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DEPLOYER PERFORMANCE RESULTS FOR THE TSS-1 MISSION[1]

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Abstract

Performance of the Tethered Satellite System (TSS) Deployer during the STS-46 mission (July and August 1992) is analyzed in terms of hardware operation at the component and system level. Although only a limited deployment of the satellite was achieved (256 meters vs 20 kilometers planned), the mission served to verify the basic capability of the Deployer to release, control and retrieve a tethered satellite. Deployer operational flexibility that was demonstrated during the flight is also addressed. Martin Marietta was the prime contractor for the devleopment of the Deployer, under management of the NASA George C. Marshall Space Flight Center (MSFC). The satellite was provided by Alenia, Torino, Italy under contract to the Agencia Spaziale Italiana (ASI).

Proper operation of the avionics components and the majority of mechanisms was observed during the flight. System operations driven by control laws for the deployment and retrieval of the satellite were also successful for the limited deployment distance. Anomalies included separation problems for one of the two umbilical connectors between the Deployer and satellite, tether jamming (at initial Satellite flyaway and at a deployment distance of 224 meters), and a mechanical interference which prevented tether deployment beyond 256 meters. The Deployer was used in several off-nominal conditions to respond to these anomalies, which ultimately enabled a successful satellite retrieval and preservation of hardware integrity for a future reflight.

The paper begins with an introduction defining the significance of the TSS-1 mission. The body of the paper is divided into four major sections: I) Description of Deployer System and Components, II) Deployer Components/Systems Demonstrating Successful Operation, III) Hardware Anomalies and Operational Responses, and IV) Design Modifications for the TSS-1R Reflight Mission. Conclusions from the TSS-1 mission, including lessons learned are presented at the end of the manuscript.

Introduction

The Deployer is a unique Orbiter-based flight facility which has the capability to deploy, control and retrieve a tethered satellite. It is designed for multiple mission usage and has the ability to deploy a satellite above (away from Earth) or below the Orbiter altitude. The TSS-1 mission represented the first opportunity to demonstrate deployment and retrieval of a tethered satellite system from the Orbiter. The nominal TSS-1 mission scenario is presented in Figure 1. Satellite deployment was planned for a distance of 20 km above the Orbiter. This paper serves to document the performance of the Deployer during its first mission. Successes and anomalies are presented with the intent of furthering the overall knowledge of hardware design for tethered systems. Results from this mission were important in determining the feasibility of

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future applications of space tethers including atmospheric study missions, high power generation techniques and tether-assisted Shuttle deorbit to provide space station boost capability.

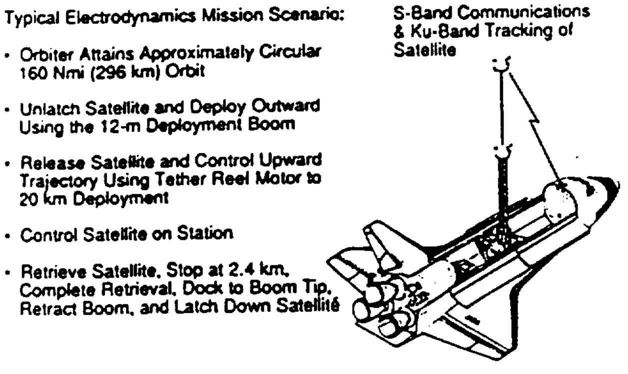

Figure 1. Nominal TSS-1 Mission Scenario

I. Description of Deployer System and Components

The Deployer mounted onto the Spacelab Enhanced Multiplexer/Demultiplexer Pallet (EMP) and was installed in the Orbiter cargo bay as shown in Figure 2. The Deployer provided the structures/mechanisms, electrical power distribution, communications/data management, and thermal control subsystems for the checkout, deployment, control and retrieval of the tethered satellite. Control and monitoring of the Deployer was accomplished by ground and flight crews.

