity. The brake mechanism is a friction multiplier and the multiplier function is proportional to the friction surface area between the tether and brake post. SEDS functional diagram is shown in figure 1.10.

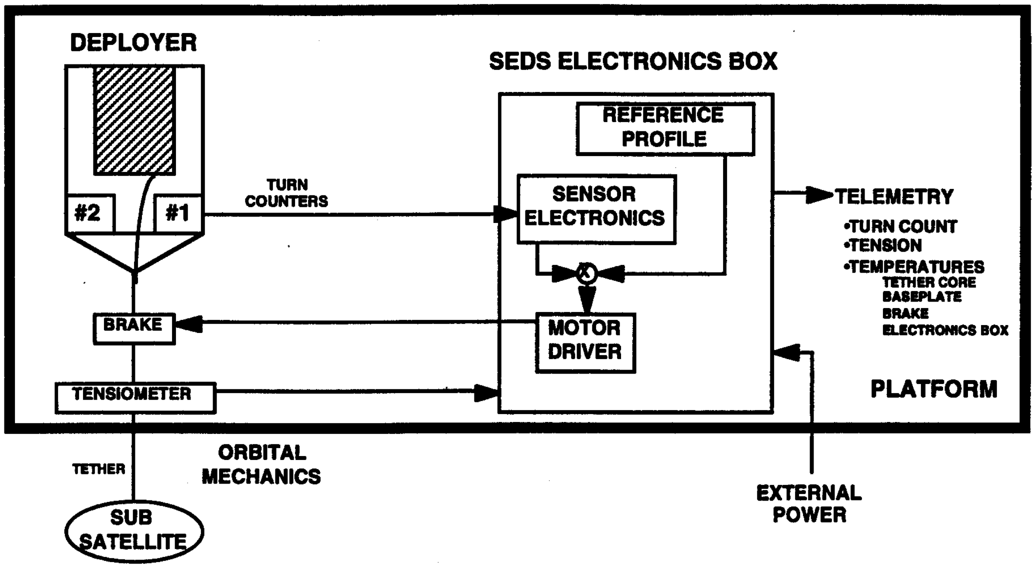

Figure 1.10 SEDS Functional Diagram

The main differences between SEDS 1 and SEDS-2 are shown in table 1. SEDS-2 closed loop was implemented by deploying the tether according to a pre-mission profile. The deployment control logic acted on the brake mechanism by increasing or decreasing the deployment velocity to follow the profile and bring the payload at the end of the tether deployment to a smooth stop along the local vertical.

Table 1. Main differences between SEDS-1 and SEDS-2

	SEDS-1	SEDS-2
Tether Cutter Pyrotechnics	Active	Inactive
Control Law	Open Loop	Closed Loop
Tether Solder Lumps	Study Tension Pulses	None
Tether Fabrication	Tether Application	Cortland/Hughes
Mission Initiation	Prior to Depletion Burn	After Depletion Burn
Brake Usage	Minor	Significant after 1 Km
Tether Stabilization	None	Yes

The end-mass payload (EMP) was developed by NASA LaRC in order to monitor the dynamics of a tethered susbsatellite. EMP consisted of three primary science sensors: a three-axis accelerometer, a three axis tensiometer and a three axis magnetometer. The EMP measured 40.6X30.5X20.3 cm and weighted about 26 kg. The end-mass was completely autonomous and carried its own battery, electronics, computer and S-band telemetry system. As schematic of EMP is shown in fig. 1.11. The three axis tensiometer was also developed at NASA LaRC.

SEDS-1 mission objectives were to demonstrate that SEDS hardware could be used to deploy a paylod at the end of a 20 km-long tether and study its reentry after the tether was cut. The orbit chosen had an inclination of 34 degrees and a perigee altitude of 190 km and

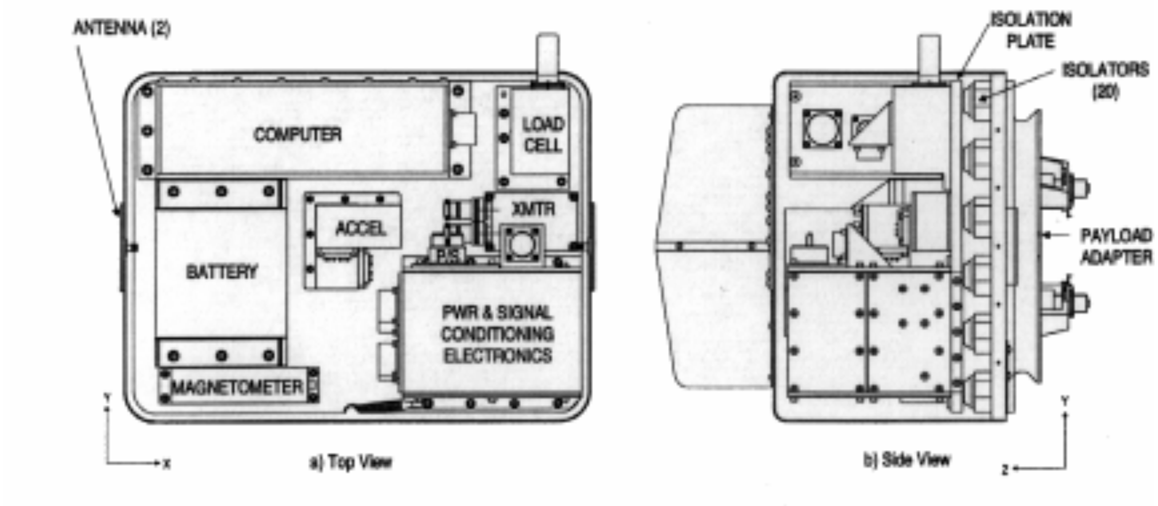

Figure 1.11 Schematic of SEDS EMP

an apogee altitude of 720 km. The EMP transmitted over 7900 seconds of data before burning into the atmosphere (1Hz sampling rate for the magnetometer and 8 Hz for the tensiometers and accelerometers). As predicted, SEDS-1 reentry was off the coast of Mexico (see fig. 1.12a). NASA stationed personnel at Cabo San Lucas, Puerto Vallarta and Manzanillo to make photographic and video observations. The Puerto Vallarta site was able to obtain observational data as shown in figure 1.12b

