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TETHERED SATELLITE CONTROL MECHANISM

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ABSTRACT

The tethered satellite system (TSS), under development by the Marshall Space Flight Center (MSFC), is used for deployment and retrieval of instrumented satellites from the Space Shuttle orbiter cargo bay. These satellites can operate at very low orbital altitudes not attainable by conventional satellites. They can also operate above the Space Shuttle (higher orbital altitudes) when called for by specific missions.

The concept of maintaining satellites at low altitude by tether attachment to the Shuttle was first suggested by Professor G. Colombo of the Smithsonian Astrophysical Observatory in 1974.

Martin Marietta Corporation, under contract to MSFC, is developing the Space Shuttle mechanical equipment required to deploy, retrieve, and control a 500-kg satellite of approximately 1.4-m diameter, attached to a tether 100 km (65 to 75 miles) long. Under a U.S.-Italian agreement, Aeritalia was given the responsibility of developing the first satellite.

The system includes the satellite control mechanism mounted on a European spacelab pallet. This pallet is located in the Space Shuttle cargo bay, and includes a tether for attachment to the satellite. Figure 1 is an artist's concept of a deployed satellite and attached tether, with the Space Shuttle in the background.

TSS is a multimission program with broad science- and defense-community interest. One of the early missions selected for the tethered satellite will be operation in a region of the Earth's atmosphere too high for aircraft operations and too low for normal satellites. Presently, this region is accessible using sounding rockets that can return spot information only in areas where launch facilities are available. The tethered satellite will be capable of remaining in this atmosphere during several orbits, returning atmospheric data on a worldwide basis. A possible configuration for this type of satellite is shown in Figure 2.

The first mission selected may be an electrodynamic experiment. This mission will use an electrically conductive satellite with tether that will collect an electrical charge and flow current as it passes through the Earth's magnetic field. Figure 3 shows this type of satellite and its possible complement of instruments.

Many other science experiments are planned for the tethered satellite. It is expected that the tethered satellite will find extensive use for many years and will open the door for development of other applications, such as tethered habitable modules that create artificial gravity.

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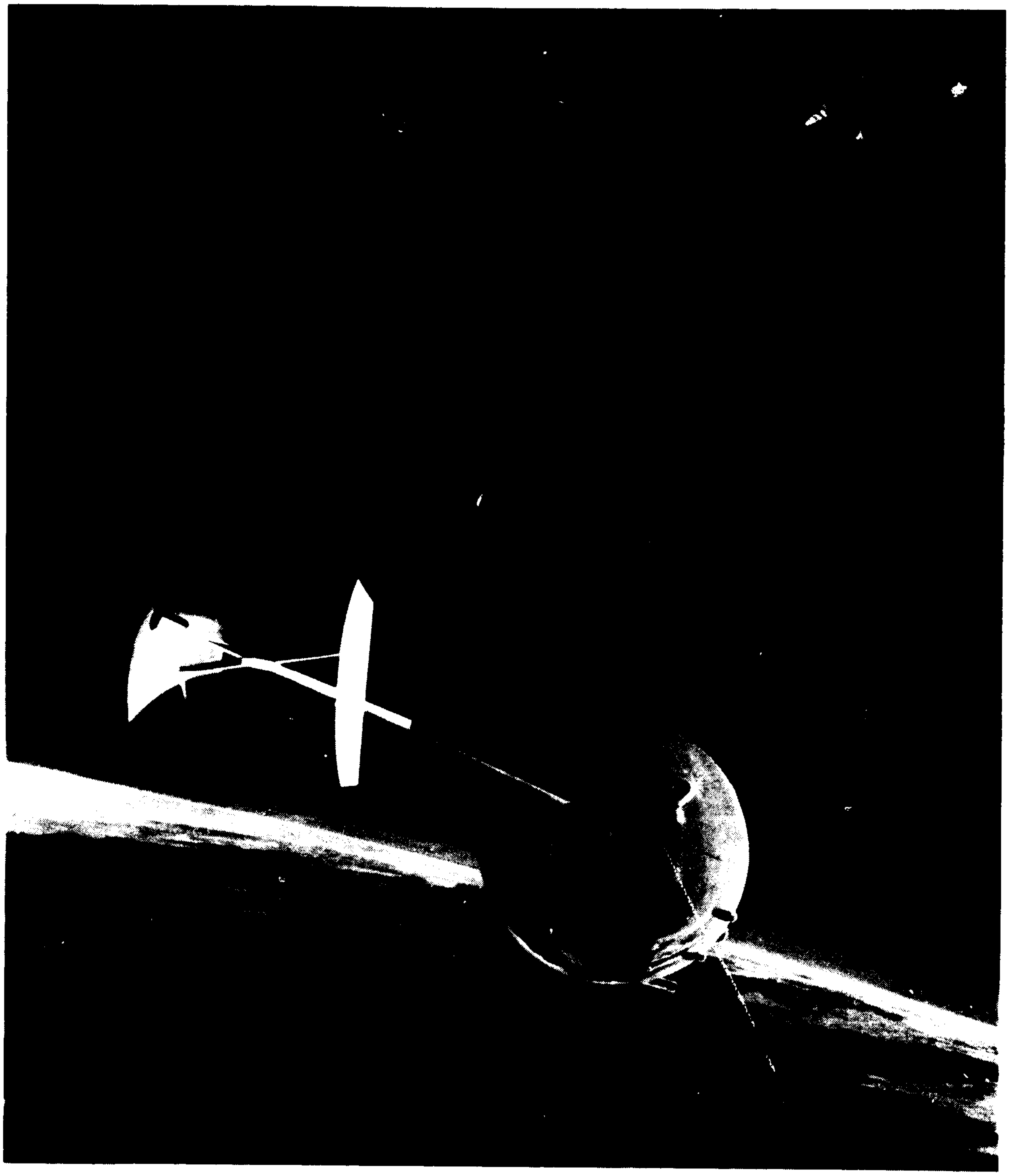