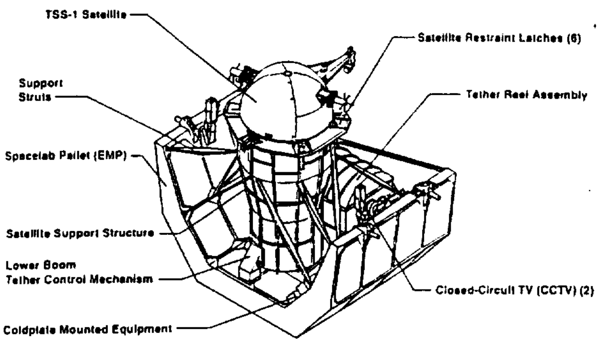

Figure 2. Deployer/EMP Configuration

A brief description of the control technique for tether deployment/retrieval is presented to aid in understanding the overall Deployer system (refer to Figure 3). Tether is routed from the reel assembly and passes through the lower tether control mechanism (LTCM), satellite deployment boom (hereinafter referred to as the boom) and upper tether control mechanism (UTCM) before terminating to the satellite.

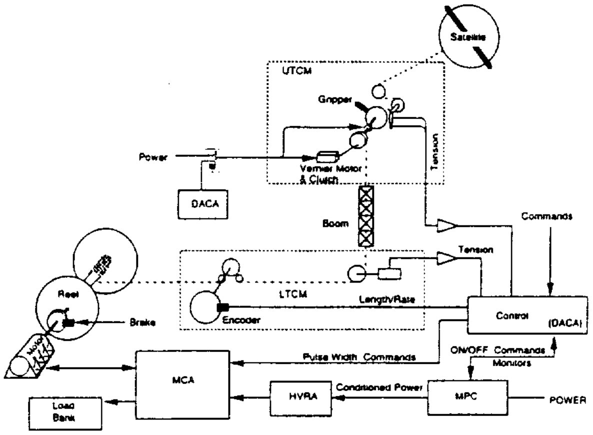

Figure 3. Deployer Tether Control Technique

The Deployer uses a closed loop scheme where reel motor voltage is pulse width modulated to control tether length and velocity. The Data Acquisition and Control Assembly (DACA) reads digital pulses from an optical shaft encoder in the LTCM and converts this information into actual tether length and tether velocity parameters. The actual values are compared to pre-stored profile variables converted to desired length and velocity in the DACA. Corrections are then made, as needed, to the pulse width commands sent back through the Motor Control Assembly (MCA) and ultimately to the reel motor. The reel motor generally acts as a generator when the satellite is being deployed, and provides resistance to control tether velocity (the generator mode is analogous to the state of an elevator motor when the elevator is descending). During satellite retrieval, the motor acts in a true motor mode and pulls tether inward at a rate directed by the DACA software control laws.

The vernier motor is used in the UTCM to overcome inboard system friction and aid in the tether deployment. The vernier motor drives a gripper pulley through a clutch, which pulls tether off of the reel during deployment. Tensiometers are located in the LTCM and

UTCM for measuring inboard and outboard tether tensions, respectively. The UTCM tensiometer is located outboard of the vernier motor and has a dual range load cell for measuring coarse tension (0 - 60 N) and fine tension (0 - 9 N). The LTCM and UTCM tension readings are not used in the direct control of the tether deployment/retrieval, but are monitored frequently by ground and flight crew operators to assess Deployer friction levels and overall performance.

The Deployer is comprised of four subsystems: structures and mechanisms, electrical power and distribution, command and data management, and thermal control.

The Deployer Structures and Mechanisms subsystem includes the reel and satellite support assemblies, upper and lower tether control mechanisms, and the conducting tether. The reel can accommodate a 22 km conducting tether for the TSS-1 mission. A timing gear/level wind mechanism is used for laying tether on the reel in a uniform manner. The reel is powered by a 5 hp dc brushless motor. The reel launch lock mechanism prevents reel rotation (and possible tether entanglement) during launch. A brake mechanism is used for stopping reel movement upon crew command, or automatically when pre-set tether velocities are exceeded.

The Satellite Support Assembly (SSA) consists of the Satellite Support Structure (SSS), with latch mechanisms and alignment guides installed on its exterior surface (see Figure 4). The SSA also houses the U1 umbilical mechanism, U2 umbilical mechanism (for TSS-1 only), boom, boom ejection mechanism and docking ring mechanism.

Six restraint latch mechanisms secure the satellite during non-deployed operations. Two motor driven mechanisms provide separation capability of the Deployer to satellite umbilical connections. The U1 mechanism separation occurs after the satellite is switched to internal power and prior to boom extension. For TSS-1 the second umbilical connector (U2) was separated after the Orbiter to satellite RF communication link was verified. The satellite deployment boom is mounted inside the SSS and consists of a deployable/retractable mast (measuring 12 m when fully extended) with redundant drive motors. The boom ejection mechanism allows ejection of the boom as a contingency. The docking ring mechanism is mounted at the top of the boom and provides a compliant interface for satellite docking. The docking ring can also rotate the satellite for proper orientation during latching and RF communication alignment operations.