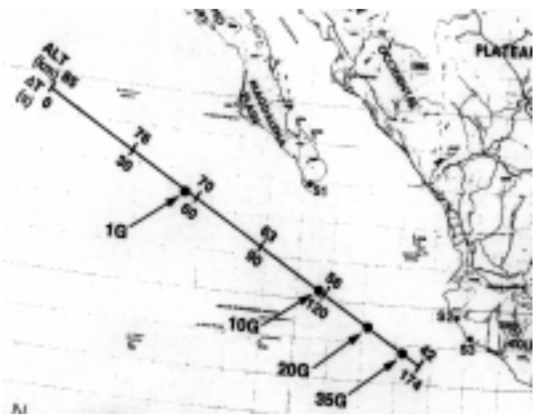

Figure 1.12a SEDS-1 EMP reentry trajectory

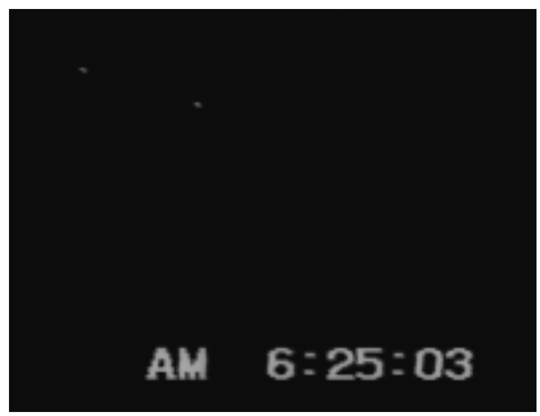

Figure 1.12b Observational Data of SEDS-1 reentry

SEDS-2 mission objectives were to demonstrate the feasibility of deploying a payload with a closed-loop control law (i.e. a predetermined trajectory) and bring it to a small final angle (<10 degrees) along the local vertical. A secondary objective was to study the long term evolution of a tethered system. The orbit this time was chosen to be circular with an altitude of about 350 km. The SEDS-2 tether was allegedly cut by a micrometeoroid or debris after five days. The EMP transmitted over 39,000 seconds of data before the battery died (1 Hz sampling rate for all the three primary science sensors).

SEDS-1 and SEDS-2 Flight Data

SEDS data base is available through anonymous ftp at the node optimu@gsfc.nasa.gov (128.183.76.209) SEDS1 data are in the subdirectory /pub/projects/tether/SEDSMission1 and SEDS-2 data are in the directory /pub/projects/tether/SEDSMission2. Each directory is organized in different subdirectories with deployer data, EMP data, radar, etc.. Each content of a directory is described in a read.me file.

SEDS-1

The turn counter data are shown in Figure 1.13a, the tension at the deployer is shown in figure 1.13b and the tether rate in 1.13c. In order to compute the tether length and its rate, the turns had to be mapped and converted into deployed length. Note that the velocity at the end of the deployment was about 7 m/s explaining the huge jump in tension and the consequent rebounds.

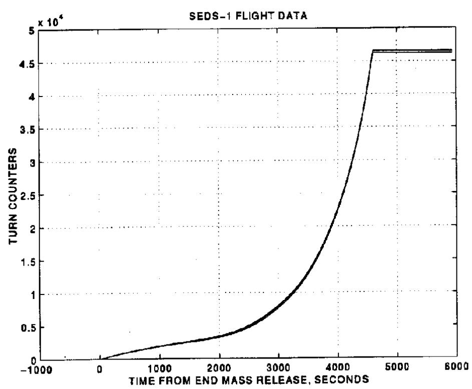

Figure 1.13a. SEDS Deployer Turns Counts

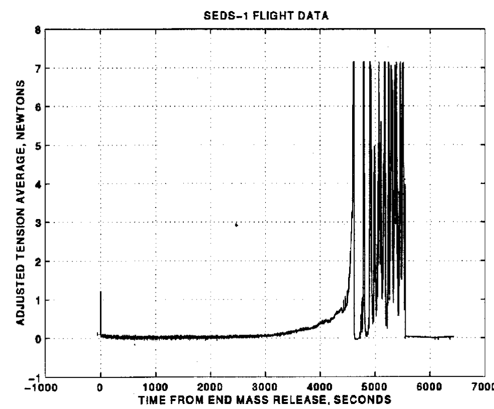

Figure 1.13b. SEDS Deployer Tension

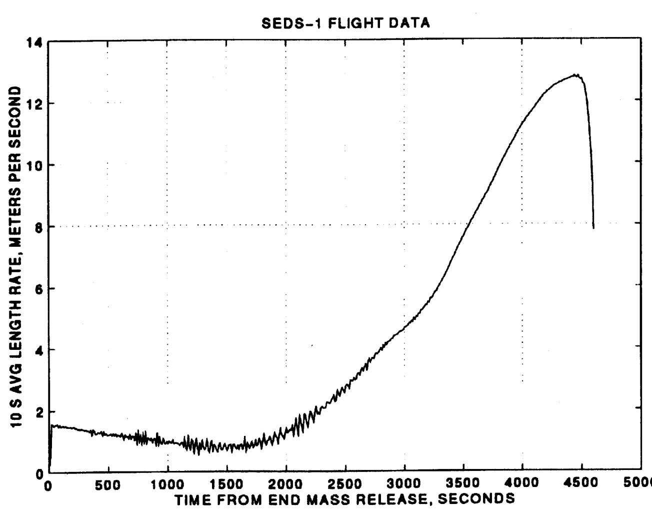

Figure 1.13c. SEDS Deployer 10-sec Average Length Rate

The magnetometer and tension moduli at the EMP are shown in figures 1.13d and 1.13e, respectively. Note that the magnetometer was affected by a bias estimated to be 3065 nT, -3355 nT and -4188 nT on the x, y and z axes, respectively. Procedures on the data calibration and validation are given at the ftp site as well as are described in several papers presented at the Washington Conference.

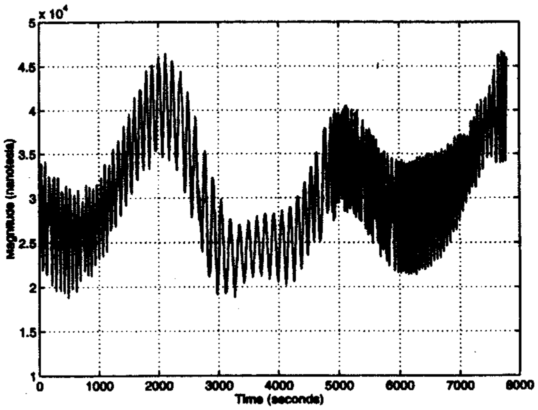

Figure 1.13d. EMP Magnetometer Modulus

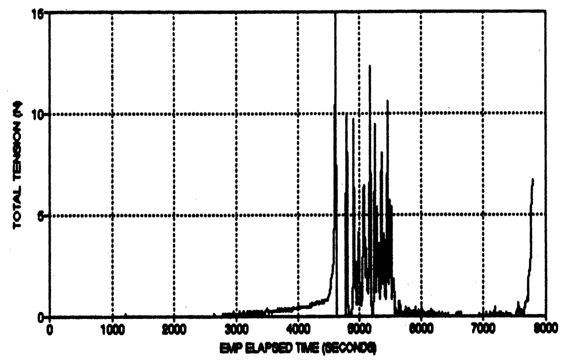

Figure 1.13e. EMP Tension Modulus

SEDS-2

The tether deployment rate and the tension at the deployer are shown in figure 1.14a, and 1.14b, respectively. The deployment law was so effective that the final tether rate was about 2 cm/s. As computed by the modulus of the EMP tension, shown in fig 1.14c, the final libration was about 4 degrees, and it was confirmed also by the radar tracking. Even in SEDS-2 the magnetometer signal was affected by a bias anomaly that was estimated to be -1128 nT, 1312 nT, and 2644 nT on the x,y and z axes, respectively.