Figure 1 Tethered Satellite

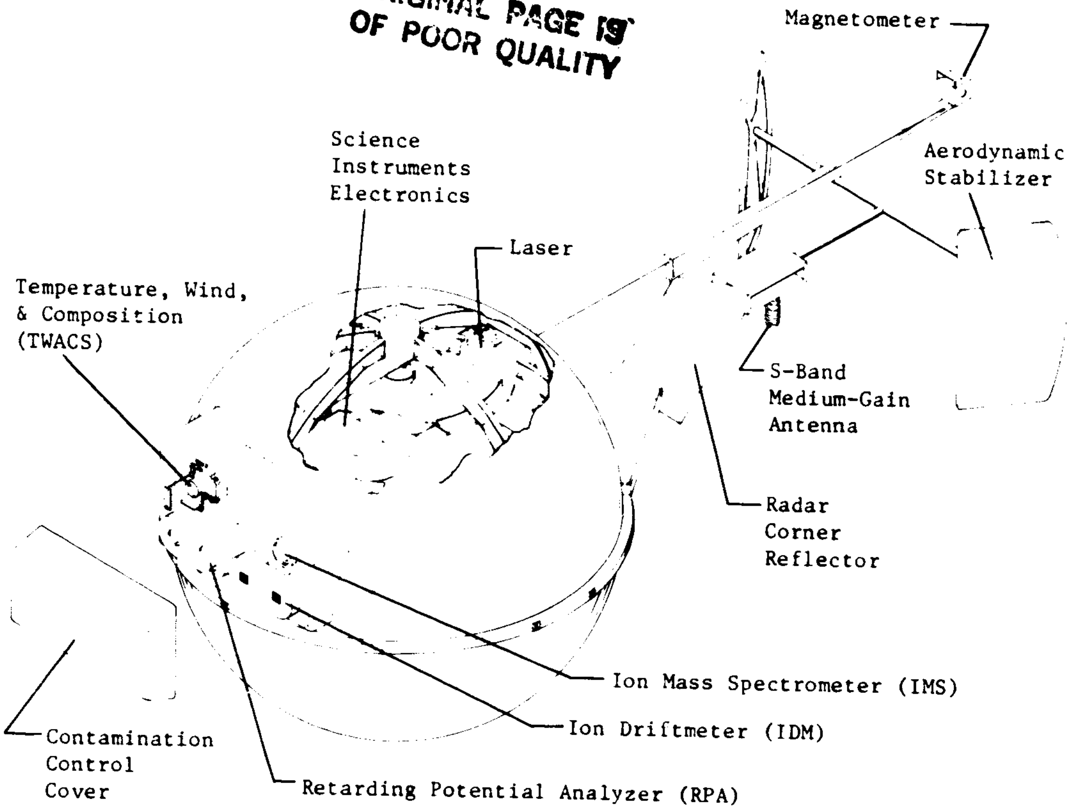


Figure 2 Atmospheric Probe Satellite

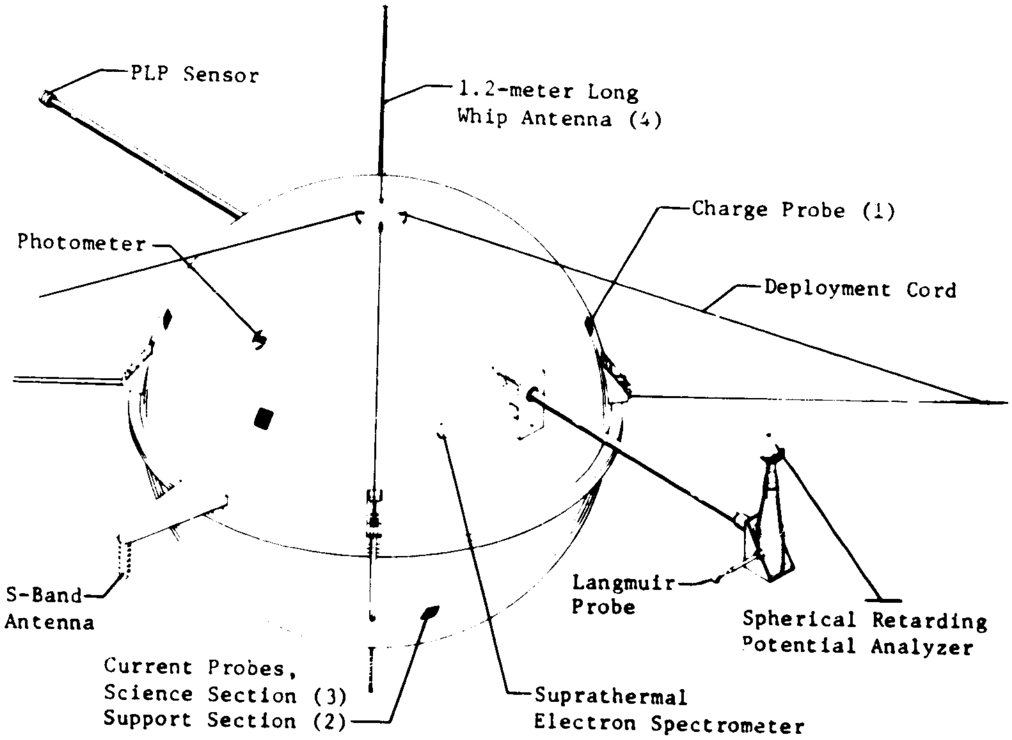


Figure 3 Electrodynamics Satellite

INTRODUCTION

When two masses are linked together (tethered) and separated a distance apart in space, a gravity gradient force between the masses exists, creating tension in the tether. The line of force points to Earth; thus, a gravity gradient stabilization exists. This physical law is the fundamental basis in the operation of a tethered satellite. Whether the satellite is positioned above or below the Space Shuttle, the same rule applies--tether tension is a function of separation distance. When separation is small, tether tension will be nearly zero. Large separations will result in high tether tensions. When the satellite is initially deployed, or is close to the Space Shuttle during retrieval, the gravity gradient force can be as low as a few grams. For practical purposes, this force is too low to affect separation velocity.

As the satellite moves away from the Space Shuttle, the satellite changes orbital altitude. As orbital altitude changes, so does orbital velocity. The result is that the satellite will move ahead of the Space Shuttle when deployed to a lower altitude and then trail behind the Space Shuttle when being retrieved.

Low gravity gradient forces at small separation distances, coupled with the changing orbital velocities of the satellite with respect to the Space Shuttle, require increased control sensitivity during close-in operations. The control sensitivity remains quite high, up to 1-km separation. At this point (1 km), tether tension will be about 2 Newtons (0.43 lb) for a 500-kg satellite. The gravity gradient tension at 125-km separation is about 250 Newtons (56 lb), which will not require such precise control.

Requirements for the tethered satellite control mechanisms, therefore, are dictated by tether and satellite orbital dynamics as they exist at time of deployment, deployment to stationkeeping (at operating orbit), stationkeeping, retrieval, and docking. The wide range of operating parameters dictate challenging design requirements for the mechanical equipment. Tether velocities range from 25 m/h to 10 m/s. At time of deployment and before docking, the tether tension (gravity gradient force) will be about 0.1 Newton (0.04 oz), while early retrieval from stationkeeping can produce tensions as high as 320 Newtons (72 lb). The high retrieval tension forces are a result of the gravity gradient force, acceleration, and aerodynamic drag.

The mission will be flown according to a preprogrammed profile made from a computer-predicted analysis of the tether dynamics. The computer output will specify tether tension, velocity, and position throughout the mission. Data produced by the mechanisms at a given time will be compared to the computer values for control of the system.

It was deemed impractical to depend on natural gravity gradient forces below 1.0 Newton (0.23 lb) for satellite control within the 1-km range. Four 0.5-Newton in-line tether thrusters on the satellite will augment tether tension during close-in operation. Pitch, yaw, and roll thrusters may be included depending on mission requirements.

The tethered satellite control mechanisms described in this paper are designed to be compatible with the characteristics of a tethered mass attached to the Space Shuttle and to accommodate a variety of future satellite missions of various sizes, weights, shapes, and purposes.

A major consideration in the design of these mechanisms is the safety of the Space Shuttle and crew. To prevent Space Shuttle damage, precautions are taken to ensure that the 500-kg satellite is always under control. Operating machinery in this environment requires close attention to safety margins, emergency shutdown, and recovery procedures.

TETHERED SATELLITE CONTROL MECHANISMS

The tethered satellite control mechanisms consist of four major subassemblies. These are shown in Figure 4.