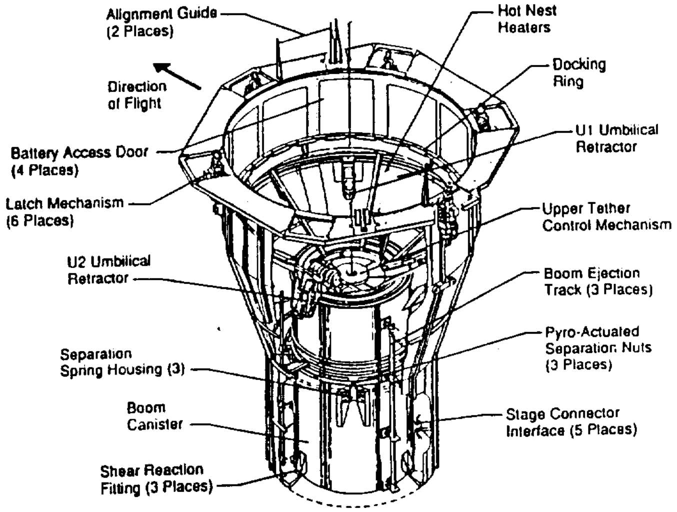

Figure 4. Deployer Satellite Support Assembly (SSA) Configuration

The LTCM is located near the base of the SSS and consists of tether guards, tensiometer and encoder. A tether cutter located outside the LTCM is used for severing the tether near the base of the boom in the event of an emergency. The primary components in the UTCM (installed on top of the boom) include the vernier motor, tensiometer and upper tether cutter.

The conducting tether measures 22 km in total length to accommodate a planned satellite deployment distance of 20 km (TSS-1 mission). The tether has a rated breakstrength of 1780 N, and a voltage withstand capability of 10 kV.

The Deployer Electrical Power and Distribution Subsystem (EPDS) provides power conditioning and distribution equipment for Deployer components and the satellite during pre-deployment checkout operations. Orbiter +28 V power is routed to the Deployer EPDS via the EMP Power Control Box. The EPDS consists of the Motor Power

Conditioner (MPC), Motor Control Assembly (MCA), Data Acquisition and Control Assembly (DACA), High Voltage Relay Assembly (HVRA), and the Pyrotechnic Initiator Controller Assembly (PICA).

The Motor Power Conditioner (MPC) regulates Orbiter power to provide continuous 26 V power for driving the reel motor. The MPC also provides regulated 33V power to the satellite (via the U1 umbilical) during predeployment checkout operations, thus preserving the satellite batteries for deployed operations after satellite release. The Motor Control Assembly (MCA) provides three phase pulse-width modulated power to the reel motor as well as distribution power to Deployer mechanisms and heaters. Switching of the reel motor between motor mode and generator mode is accomplished with circuitry inside the MCA. Motor current is limited to 6 A (TSS-1 and 1R missions) by the MCA.

The Data Acquisition and Control Assembly (DACA) serves as the primary component in command and telemetry processing for the Deployer (i.e., the "brain" of the Deployer). Its primary purpose is to execute the pre-stored mission profile, using control laws for tether deployment/retrieval by calculating the pulse width modulated voltage to be applied to the reel motor. The DACA also receives input signals from an incremental encoder for determining deployed tether length and tether velocity. During pre-deployment checkout activities the DACA issues discrete satellite commands and collects discrete satellite monitors via the U1 and U2 connections. In addition, satellite telemetry is received by the DACA and sent to the Orbiter Payload Data Interleaver (PDI) during the checkout operations. The DACA provides telemetry to the Orbiter for on-board display and transmission to the ground.

The High Voltage Relay Assembly (HVRA) provides power isolation between the MPC and the MCA/reel motor to prevent inadvertent reel motor powering. Two Pyrotechnic Initiator Controller Assemblies (PICAs) are used for providing separate and redundant power to initiate tether cutting and boom ejection operations. The PICAs are controlled by the crew via the Deployment Pointing Panel (DPP) in the Orbiter Aft Flight Deck (AFD).