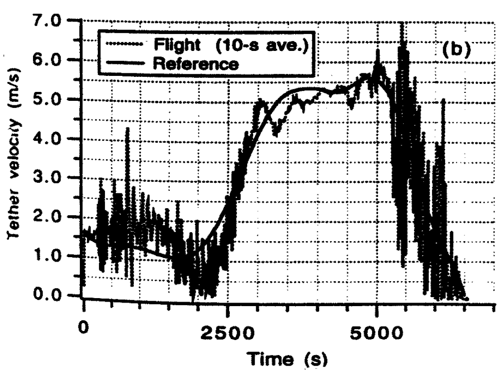

Figure 1.14a. Tether Rate

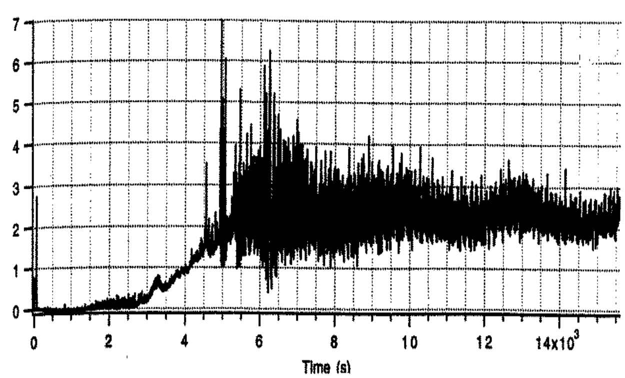

Figure 1.14b. Tension at Deployer

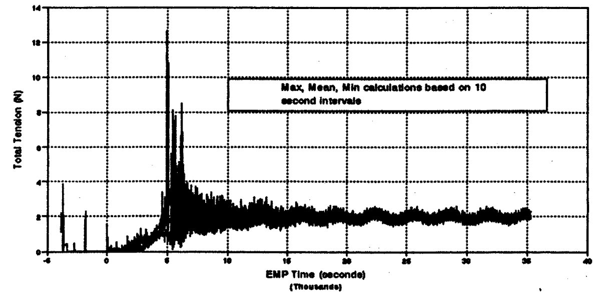

Figure 1.14c. EMP Tension Modulus

Contacts for the SEDS Project:

- J.Harrison , H.Frayne Smith, K.Mowery, C.C. Rupp - NASA/MSFC
- J.Carroll - Tether Applications
- J. Glaese - Control Dynamics
- M.L. Cosmo, E.C.Lorenzini, G.E. Gullahorn -SAO
- T.Finley ,R.Rhew, J.Stadler - NASA/LaRC
- W.Webster - NASA/GSFC

1.3 The Plasma Motor Generator (PMG)

The PMG experiment was designed to test the ability of a hollow cathode assembly (HCA) to provide a low impedance bipolar electrical current between a spacecraft and the ionosphere. The 500m-long tether was chosen to assure complete separation between the grounded ends, forcing current closure through the ionosphere rather than with local overlap of the two plasma clouds. In order to function properly, an electrodynamic tether needs to be effectively "grounded"on both ends. The experiment aimed at demonstrating that such configuration could function either as a orbit-boosting motor or as a generator converting orbital energy into electricity, as shown in figure 1.15.

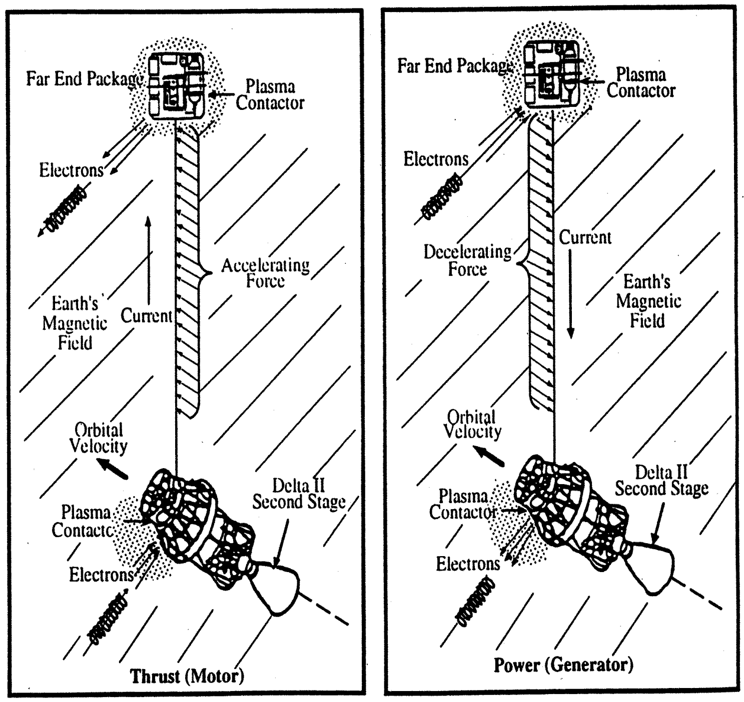

Figure 1.15 PMG investigation of an electrodynamic tether

The mission objectives were:

- HCA Operation
- End-mass separation greater than 200 m
- Induced voltage of 30 V or higher
- PMG Plasma clouds completely separated
- Achieve currents in the 0.1 -1 Amp
- Reverese current in tether using bias voltage
- Observe tether stability for gravity gradient vs. $\underline{I}X\underline{B}$ forces
- Collect I-V Characteristics for full orbit

As shown in figure 1.16, PMG consisted of four major subsystems: The Far-End Package (FEP), the Near-End Package (NEP), an electronics box (SEDS) and the Plasma Diagnostic Package (PDP). The system was launched as a secondary payload on a Delta II on June 26,

1993. After the third stage separation, PMG was left in an elliptical orbit (193X869) at 25.7 deg inclination. The FEP was ejected upward with an initial velocity of about 2-3 m/s. PMG was programmed to operate in three different data modes, by using a microprocessor to control selectable load resistors, to change 1) bias voltage levels, 2) polarity reversal 3) bypass relays.

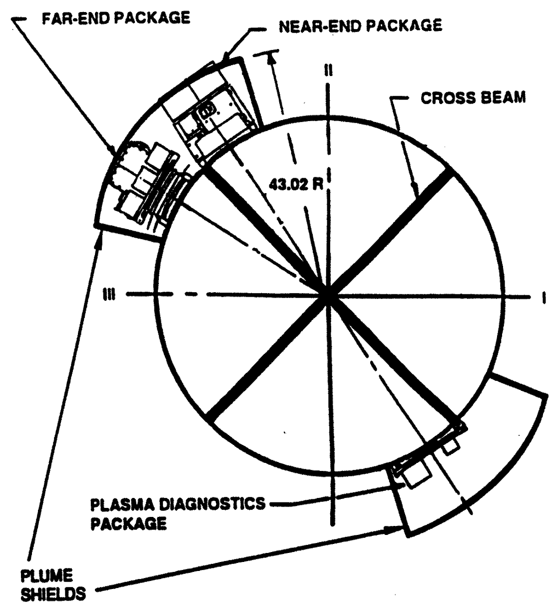

Figure 1.16 PMG Major hardware components

The SEDS deployer fixed spool concept was adapted for use, without the brake mechanism to provide minimum friction deploymnet of the relatively massive tether. The PDP experiment, developed by NASA/LeRC/U. of New Hampshire, was added in order to measure the deployer potential.