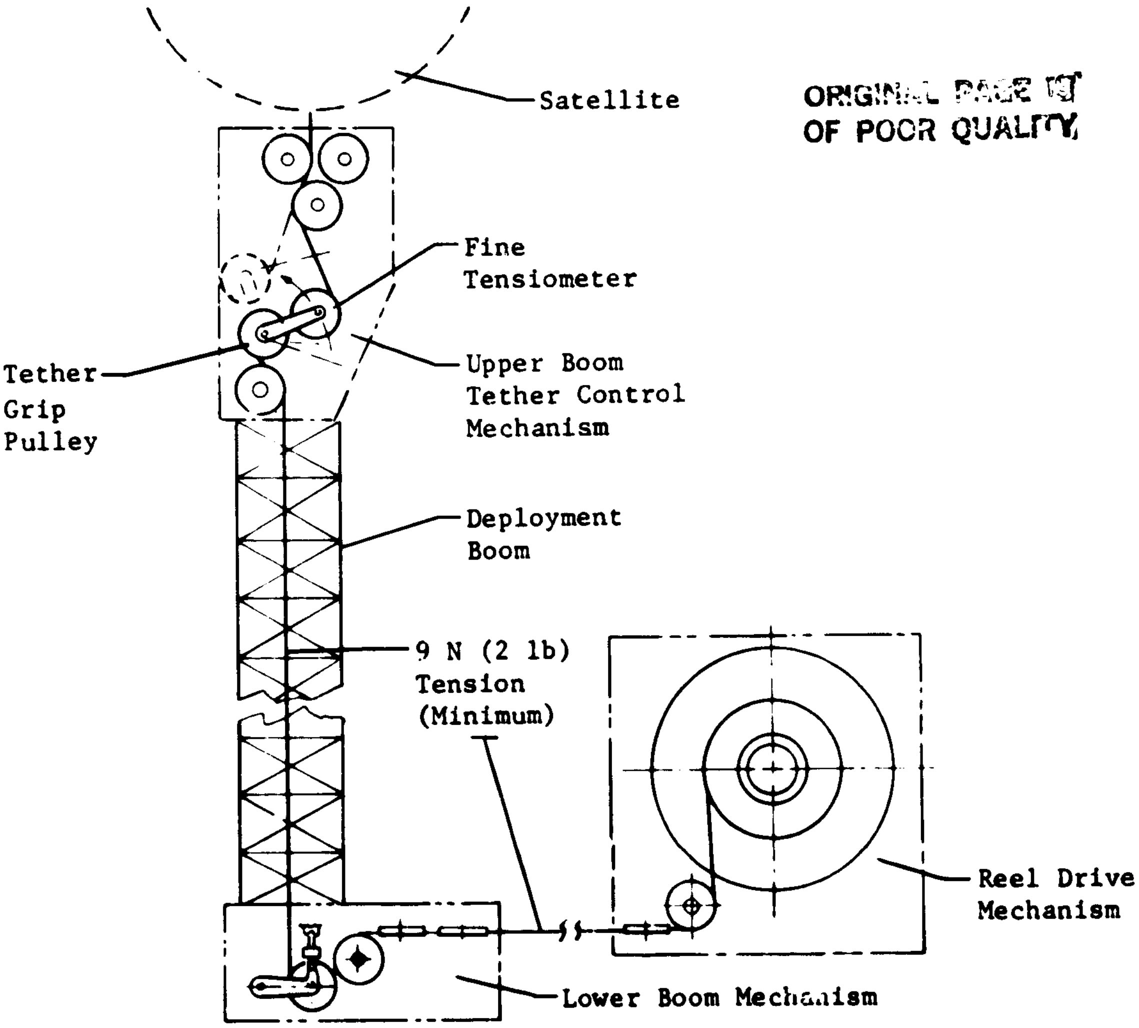


Figure 4 Tethered Satellite Control Mechanisms

Reel Drive Mechanism - This mechanism stores the tether. It is motor-driven and includes a level wind to uniformly feed the tether to the reel.

Lower Boom Mechanism (LBM) - This device serves two primary functions: (1) it measures tether length and velocity as the tether runs through the mechanism, and (2) it reads the tether tension at the reel. It also provides change of direction for the tether from the reel to the upper boom mechanism.

Deployment Boom - The deployment boom positions the upper boom mechanism with satellite out of the cargo bay. The deployment function places the 500-kg satellite 20 m away from the Space Shuttle (producing a small natural gravity gradient force), imparts an initial velocity to the satellite for deployment, and allows for satellite docking at a safe distance from the body of the Space Shuttle.

Upper Boom Mechanism (UBM) - The UBM serves three functions: (1) it provides tether control to the satellite as the satellite swings in and out of plane; (2) it reads tether tension in the low range during the early deployment and final retrieval parts of the mission; and (3) it produces additional tether tension at the reel when tether tension to the satellite is in the low range.

In addition to these four mechanisms required for operations, jettisoning devices provide for emergency ejection of any equipment that may prevent closure of the cargo bay doors.

Figure 5 shows the general arrangement of the total system installed on the European spacelab pallet. Launch and landing configuration is with the boom retracted and the satellite locked in the restraining ring. Satellite flight configuration is with the satellite launch locks released and the boom extended.

Reel Mechanism

The reel drive mechanism consists of the tether storage reel, the tether level-wind device and a 5-hp drive motor. The reel assembly is illustrated in Figure 6.

The size of the reel was determined by tether diameter and length requirements established by a number of candidate missions. Two types of tether, conductive and nonconductive, can be used. Conductive tethers (stainless-steel or copper-core cable) are required for all missions with electrodynamic experiments.

The tether diameter for these missions will range from 1.15 mm to 3.17 mm, including insulation. Nonconductive (Kevlar) tether diameter is 1.70 mm for satellites of the 500-kg size. Figure 7 shows tether reel capacity as a function of tether diameter.

A level wind geared to the reel shaft ensures proper lay of the tether on the reel. Because the tether diameter varies for each mission, the level-wind traverse rate must be variable. The method for changing this rate is shown in Figure 8. The level-wind rate is set by gears and a timing belt between the reel shaft and level-wind ball reverser. Different change-gear sets are needed to obtain the desired level-wind rate.