The Command and Data Management Subsystem (CDMS) uses the DACA and MCA for command and data processing. DACA software processes sequential command routines in response to AFD and ground initiated commands to perform Deployer functions and executes the stored control laws for tether deployment and retrieval. The MCA receives commands from the Orbiter and the DACA and has the capability to monitor analog parameters throughout the Deployer.

The Thermal Control Subsystem (TCS) is designed to maintain Deployer equipment and structure temperatures within limits required to ensure successful operation. Specifically, the TCS uses the EMP active coolant loop, thermostat-controlled heaters, selective surface coatings and multi-layer insulation (MLI) blankets for regulating the thermal environment. A dedicated series of heaters (Hot Nest Heaters) located inside the SSS are used to maintain a proper temperature range for the satellite gyroscopes following satellite docking.

II. Deployer Components/Systems Demonstrating Successful Operation

The following section describes the Deployer elements that operated successfully during the TSS-1 mission. The results are presented in the chronological order of mission events. Brief references will be made to anomalies, which are described more fully in the next section.

Deployer activation was successful including power up of the DACA, MCA and Deployer heater circuits after opening the payload bay doors. The DACA self check sequence was nominal at the beginning of Deployer activation; the DACA performed all functions without error throughout the remainder of the mission. The reel launch lock mechanism successfully held the reel in a fixed position during launch and was released after initial DACA power-up. Proper monitor readings indicating launch lock release were observed. The reel motor checkout performance was nominal. This was run to verify the integrity of the current limit circuit and to eliminate any slack tether in the system.

Reel motor current seen in Figure 5 compared favorably with the expected maximum of 6 A.

The vernier motor checkout was run after the reel motor checkout. This sequence served to verify proper operation of the vernier motor, vernier clutch and control electronics. Figure 6 shows the inboard tension is approximately 26 N greater than the outboard tension during the checkout; this met the criterion that a 15 N minimum tension difference be present.

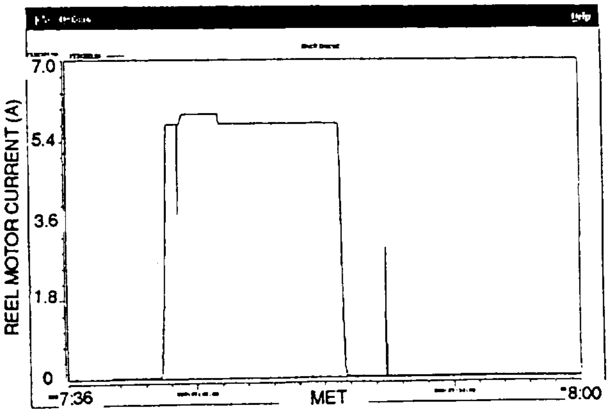

Figure 5. Reel Motor Checkout Current

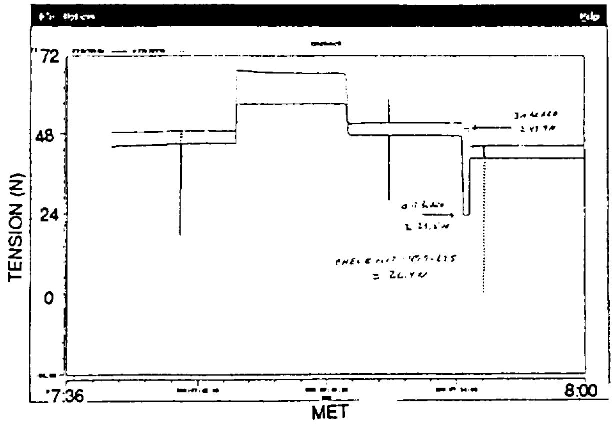

Figure 6. Vernier Motor Checkout

Satellite restraint latch checkout was completed successfully. This sequence consisted of opening one group of three latches (Latch Group 1) and closing them via the Orbiter PF1 command line. Latch Group 2 was subsequently opened and left open as planned. Latch Group 1 was used to secure the satellite to the Deployer until deployment was initiated. The maximum current values (2.5 A maximum for each latch group) and drive times to open the latches (90 seconds nominal) were not exceeded.