The NEP included a power "ON" relay, a microprocessor based control/data module and electrometer, and a tether bias voltage power supply.

Each HCA was equipped with a 1 liter gas bottle, on/off solenoid, gas metering block and power supplies to produce a weakly ionized xenon cloud. Both end platforms carried a 28 volt silver cell battery for a nominal 3-6 hours lifetime. The tether was a #18 AWG teflon insulated copper wire.

After deployment, during the first 150 minutes, sets of I vs. V performance data were obtained by applying bias voltages of +65V to -130V in series with the **IXB** induced emf, while varying load resistance in steps from 200 to 700 ohms total tether current path internal resistance (see figure 1.17). Total tether voltage was measure by placing a 2.2 MOhms resistance in series with the tether.

The PMG current showed to be fully reversible, operating either as a generator system with electron current flow down the tether or as a motor with electron current driven up the tether.

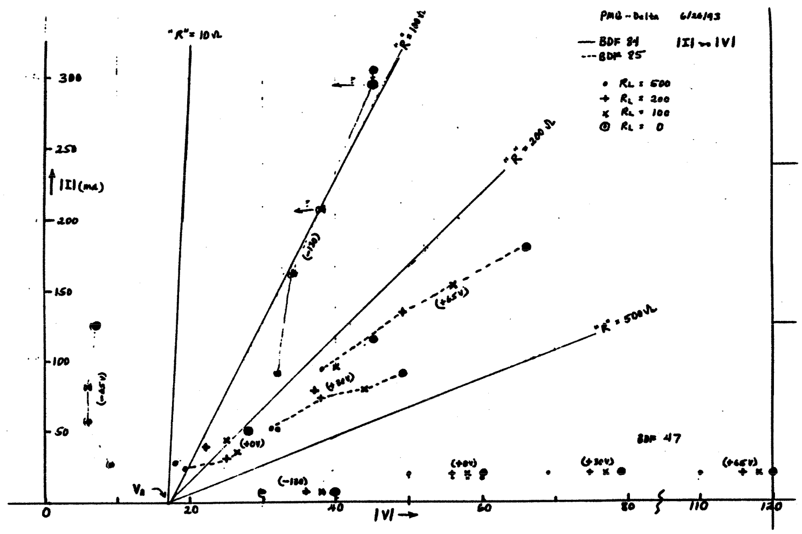

Figure 1.17 PMG I-V Curves

The data confirmed that the HCAs were able to complete PMG's current loop and 100-300 mA currents were observed in the daytime portion (probably due to the enhanced plasma denity) of the orbit and 10-50 mA on the nightime side, as shown in figure 1.18.

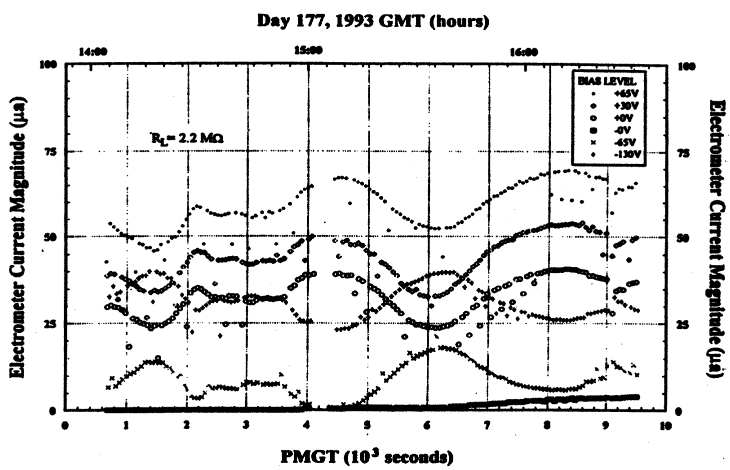

Figure 1.18 PMG Electrometer Reading of 2.2 MOhms Load and all bias voltages

The induced emf was measured with total voltage biased from +150 to -90 volts, and also with the bias turned off, by using only the induced emf. Variability of the induced emf has been matched against different models of electrodynamic interactions.

A contingent study was the detection with ground-based radars and squid magnetometers (see OESEE experiment on TSS1, G. Tacconi PI) of the plasma disturbances, ELF waves radiated by the system, the HCA plasma clouds and their associated plasma/ionosphere currents.

The experiment duration, in terms of plasma contactor operation and consequential active environment interaction, lasted about seven hours, until the batteries expired.

PMG data base is available through anonymous ftp at the node optimu@gsfc.nasa.gov (128.183.76.209) under the directory /pub/projects/tether/PlasmaMotorGenExp.

Contacts for the PMG Project:

- J.McCoy - NASA/JSC
- J.Carroll - Tether Applications
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- R.J.Jost - System Planning Corporation
- R.C. Olsen -Naval Postgraduate School
- I.Katz - S-Cubed
- G. Tacconi, L. Minna - U. of Genoa
- D.C. Ferguson -NASA/LeRC
- R.Tolbert -U. of New Hampshire
- W.Webster - NASA/GSFC

1.4 The Tether Physics and Survivability Spacecraft (TiPS)

TiPS Program Overview

The Tether Physics and Survivability (TiPS) Experiment was conceived as a quick response, simple experiment to study the long term dynamics and survivability of tethered space systems. The knowledge gained from this experiment will help DOD and the nation gain experience with tethered systems for eventual use in operational spacecraft. The Naval Research Laboratory's, the Naval Center for Space Technology (NCST) designed, built and now operates the experiment for the National Reconnaissance Office (NRO). The experiment is a free flying satellite consisting of two end bodies connected by a 4 kilometer non-conducting tether. In this respect it is different from other tether experiments, like those flown on the Shuttle, where one endmass was connected to a massive host vehicle.

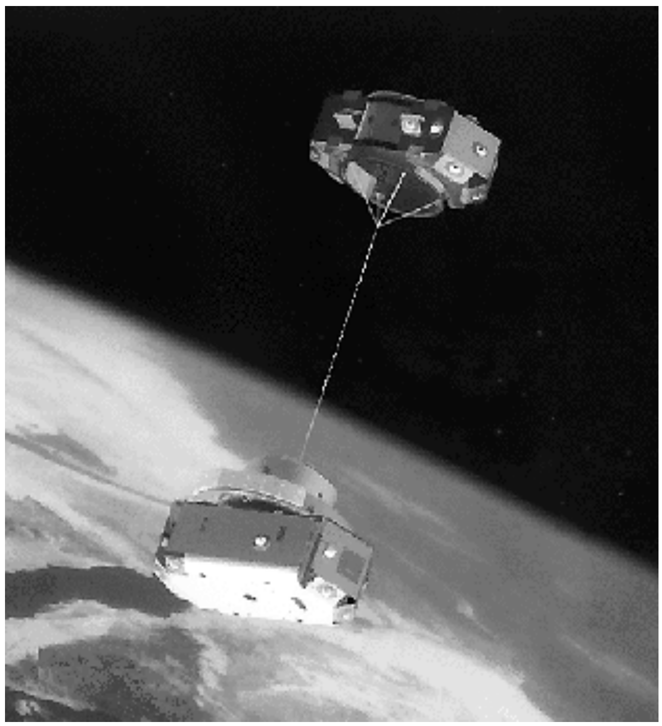


Figure 1.19 Artist Rendition of TiPS in Orbit. Ralph is on the bottom. TiPS has been in this orientation since deployment.