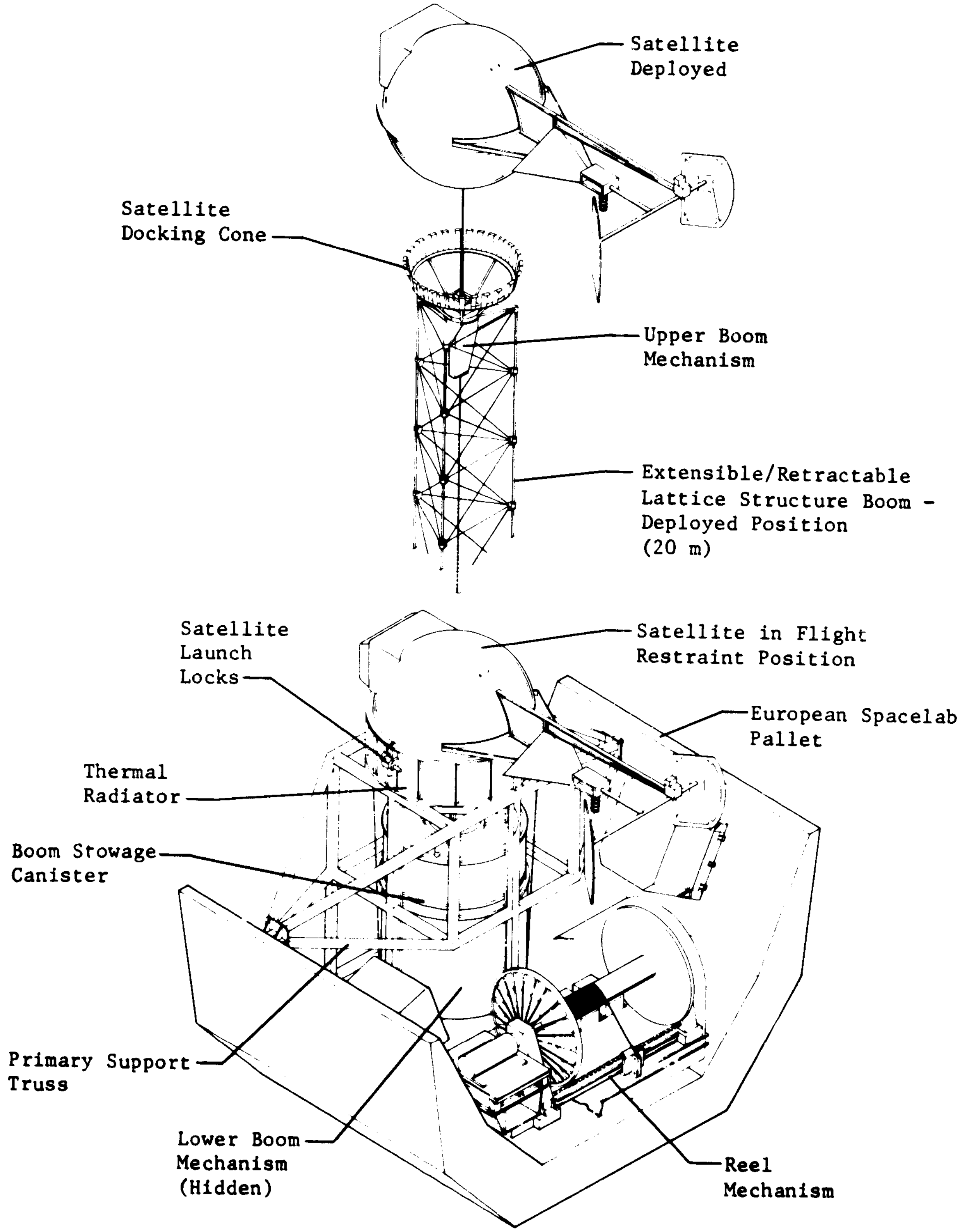


Figure 5 System Installed

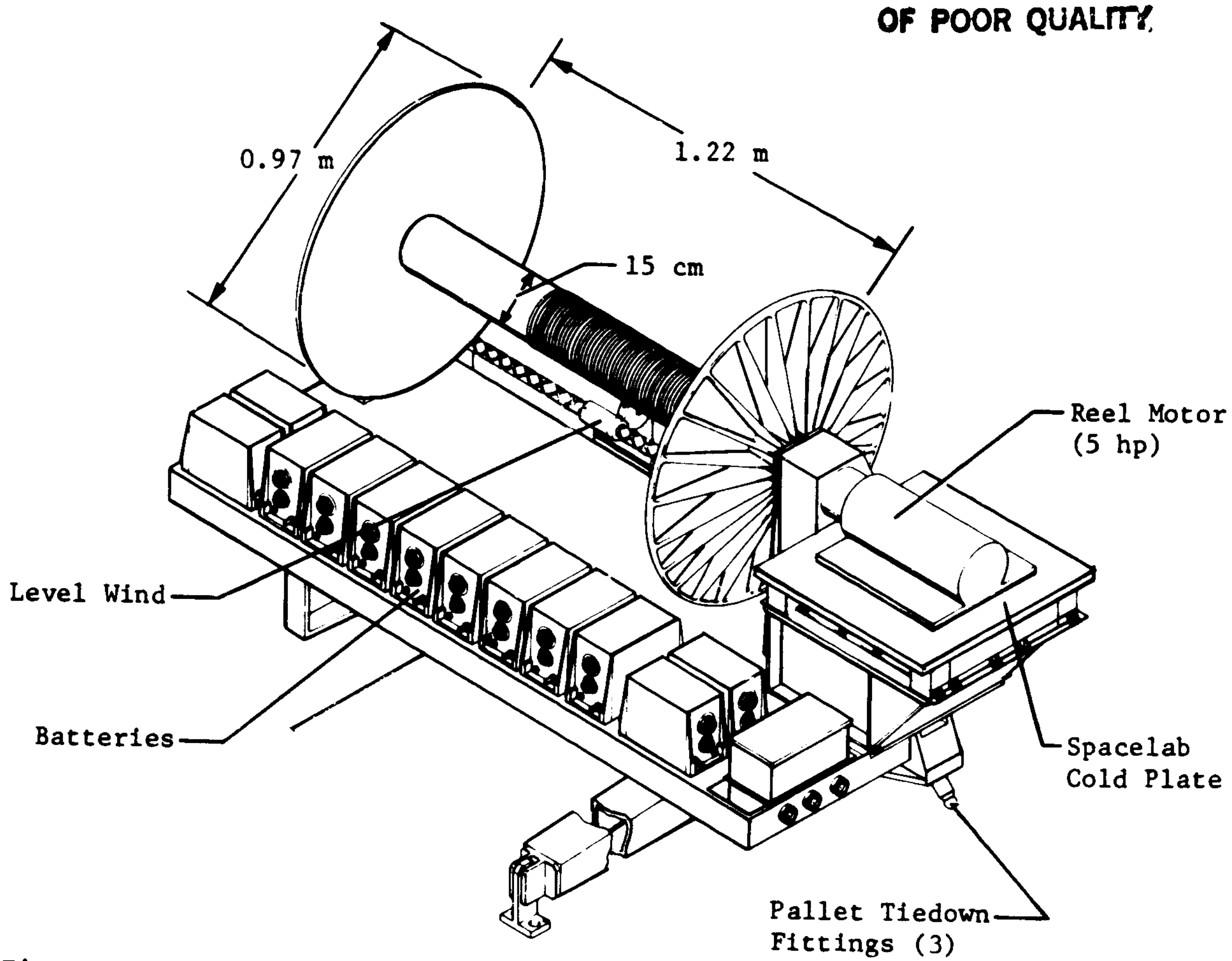


Figure 6 Reel Mechanism

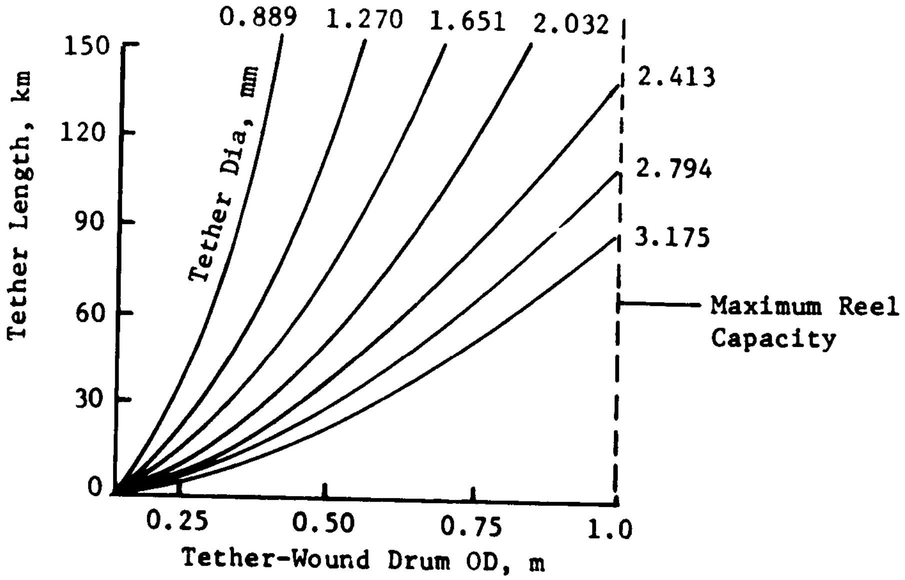


Figure 7 Tether Reel Capacity vs Tether Diameter

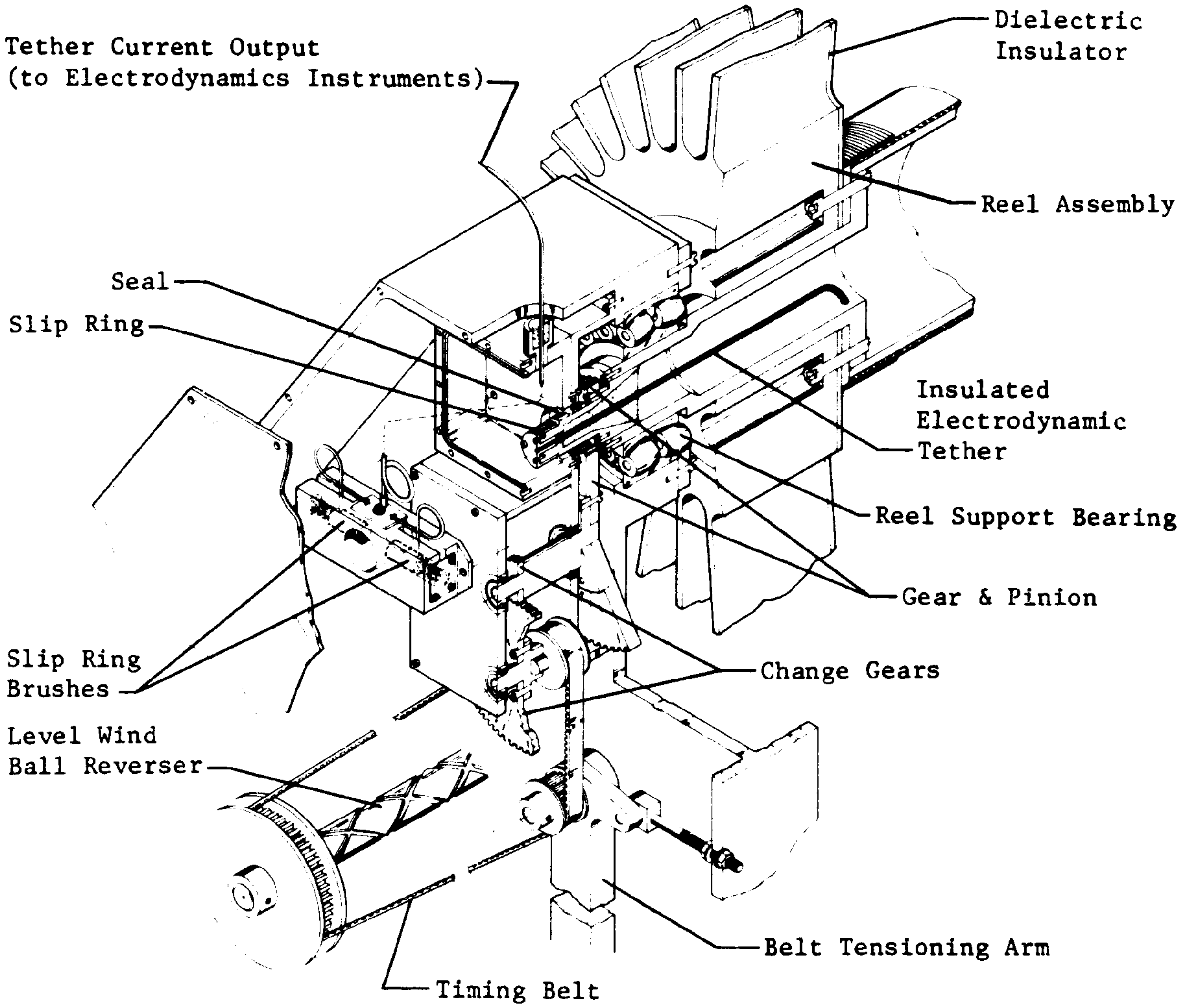


Figure 8 Reel Mechanisms and Tether Current Slip Ring

Figure 8 also shows the method used to carry electrical current out of the conductive tether (electrodynamics experiment) through the rotating reel to the cargo bay supporting equipment. The insulated conductive tether terminates at the slip-ring rotor. Slip-ring brushes complete the circuit to the supporting equipment. If tether insulation becomes damaged, a current leak could occur at any conductive point in the mechanism that is near the tether. To safeguard against arcing, all conductive surfaces near the tether are protected by dielectric material and pulleys are fabricated from nonconductive materials.

The reel is direct-driven by a 5-hp permanent magnet dc motor with tach generator and brake. The motor was selected for its wide operating range. A torque of 25 ft-lb at 2000 rpm is required during the early retrieval period when maximum tether tension may be as great as 320 Newtons (72 lb), with velocities as high as 10 m/s. Early deployment and final retrieval rates are very low (in the 25-m/h range). The motor is capable of operating as low as 3 rev/h. If the spooled tether diameter on the reel is 0.66 m minimum (26 in.), a tether velocity as low as 6 m/h is possible. These slow speeds are accomplished by supplying the motor with pulse-modulated power.

During high-horsepower operation, the motor will generate more heat than can be radiated from the motor housing surface when operating in vacuum. Therefore, the motor must be mounted on an actively cooled cold plate, as shown in Figure 6. During deployment, the motor will not be driving, but will be operating as a generator. The electrical energy generated is dissipated through resistive heaters located above the primary support truss (Fig. 5).

Lower Boom Mechanism

Figure 9 is an exploded view of the lower boom mechanism. The LBM receives the tether from the reel mechanism through a set of flat fairlead rollers. As the reel mechanism level wind traverses the length of the reel, the tether angle changes up to ±30 deg. The fairlead rollers that also appear on the level wind maintain alignment of the tether into the mechanism.

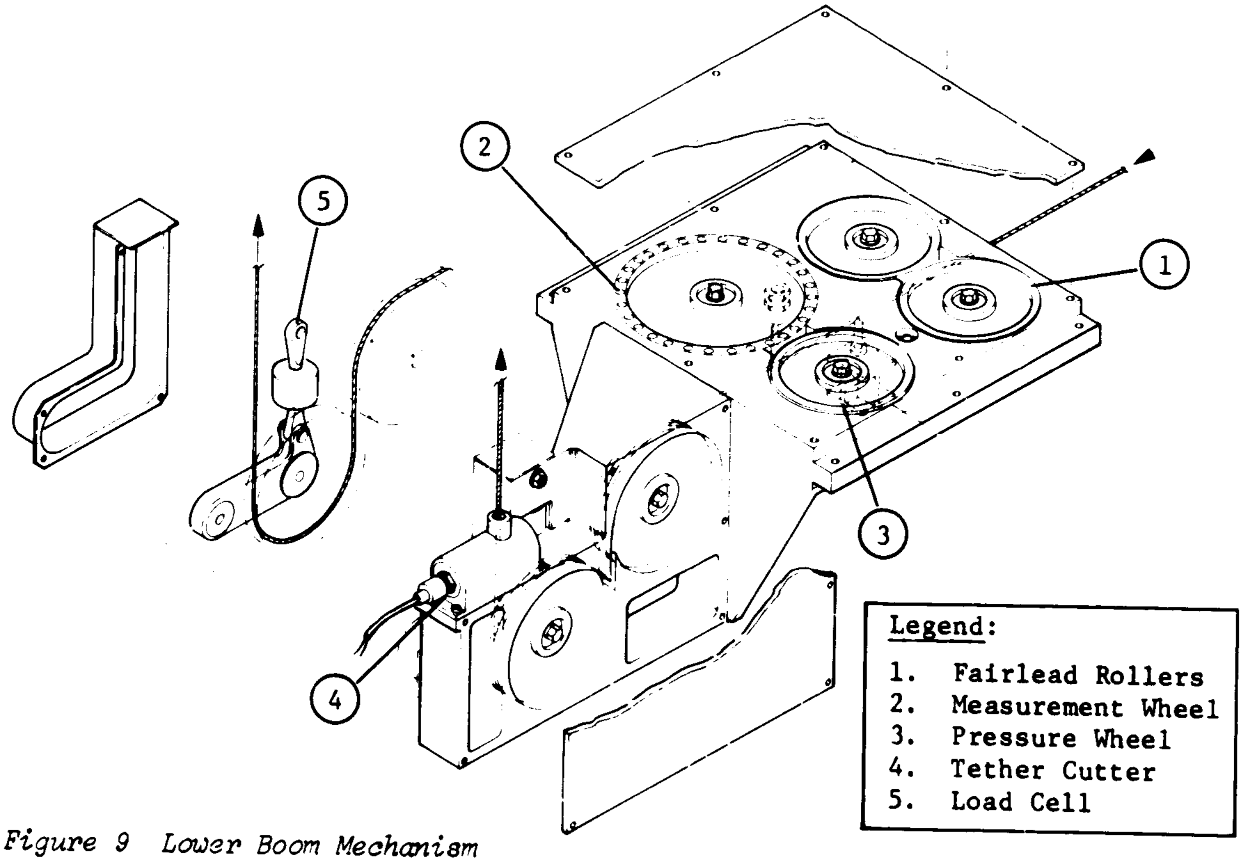


Figure 9 Lower Boom Mechanism