Satellite checkout operations were initiated with the successful powering of the Deployer MPC. This operation marked a significant technical accomplishment, since the MPC was developed late in the program, well after the satellite electrical design was finished. A significant amount of ground testing with electronic breadboards and flight hardware pre-flight led to the successful operation of this interface during the mission. Following satellite activation, the reel and vernier motor checkouts were repeated with nominal results.

Latch Group 1 was subsequently opened in preparation for boom extension. Latch motor operations were nominal. All fully open monitors were received. The U1 umbilical separation command was sent, and the umbilical separated successfully. The separation monitor (indicated by loss of signal in a wiring turnaround) and the three fully retracted monitors (indicated by mechanical limit switches) were received. Boom extension was initiated, with a smooth boom extension observed. Nominal boom motor currents were seen to be within the expected range of 1.0 to 4.5 A. The total extension time was approximately 11 minutes, which was within the pre-flight prediction of 10 to 17 minutes. This successful operation represented the first time the boom was operated in a zero-g environment.

While the tether was pulled off the reel during boom extension, the tension readings were somewhat higher than expected: approximately 100 to 120 N vs 60 N observed in ground tests. This tension, and the resulting brake torque, however were still within the range of the brake design. The increased brake torque proved to be advantageous during recovery from a tether jam condition that occurred later in the mission (details of this recovery procedure are discussed in Section III). The fully extended monitor readings for the boom were received at the completion of the extension.

The command to separate the U2 umbilical connector was then sent. This operation was unsuccessful. Multiple attempts were made to separate the U2 connector with no success, until a successful separation was achieved with the aid of an Orbiter Z thruster burn. This anomaly is more fully described in Section III.

The first attempt to deploy the satellite resulted in a deployed length of 0.13 m before a stop was reached. Post-flight analysis indicated the stop was caused by a jam in the UTCM. The tether was subsequently retrieved, and the second deploy attempt was successful using an altered sequence of events. The details of this anomaly are contained in the next section of the paper.

Satellite deployment continued to a distance of 179 m, where a stop occurred. All parameters were within expected ranges up to this stop point. Post-flight findings indicated a mechanical interference with the reel level wind assembly caused the system to stop at this position. Additional information on the mechanical interference is presented in Section III. Recovery from this position included retrieving the tether approximately 13 meters using manual pulse width control of the reel motor, and restarting the deploy sequence in a manual mode. The manual pulse width mode was accomplished with the crew issuing pulse width commands (vs following pulse width commands controlled by the DACA). The use of the manual pulse width technique demonstrated an important contingency capability of the Deployer.

Deployment was resumed to a distance of 256 m, where tether movement stopped again. The previously mentioned mechanical interference was determined (during post-flight inspections) to cause this stop, as well. The system remained at this length for approximately ten hours while flight and ground crews developed recovery plans. During this time, the satellite and tether dynamics were stable. An apparent twist of the tether required periodic firing of the satellite yaw thrusters to maintain a fixed satellite attitude, however the tether twist did not degrade the overall stability of the Orbiter-satellite tethered system.

The tether was subsequently reeled in to a distance of 224 m (an attempt to get a "running" start in order to move past the 256 m stop point), where a tether jam in the UTCM prevented further movement when deployment was reinitiated. A troubleshooting sequence was required to clear the jam as described in Section III. Following the successful clearing of the jam, no more attempts were made to continue satellite deployment. Retrieval of the satellite was performed under manual pulse width control. System tensions, frictions and currents were within expected ranges during the retrieval sequence. The brake trip circuits were enabled at the proper times per the flight plan and operated properly (i.e., no automatic brake application occurred since velocities remained below the specified limits during the retrieval period).

Satellite docking was performed with no anomalies. The docking process consisted of pulling the satellite in with the tether until it rested on the Deployer docking ring assembly. Retraction of the boom was initiated during a loss of signal (LOS) period between Orbiter and ground. Crew reports following the LOS, and a review of post-flight data indicated successful operation of the boom during this period. Fine alignment of the satellite was performed to ensure proper positioning for subsequent latchdown. This was a critical activity that had been studied extensively prior to the flight. The alignment action took place with the activation of the docking ring motor, which rotated the satellite in an azimuthal direction and a series of boom operations to assure the satellite was in the proper orientation for final boom retraction and latchdown. Boom retraction was then continued until the three redundant fully retracted monitor indications were received. Boom motor current and retraction time were within expected ranges.