TiPS was jettisoned from a host spacecraft on June 20, 1996, with the deployment of the tether occurring shortly after jettison. The TiPS tether is intact through this writing (12/9/96), while no other space tether has lasted longer than five days. TiPS is the sixth known orbital tethered system flown to date.

To meet an early launch opportunity, TiPS had to be designed and built in approximately one year. Due to a very tight budget, the experiment objectives were limited to only those that had the highest payoff, these were : 1) Long term orbit and attitude dynamics and 2) tether survivability.

TiPS Hardware

The program constraints of limited time and money dictated that the experiment design be as simple as possible and consist largely of existing component hardware and/or designs.

The experiment goals only required a simple electrical power system that used a battery for all its electrical needs. The battery supported the initiation of deployment, recording of data on the deployment characteristics and transmitting this data to ground stations. TiPS consists of two end bodies, dubbed Ralph and Norton, connected by a 4 kilometer tether. Ralph contains a Small Expendable Deployer System (SEDS) tether deployer, a battery consisting of 10 Lithium Thionyl Chloride D cells, a timer to initiate deployment, a SEDS data acquisition electronics box and a transmitter and antennas to downlink the deployment data. The SEDS deployer, SEDS electronics and the transmitter were existing flight spare hardware from the SEDS 2 tether experiment that was successfully flown in space by NASA. NASA provided this hardware to NRL for the TiPS program. This was in keeping with the approach of using off the shelf components so that tight budgets and short schedules could be met. Norton is an inert body containing the ten spring cartridges used to rapidly push the two bodies away from each other, pulling the tether out of its deployer mounted on Ralph. Ralph and Norton each have 18 optical retroreflectors mounted on them. Fig. 1.20 is a picture of the completed satellite without its thermal blankets. In this figure, several of the small round retroreflectors can be seen.

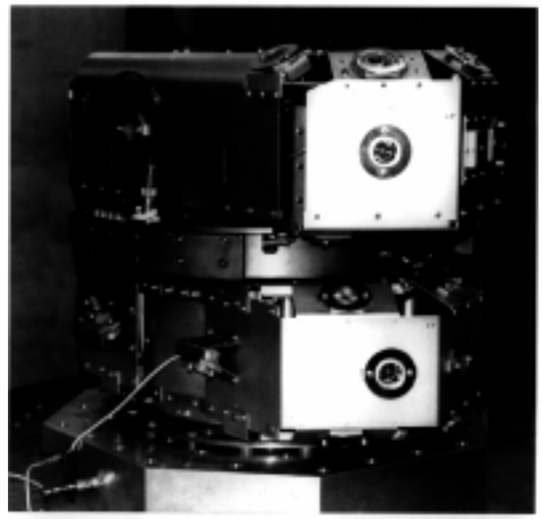


Fig 1.20 TiPS Satellite Without Thermal Blankets. The small round objects are the laser retroreflectors.

Satellite Tracking and Dynamics

The motion of the end bodies is observed by a ground based Satellite Laser Ranging (SLR) network and by ground based visual observations. Fig. 1.21 is an image of TiPS taken as the two endmasses were separating. The tracking data consists largely of range data provided by timing the two way round trip delay for a laser bounced off the retroreflectors on the spacecraft. The data is transmitted across the Internet to NASA Goddard in Greenbelt, Maryland.

The tracking data is analyzed, at NRL, to determine the dynamic motion of the tethered system. Since, there is no object at the center of mass of the tethered system, both the attitude motion and the

Figure 1.21 Telescope image of TiPS during deployment (Image taken by Starfire Optical Range at the Air Force's Phillips Laboratory).

orbital motion are inferred from observations of the endmasses only. This has proved to be a difficult task requiring frequent observational data and new estimation algorithms that were incorporated in the traditional orbit determination system used by NASA. The tracking data is also processed to provide updates to the state vector used to predict the motion of the endmasses. These predictions are used by the SLR sites for subsequent observations.

The requirement of determining the tether survivability will be met through ground based radar tracking of TiPS which will determine when or if the tether is cut.

TiPS Findings to Date

The findings of the TiPS program are best summarized by saying that they provide "confidence" that tether technology will be viable for future operational missions. There is still a lot of technology development required before operational systems would be ready to incorporate this technology, but TiPS has provided a significant step in that direction. The initial results show that tethers can be made to be survivable. With regard to the librational motion, our estimates now indicate that the tether is librating with a smaller amplitude than at deployment. Visual observations made shortly after the initial separation of the end-bodies suggested that the tether was librating with an amplitude of 47 degrees with respect to vertical alignment. Over the course of the next three months, we have determined with high confidence that the amplitude of that motion has decreased to approximately 12 degrees. At this lower amplitude, the tether behaves much more predictably. During the month of October, 1996, we were able to validate our ability to predict tether motion 6 to 12 hours into the future. While this was only possible during a period when an abundance of data is available, this provides a great deal of confidence in our ability to model tether dynamics.

NRL has set up a Web site where information and data can be obtained. The URL is http://hyperspace.nrl.navy.mil/tips.

Contacts for the Tips Project:

- Shannon L. Coffey, William E. Purdy, NRL

1.5 The OEDIPUS Tethered Sounding Rocket Missions

OEDIPUS A

OEDIPUS stands for **O**bservations of **E**lectric-field **D**istribution in the **I**onospheric **P**lasma - a **U**nique **S**trategy. Canadian activities in space tethers began with OEDIPUS A which was designed as a large double probe for sensitive measurements of weak electric fields in the plasma of the aurora. It was launched using a Black Brant X, 3-stage sounding rocket. The OEDIPUS program was a joint program between National Research Council of Canada and NASA with participation of the Communication Research Center in Ottawa, Canada (Principal Investigator), various Canadian universities, and the US Air Force Phillips Laboratory, the payload prime contractor was Bristol Aerospace Ltd. The major objectives of the OEDIPUS-A mission were:

- to make passive observations of auroral ionosphere, in particular, the natural magnetic-field-aligned dc electric field $\mathbf{E}_{\|}$, utilizing a large double probe;
- to measure response of the large probe in the inospheric plasma;
- to seek new insights into plane- and sheath-wave rf propagation in plasma.

The rocket payload OEDIPUS A was flown on January 30, 1989 from Andøya in Norway. The tethered payload consisted of two spinning subpayloads with a mass of 84 and 131 kg, with their own experiment complement and telemetry systems, that were connected by a thin 0.85 mm diameter conductive and also spinning tether. The mission achieved its scientific objectives to detect the natural magnetic-field-aligned dc electric field $\mathbf{E}_{\|}$ utilizing a large double probe, and to carry out novel bistatic propagation experiments. The flight established a record for the length of an electrodynamic tether in space at that time: 958 m. Although the mission was successful, flight data indicated that the aft subpayload experienced a rapid increase in its coning angle to nearly 35 degrees (half angle). A post-flight investigations concluded that the dynamic behavior was caused by interaction of the tether with the subpayloads. This observation was unexpected due the fact that the tether mass was negligible relative to masses of both subpayloads, and the tether dynamic interaction was expected to be negligible in the relatively short time (11 minutes) of a suborbital flight.