The flat pressure wheel forces the tether onto the flat measuring wheel, ensuring no slip rotation as the tether moves by. The measuring wheel, which is precisely 0.5000 m around, contains 30 permanent magnets at 12-deg spacing. As the wheel turns, the magnets activate the Hall-effect sensor, generating a voltage that is converted into tether velocity. The pulse counter will produce information from 1 per second to 60 pulses per second as the tether velocity varies from 1 m/min to 10 m/s. Each pulse from the Hall-effect device is totaled to supply tether length information.

Tests conducted on a breadboard measurement wheel resulted in measurement accuracies of 99.83% over 800-m lengths. The system should be very accurate for both length and velocity measurements during the first several kilometers of deployment, at which time the orbiter rendezvous radar can be used for updates; however, a computer algorithm will be required to compensate for load and thermal stretch of the tether for length measurements.

From the measuring wheel, the tether passes over a grooved pulley, under the grooved load-cell pulley, through the pyro tether cutter, and into the deployment boom to accomplish a direction change and to produce tension information. The load-cell pulley is attached to a pivoting arm, allowing free movement of the load-cell shaft. The load-cell reading is double the actual tether tension due to stroke reduction, producing a high-resolution output signal. The 890-Newton (200 lb) load cell is identified as the coarse tensiometer, because its job is to ensure adequate tether tension for proper spooling of tether on the reel. A coarse tensiometer is also needed when the tension of the deployed tether exceeds the measuring capability of the fine tensiometer located in the upper boom mechanism.

A pyro-operated tether cutter is located in the LBM in case emergency jettison of the deployment boom is required. Also, the LBM is thoroughly insulated internally and uses nonconductive pulleys for electrical isolation when conductive tethers are in use.

Deployment Boom

Telescoping, furlable tubular- and lattice-structure booms were evaluated in selecting the deployment boom design. The lattice structure boom was chosen because of its inherently greater strength margin and higher damping properties. The boom will be the continuous longeron type stowed in a spiral configuration within a canister. Deployment and retraction is accomplished by feeding the collapsed boom through a motor-driven nut at the canister outlet. This type of boom is available through manufacturers with flight-qualifying experience.

The deployed boom, which extends past the open cargo bay doors, must be capable of emergency jettison if required.