The OEDIPUS-A payload configuration is shown in Fig. *1.22*. The two subpayloads were initially connected and ejected from a Black Brant X with a spin rate about the longitudinal axis. The radial booms on the forward and aft payloads were used as dipoles for science experiments. The ACS module, located at the aft end of the aft subpayload, was used to align the spin axis to within 1 degree to the Earth's magnetic field. The tether was a teflon coated stranded tin-copper wire and it was deployed from a spool-type reel located on the forward subpayload. To separate the subpaylaods and deploy the tether, a spring ejection system was provided and followed by the cold gas thruster system in the forward subpayload. A magnetic hysteresis brake was provided to control the tether spool by applying a small constant torque, to smoothly decelerate the relative motion of subpayloads.

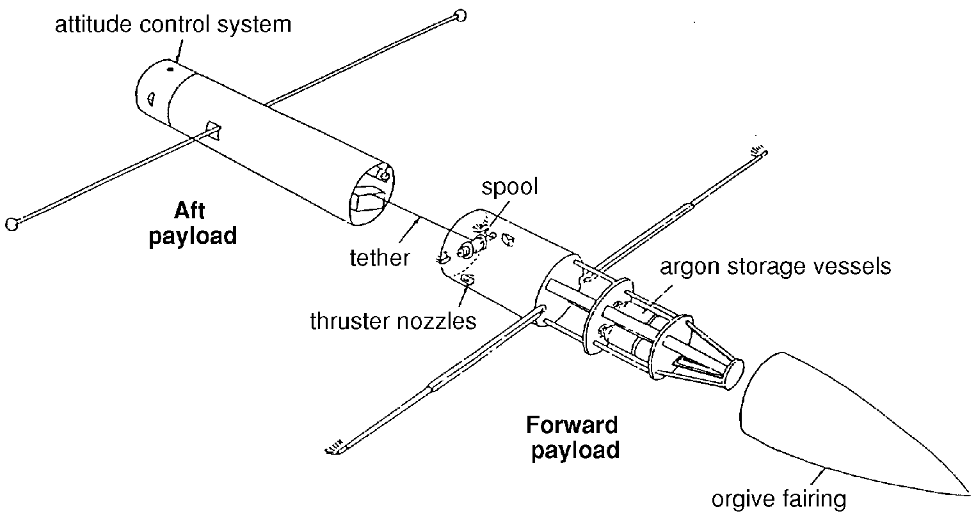


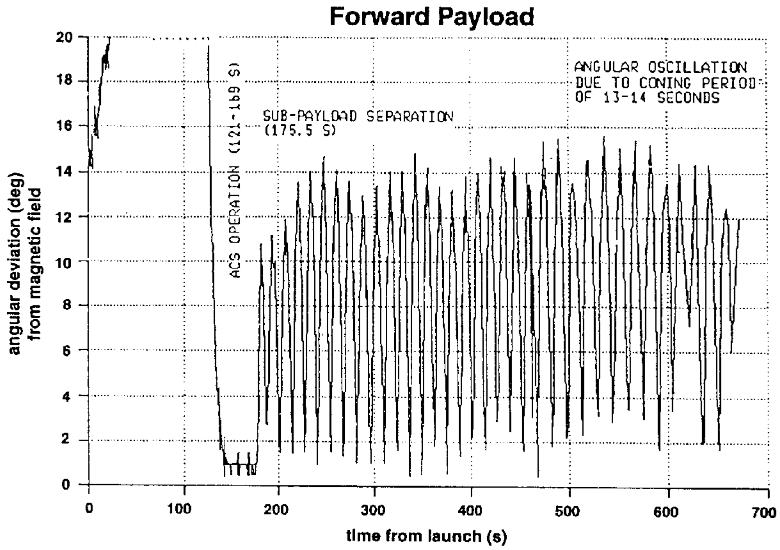
Figure 1.22 Some subsystems in the OEDIPUS-A payload configuration

Shortly after motor burn-out, the fairing was jettisoned along with a number of experiment doors, and the two sets of radial booms were deployed. At T+121 seconds, the ACS maneuver was initiated which aligned the payload within 1 degree of the local geomagnetic field line. At this point, the separation using cold gas system was initiated. At T+448 s, apogee was reached (about 512 km) and the payload separation was completed with tether length of 958 m. This configuration was maintained for the remainder of the flight. Due to gravity-gradient torque on the two-body system, the entire configuration experienced a slight rotation through-out the flight. At approximately T+800 s the payload re-entered the atmosphere and was not recovered.

Flight dynamics data are presented in Fig. *1.23*. These are processed magnetometer data used to compute the angular deviation of each payload's spin axis from the magnetic field vector. Data is shown for both forward and aft subpayloads. The forward subpayload experienced a tip-off at separation that caused a coning angle of approximately 7 degrees which varied only slightly during the flight. The aft subpayload, which also experienced a small tip-off, had an increase in the coning angle and it approached almost 35 degrees at the end of the flight. The post-flight investigations concluded that the increase coning was the interaction between tether and the aft subpayload.

OEDIPUS C

The second flight of OEDIPUS configuration, namely, OEDIPUS C took place on November 6, 1995 from the Poker Flat Research Range, located near Fairbanks, Alaska. The scientific objectives of the mission were similar to the previous one but there were



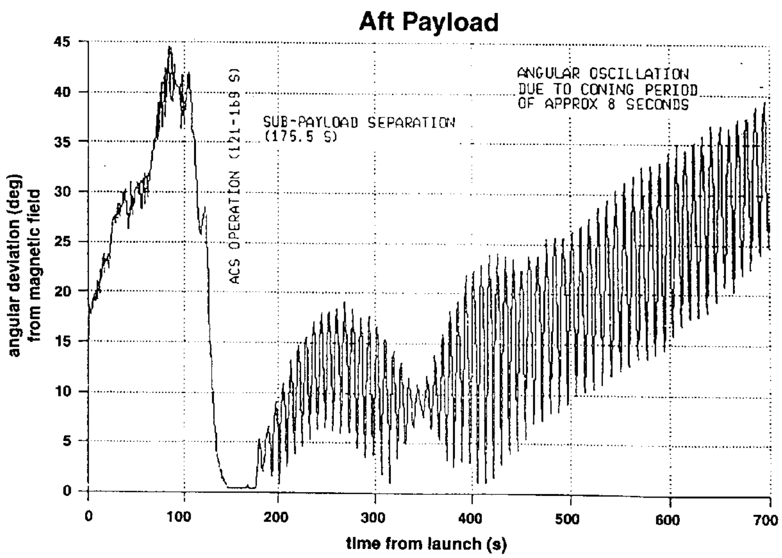


Figure *1.23* OEDIPUS-A flight dynamics data showing the time history of the angle between spin axis and the direction of the earth's magnetic field, for both subpayloads

important differences and extensions. The OEDIPUS-C payload was launched, using the Black Brant XII Sounding Rocket, to a higher trajectory with apogee of 843 km and the length of deployed tether was 1174 m. Thus, the trajectory had a greater range in plasma density than OEDIPUS A and provided an extended perspective on plane and sheath waves and their interaction with space plasma. To understand the importance of the electrically conducting tether for the propagation of rf waves between the subpayloads, the tether was cut from both ends on the downleg part of the flight. The experiments were also designed to help understand how charged particles associated with the aurora affect satellite transmissions. There were 13 experiments (three instruments from the Canadian Space Agency, seven from the National Research Council of Canada, and three others from the University of Saskatchewan and the US Air Phillips Laboratory in the USA). The OEDIPUS-C payload was sponsored by the Canadian Space Agency and the payload contractor was Bristol Aerospace

Ltd. One of the main investigations on OEDIPUS C was the project funded by the CSA's Space Science Program which involved controlled radio-wave experiments. The radio instruments (HEX and REX) were built by CAL Corporation and Routes Inc., both from Ottawa, Ontario, and the Principal Investigator was from the Communications Research Center (CRC) in Ottawa, Canada.