Figure 10 shows the boom canister mounted in tracks on the primary support truss. The canister is restrained by pyro separation nuts at the bottom of the truss, with ball fittings at the midpoint ring frame that react lateral loads. On release of the pyro nuts, the total canister/boom assembly is ejected. Four negator spring motors provide the accelerating ejection force, 267 Newtons (60 lb) over the full 203-cm (80-in.) track travel. The cables release from the bottom of the canister on ejection. Final boom/canister velocity, with satellite seated in the docking cone, is approximately 0.6 m/s, and without satellite is 1.3 m/s.

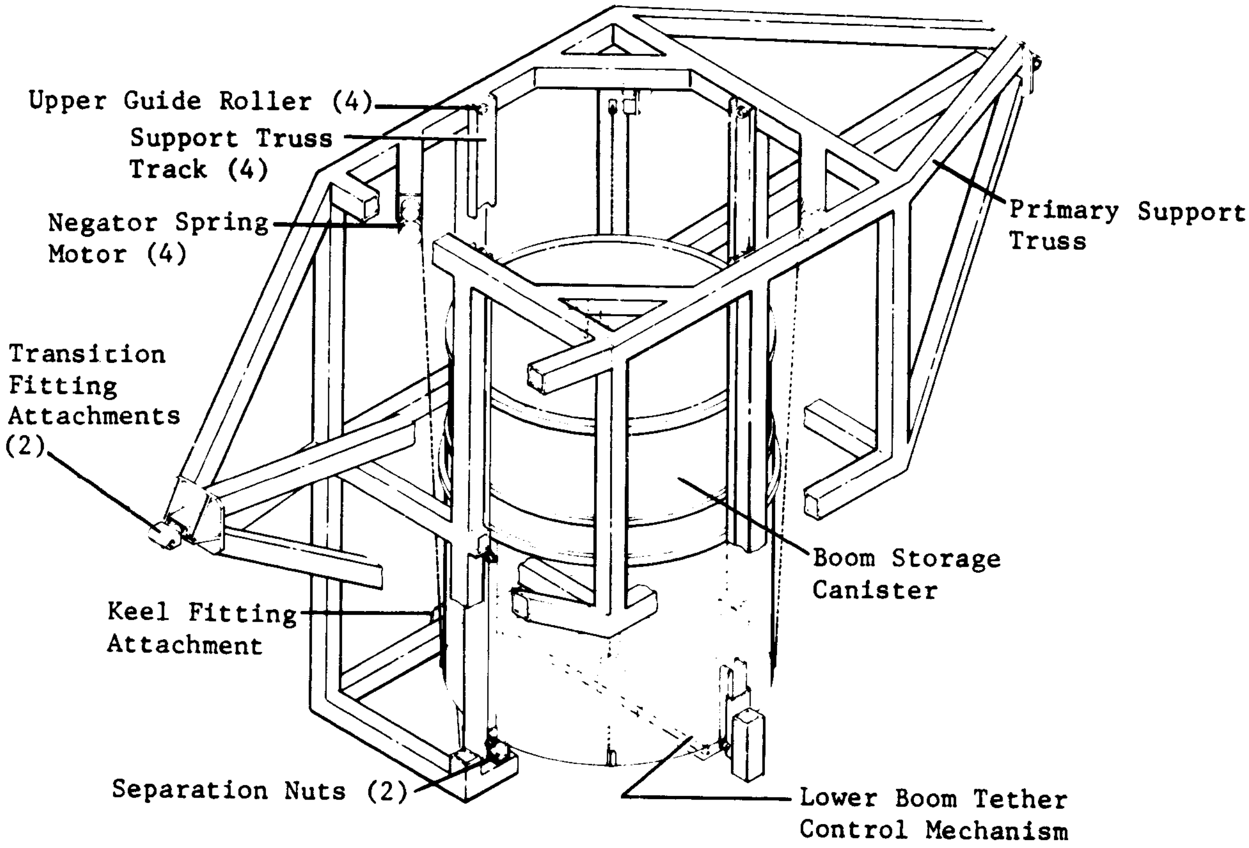


Figure 10 Boom Canister

Two electrical interface connectors are located adjacent to the pyrotechnic separation nut assemblies. These spring-loaded, nonlatched connectors separate passively when the pyrotechnic separation nuts are actuated and the canister is accelerated upward.

Two dual-cartridge tether cutters, one in the lower boom tether-control mechanism and another in the upper boom tether-control mechanism, are actuated before activation of the canister-release separation nuts.

Upper Boom Mechanism

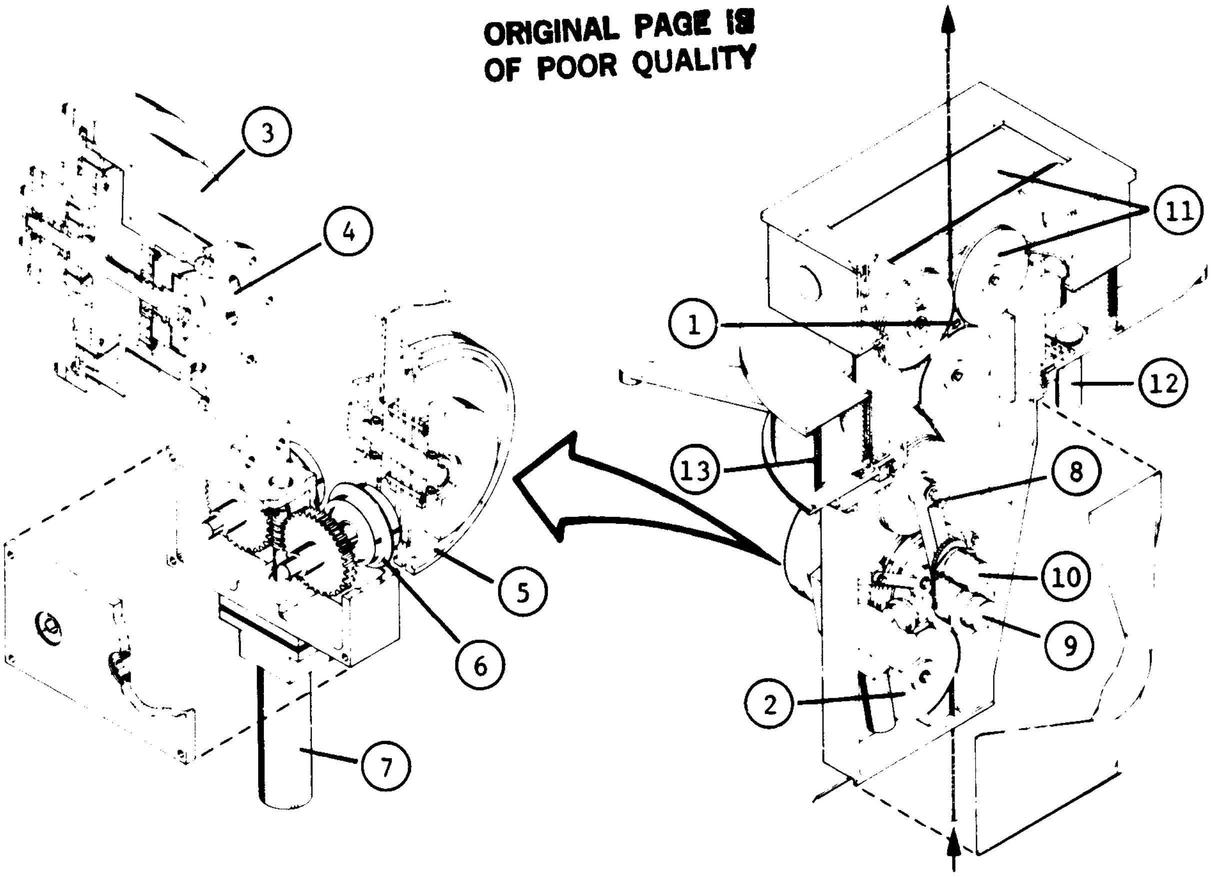
The upper boom mechanism mounts on top of the deployment boom on a large-diameter, double-angular contact ball bearing that allows the mechanism to rotate ±180 deg with respect to the Space Shuttle cargo bay. A gear motor drives a pinion and gear to cause rotation. The satellite shown in Figure 2 uses an aerodynamic stabilizer for operation in the upper atmosphere. This stabilizer must be aligned with the Space Shuttle cargo bay to allow the cargo bay doors to close, thus requiring satellite rotation before latching in the satellite support ring.