The OEDIPUS-C configuration is presented on Fig. *1.24*. The tethered payload consisted of two spinning subpayloads with a mass of 115 and 93 kg, respectively. They were connected by the same type of the tether as used in the OEDIPUS-A mission (0.85 mm diameter). The subpayloads each had four long booms (Be-Cu BI-STEM elements), forming a V-dipole antenna (13 m, tip-to-tip, on the aft subpayload; and 19 m on the forward subpayload). The tether was a 24 gauge wire per MIL-22759/32 which has a 19 strand, tin-coated copper conductor with white teflon insulation (radiation cross-linked, modified ETFE) rated at 600 V. Both subpayloads had video cameras for the determining the and the attitude solution and the relative position between the forward and aft subpayloads. The payload performance was captured in space by an aft payload video camera. The subpayloads telemetered data to a ground station for about 15 minutes before they landed in the Arctic Ocean (non-retrievable).

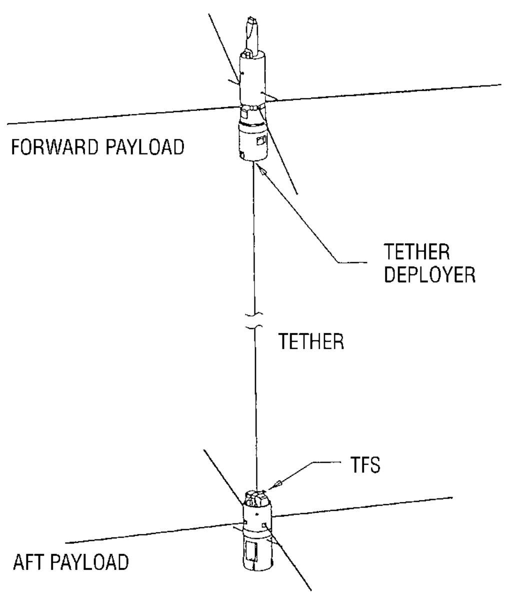


Figure 1.24 OEDIPUS-C configuration with location of the TFS

A unique Tether Dynamics Experiment (TDE) was one of the experiments flown during that mission. It was sponsored by the Space Technology Branch of the CSA in collaboration with Bristol Aerospace, University of Manitoba, University of British Columbia, McGill University, Carleton University and NASA Langley Research Center. A description of the TDE is presented in the following section.

OEDIPUS-C TETHER DYNAMICS EXPERIMENT (TDE)

The planning for this technological experiment was initiated in 1992, and culminated with the sub-orbital flight on November 6, 1995. The main objectives were as follows:

- derive theory and develop simulation and animation software for analyses of multi-body dynamics and control of the spinning tethered two-body configuration;
- provide dynamics and control expertise, for the suborbital tethered vehicle and for the science investigations, develop an attitude stabilization scheme for the payloads and support OEDIPUS C payload development;
- acquire dynamics data during flight, and compare with pre-flight simulations to demonstrate that the design technology is valid.

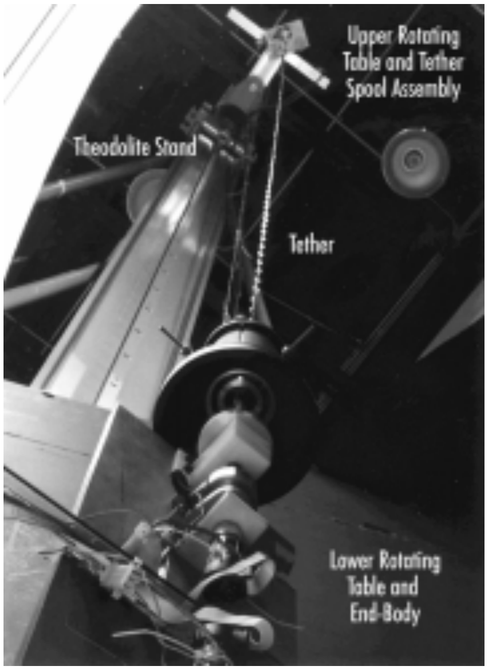


Figure 1.25 TEther LABoratory Demonstration System - TE-LAB, at DFL, CSA

Figure 1.26 Tether Force Sensor (TFS) flexure

The TDE advanced space tether technology significantly. The following are noteworthy.

- Several types of mathematical model were investigated, including both linear and non-linear approaches.
- A laboratory 'hanging spin test' facility was established at the University of British Columbia, which was able to demonstrate the essential dynamic stability characteristics of spinning tethered systems.
- A TEther LABoratory Demonstration System (TE-LAB), developed in conjunction with graduate engineering program of Carleton University, supported precise ground simulation of the OEDIPUS dynamics. The TE-LAB facility stimulated advances in gimbals suspension and in non-contact attitude measurement techniques, to meet stringent requirements of zero-g simulation in the one-g earth environment (Fig. *1.25*).
- A unique precision 3-axis tether Force Sensor (TFS) was designed by Bristol Aerospace Ltd. in conjunction with NASA Langley Research Center. The design derived from the NASA's experience with multicomponent wind tunnel balances for the aerospace industry. The TFS had two sets of strain gauges: foil gauges and piezo-resistive gauges. The TFS was manufactured by Bristol Aerospace Ltd., and Modern Machine & Tool Co., Newport News, Virginia, and was calibrated by NASA, CSA and Modern Machine & Tool Co. (Fig. *1.26*).

During the flight the subpayloads and all on-board instruments met and exceeded expectations. The deployment of the booms and tether, including severance of the tether from the payloads, was captured in space by the aft payload camera, and provided an overall confirmation of stability of the spinning subpayloads and tether dynamics. An example of the processed flight dynamics data - nutation angles of both subpayloads are presented in Fig. *1.27*.