Figure 11 is an open view of the upper boom mechanism. The tether enters the upper boom mechanism from the deployment boom where a second pyro tether cutter is located for emergency jettison. The tether rides over a grooved guide pulley into the tether grip pulley assembly. The purpose of the grip pulley is to provide tether tension between the upper boom mechanism and the reel when gravity gradient tension drops below practical tether-controlling limits. Tests determined this limit to be about 9 Newtons (2 lb). A 9-Newton tension was sufficient to ensure smooth operation through the mechanisms and to give a uniform distribution of the tether on the reel. The grip pulley engages when the fine tensiometer reading drops to 9 Newtons and disengages when the fine tensiometer reading moves above 9 Newtons.

Figure 12 illustrates the grip pulley operation. The pulley is constructed of two grip plates spaced slightly wider than the diameter of the tether. Small-diameter internal shims space the grip plates a predetermined distance from the tether bearing plate to allow for grip-plate deflection. The pinch rollers mounted on eccentric shafts move in, bearing on the grip plates, which cause them to deflect and grip the tether. (Note the deflection line.) This method produces line contact pressure on the tether over an arc of approximately 90 deg and allows the unit load to remain low while generating a high total load. Figure 11 shows the grip pulley with pinch rollers. The pinch rollers are worm gear-driven as a pair by a gear-motor reducer. A potentiometer indicates pinch roller position.

The cable grip pulley that operates only during the low tether tension and low-velocity portion of the mission is coupled directly to a magnetic clutch that engages the drive motor during operation. A dc torque motor is used to drive the grip pulley; it has a dc tachometer generator to measure pulley velocity. It is necessary to match the motor speed with the tether velocity before engaging the tether grip pulley clutch.

From the grip pulley, the tether passes over the fine tensiometer grooved pulley. The tensiometer assembly consists of a torsion spring-loaded arm pivoted about the center of the grip pulley, with a free-turning pulley on the unrestrained end of the arm. The tether passes over this pulley as it exits from the cable grip pulley. The spring-loaded tensiometer arm is free to travel through a 90-deg arc. As the external tether tension increases, the spring-loaded arm pivots from the minimum tension position to the maximum tension position. A potentiometer with a 5-arc-min resolution is used to monitor the angular position of the tensiometer arm. The mechanism can be calibrated after assembly to compensate for spring inaccuracy and to generate precise data output for the rate of tether tension.



Legend:

1. Tether Cutter
2. Guide Pulley
3. Grip Pulley Drive Motor & Tach Gen
4. Grip Pulley Clutch
5. Grip Pulley
6. Pinch Rollers
7. Pinch Roller Drive
8. Fine Tensiometer
9. Fine Tensiometer Potentiometer
10. Fine Tensiometer Damper
11. Tether Guide Rollers & Pulleys
12. UBM Gear Motor Drive
13. Wire-Wrap Housing

Figure 11 Upper Boom Mechanism

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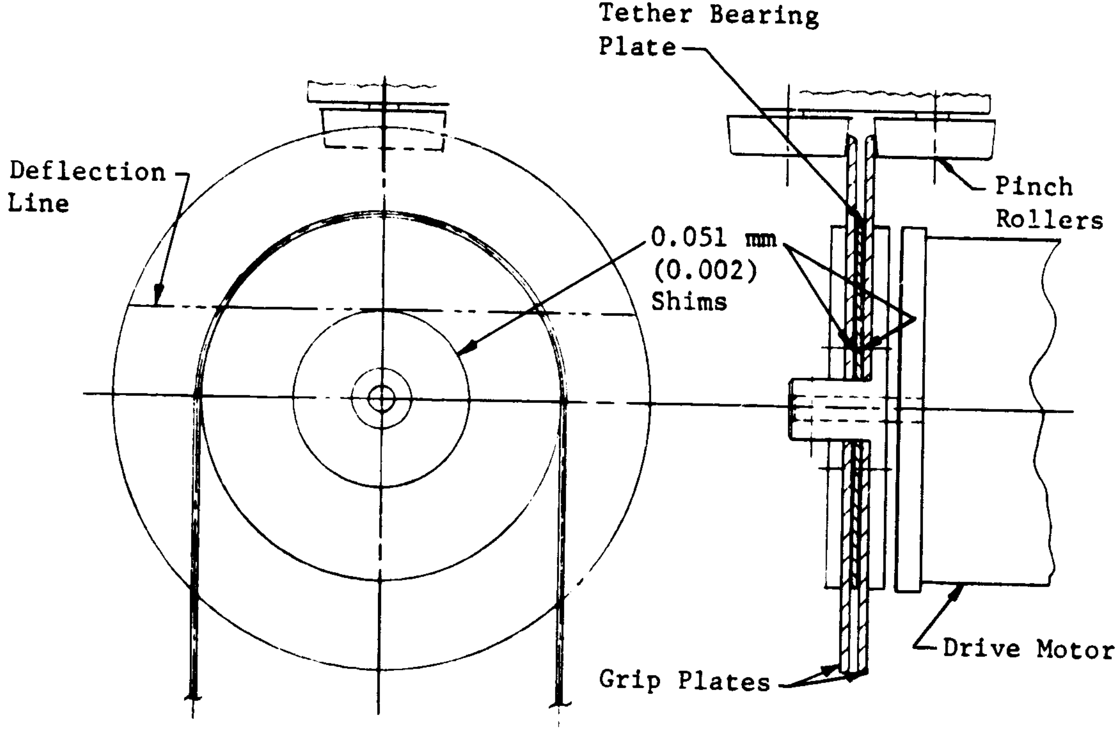

Figure 12 Grip Pulley

Figure 13 illustrates the sensitivity of the fine tensiometer. Large angle changes are generated in the low tension region, providing a 0.0022-Newton resolution. A lower resolution of 0.243 Newton is provided in the higher tension range. The tensiometer peaks at 43.75 Newtons when the arm attains a 90-deg position. The torsion spring is preloaded to 0.25 Newton and is adjusted by rotation of the slotted potentiometer coverplate. A viscous damper that provides 2.8 Newton-cm/rad/s is incorporated on the tensiometer arm.

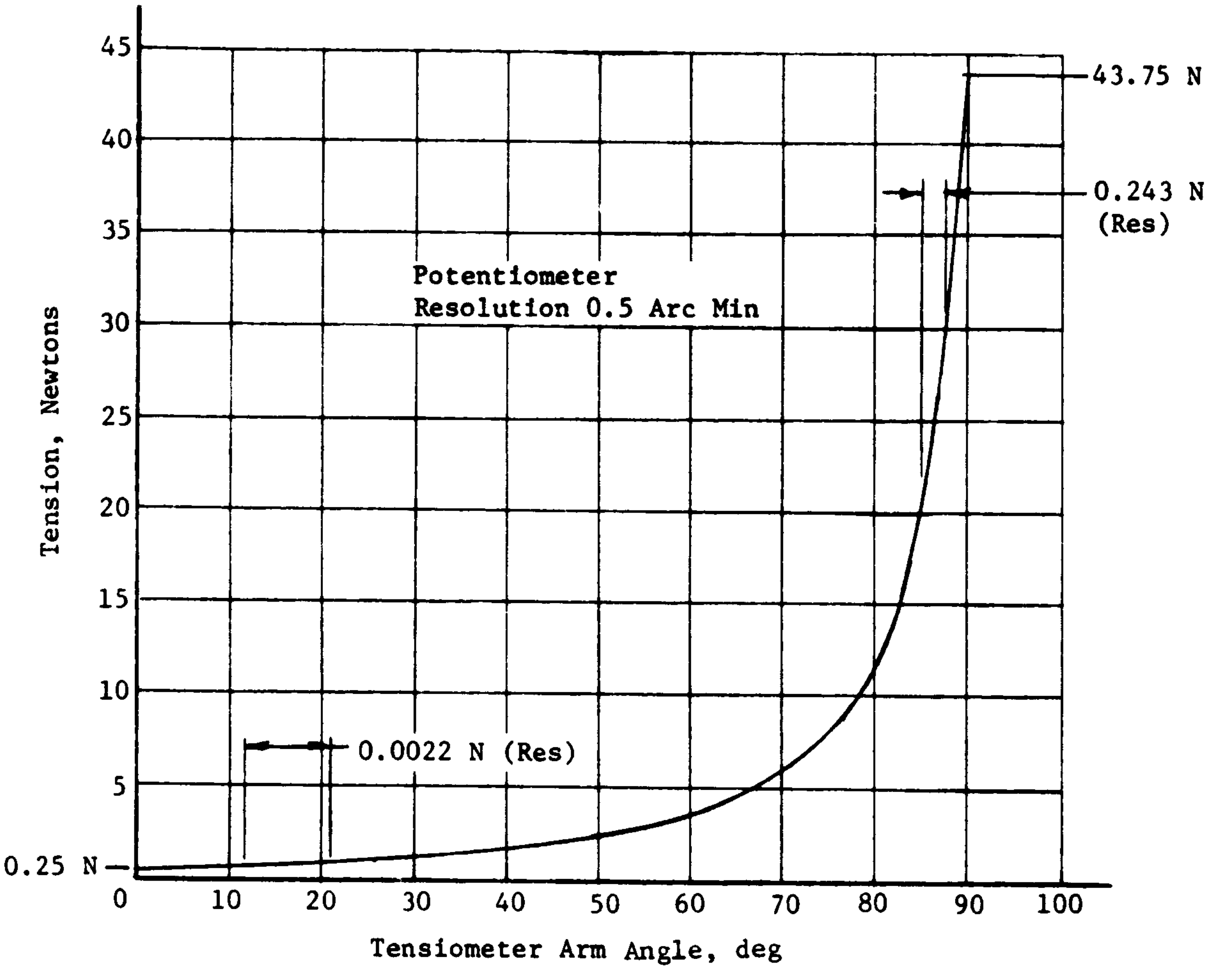

Figure 13 Tensiometer Sensitivity

The tether exits from the tensiometer and passes through the guide pulley assembly that consists of two guide pulleys and two fairlead rollers. The fairlead rollers provide a rolling surface on which the tether may bear as the satellite and tether move out of plane. In-plane tether motion is accommodated by the two guide pulleys as indicated in the drawing. The third guide pulley directs the tether to the tensiometer in a fixed plane and is positioned to set the geometry of the tether direction for proper tensiometer operation.

SATELLITE RESTRAINT ASSEMBLY AND DOCKING CONE

Figure 14 illustrates mechanisms and structures that accommodate the satellite during launch reentry and docking features.

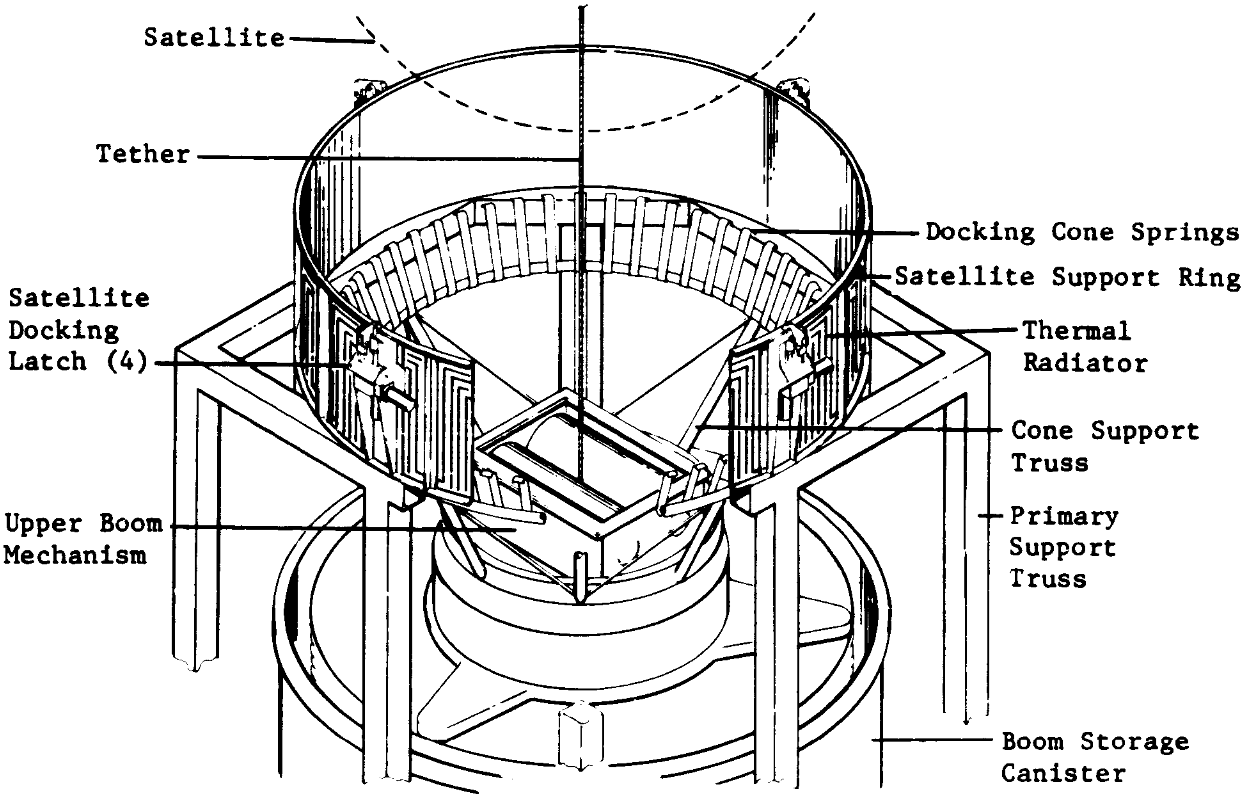

Figure 14 Satellite Restraint Assembly and Docking Cone

The assembly includes a satellite support ring that supports the satellite during launch, orbital flight, and reentry. The assembly, which is mounted on top of the primary support structure, includes an aluminum skin, stringers, ring frame, and longerons. Loads originating at the satellite are reacted into the upper ring frame and through the satellite tiedown latches.

The four satellite latching mechanisms secure the satellite circumferential flange to the restraint assembly support ring frame. The latches and ring frame are designed with enough strength that only two of the four clamps must be activated for safe reentry of the Space Shuttle.

The satellite docking cone and its support structure are mounted to the end of the deployable boom. It serves as a "soft nest" for the satellite when the boom is deployed and tether tension maintained, and during satellite docking. The cone is designed to accept docking velocities up to 0.28 m/s. The soft docking cone consists of 48 individual leaf springs fastened to a tubular, structurally supported ring frame. The docking cone is positioned to avoid tether-line contact up to the maximum tether cone half-angles of 45 deg. Docking angles are not expected to exceed a 20-deg half-cone angle, but tests are required to derive a maximum safe docking angle.

The docking cone design approach does not require precise orientation of the satellite during the docking operation. The satellite can be docked with any yaw (rotational) orientation, and any pitch and roll orientation up to approximately 20 deg. Once docking is accomplished, automatic flight control of the system is ended and boom retraction control is begun. Boom retraction control involves a boom retraction/tether-coordinated retrieval sequence that maintains a 20- to 30-Newton tether tension during boom retraction. At a position of 20 to 30 m above the cargo bay, yaw orientation of the satellite (as determined by the position of the magnetometer boom and aerostabilizer) can be visually determined. The satellite can then be properly orientated in yaw by commanding rotation of the motor-driven cone until the aerostabilizer is oriented approximately along the longitudinal centerline of the Space Shuttle cargo bay. The boom is then retracted until the satellite outer flange contacts the boom canister support ring frame. Continuing retraction of the boom until the docking cone disengages from the satellite, and maintaining tether tension will cause the satellite flange to properly seat on the support ring frame. The four satellite latches are then locked, and the boom is fully retracted.

CONCLUSIONS

Prototype, fully operational models of each tether-related mechanism described in this paper were fabricated and tested in breadboard fashion. Maximum and minimum operating velocities and tensions were simulated using a variety of tether material and sizes. These tests were performed manually (open loop), with no computer control support and with tether lengths up to 1500 m. Phase Two of the TSS project will simulate a complete mission and will incorporate automated control.

The NASA schedule calls for the first of two demonstration flights to occur in early 1987. One of the demonstration missions will be short range (10 to 20 km). The other demonstration flight will be full range (100 km). It is expected that operational tethered satellites will be flown on the average of two times each year thereafter.