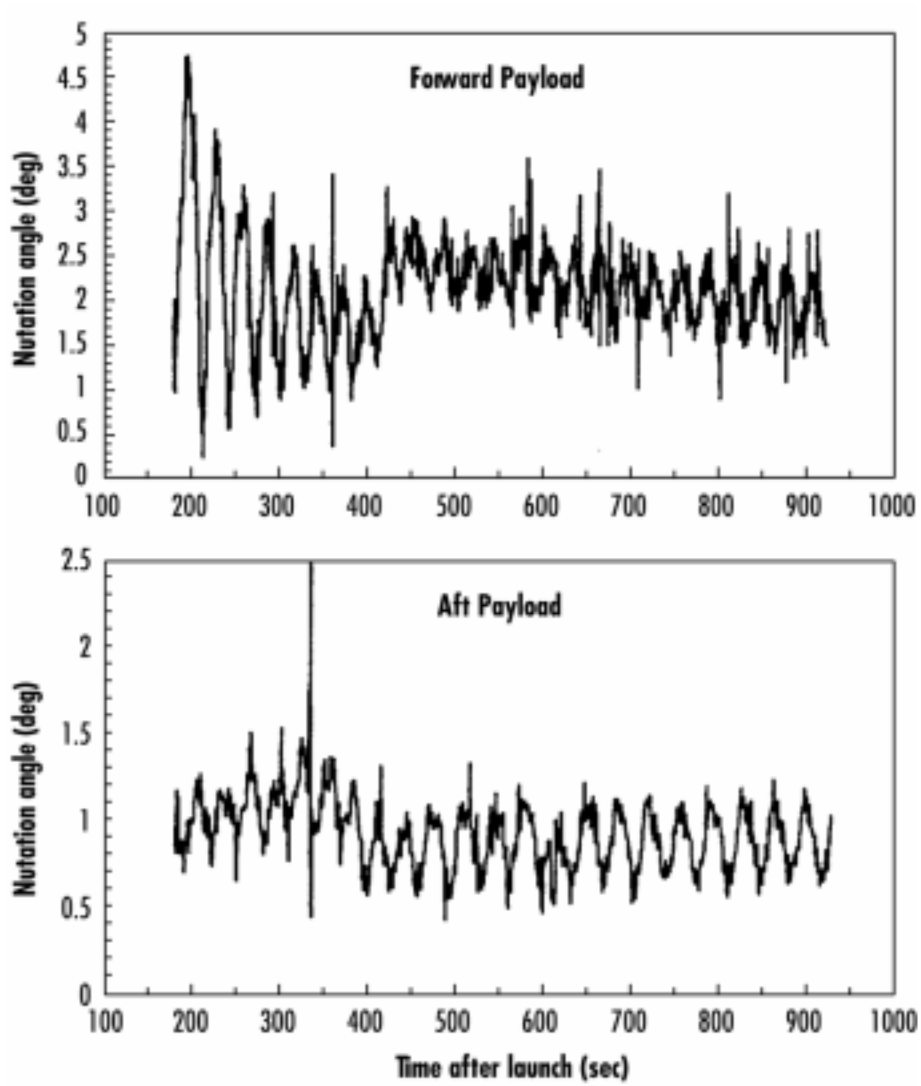


Figure 1.27 Nutation (coning) angles as function of time for OEDIPUS-C payload

The time history of the total tether force calculated based on the foil gauge outputs is presented in Fig. *1.28*. The deployment profile based on the flight data is showed in Fig. *1.29*. The major achievement was the implementation and demonstration of the major axis spinner stabilization for the tethered OEDIPUS-C subpayloads. The ground tests also served very well to understand the complicated dynamics of the spinning tethered two-body configuration and the interaction between the rigid and flexible body modes. The analysis of the damped gyroscopic modes of spinning tethered space vehicles with flexible booms turned to be a very effective tool to understand the dynamics of the *system*.

The actual spin rate during flight was 0.084 Hz well within the stable range. Full 3-D computer animation of the tethered system's dynamic behaviour and of the damped gyroscopic modes also served very well in understanding the dynamics of this configuration. The OEDIPUS-C tether deployment system is presented in Figure *1.30*. It was located in the aft end of the forward subpaylaod and it is comprised of a rotating spool, supporting structure, a magnetic hysteresis brake to control tether tension, a slip ring, high and low resolution shaft encoders, a wire guard/snare retainer, and forward tether cutter assembly.

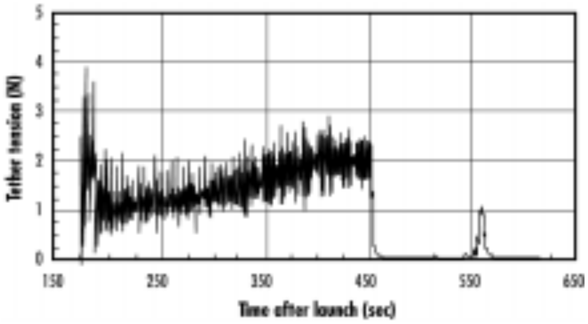


Figure 1.28 Tether tension vs. time measured by TFS during OEDIPUS C flight

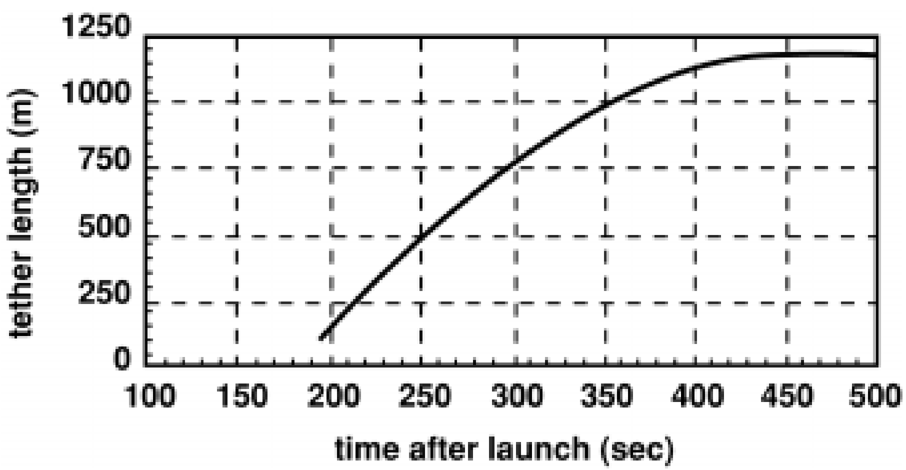


Figure *1.29* OEDIPUS-C tether deployment profile from the spool encoder data

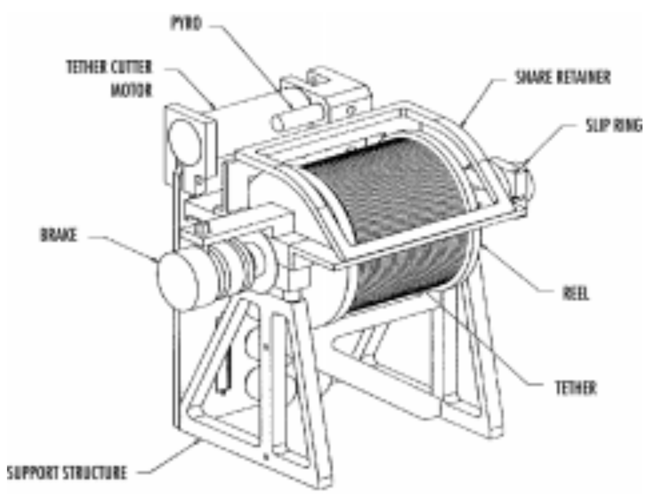


Figure 1.30
The Oedipus-C Tether Deployer

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