The satellite was latched down with nominal latch motor currents and run times. All fully closed monitors were received. This was a critical step in ensuring the safe configuration of the Deployer and satellite for payload bay door closure, and the subsequent Orbiter reentry and landing. Safe landing configurations agreed to pre-flight included: at least one group of latches closed (three latches located 120° apart) or any four latches closed.

Since all latches closed sucessfully, there were no Deployer-related safety concerns during preparation for reentry. Activation of the Deployer Hot Nest Heaters was successfully accomplished after satellite latchdown, thus maintaining the proper thermal environment for the satellite during preparation for reentry.

Post-flight inspections of the Deployer were conducted with no significant hardware degradation observed. Minor refurbishment efforts were required, in addition to the design modifications that were needed to correct the operational problems that occurred during the mission.

A thorough test program on a 300 m tether section removed from the full length tether was also conducted. The 300 m section included the 256 m length that was deployed and exposed to the free-space environment during the mission. The purpose of this test was to verify the flight worthiness of the remaining tether length on the Deployer for a reflight mission. Multiple samples taken from the ends of the 300 m length were subjected to mechanical and electrical tests. Those samples near the satellite end had been fully exposed during the mission, and had been subjected to seven mechanical cycles through the mechanisms (ground testing and flight operations combined). The samples taken from the Deployer end had remained on the reel during the flight and had been exposed to three mechanical cycles during ground tests.

No observed failures below the 1780 N requirement for a new (unused) tether were seen with the post-flight samples. A comparison of tether breakstrength results pre- and post- flight is shown in Figure 7. Pre-flight breakstrength values averaged 1906 N, while the post-flight samples near the Deployer end and satellite end averaged 1875 N and 1818 N, respectively. It is important to note that, although the exposed samples (satellite end) show a 4.6% average decrease in strength from the pre-flight value, the breakstrength was still above the acceptance limit of 1780 N for an unused tether, and well above the Deployer system requirement of 980 N. The largest factor in decreasing tether breakstrength has been attirbuted to repeated cycling through the mechanisms. This has been further substantiated with additional ground tests at Martin Marietta, where repeated cycles were shown to decrease breakstrength approximately the same amount seen on the flight tether samples. Post-flight visual inspections revealed no damage to the tether strength member after exposure to the flight environment.

Multiple samples of the 300 m length were also subjected to a high voltage test (10 kV) with no failures observed, indicating the tether conductor insulation was not degraded. No physical deterioration of the tether was observed which could impact performance characteristics (only minor cosmetic changes were noted in some sections of the outer jacket). The results of the tether inspection/test effort indicated that no degradation of tether properties occurred during the TSS-1 mission, and that the remaining tether length was acceptable for reflight.

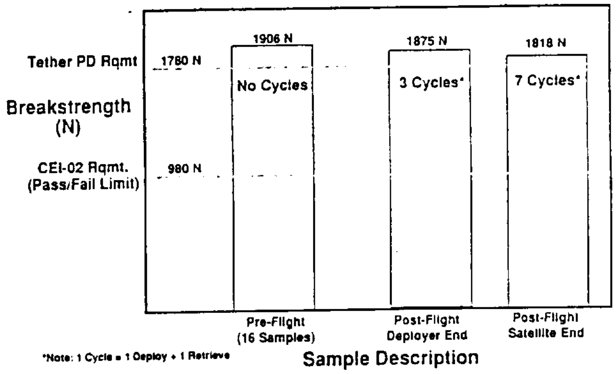

Figure 7. Tether Breakstrength Comparison (Pre- and Post-Flight)

III. Hardware Anomalies and Operational Responses

The three types of anomalies and corresponding responses referenced in Section II are described in detail in this section. They will be presented in the following order:

Anomaly 1: Deployer to Satellite U2 Connector Did Not Disconnect by Preplanned Means

Anomaly 2: Satellite Did Not Deploy During the Initial Flyaway and at 224 Meters

Anomaly 3: System Stopped Deployment and Would Not Proceed Past 256 Meters

These anomalies revealed the risk of first-time hardware operation in a space environment, and exposed the realities and limitations of ground testing before flying the system. The Deployer design, however, was robust enough to recover from the anomalies. The design enabled a successful satellite recovery and reflight opportunity. As these anomalies are discussed, it is important to note how the inherent Deployer design aided in the recovery efforts. The general design philosophy included the use of two types of commanding techniques: 1) automated sequences initiated by a single command to perform a function (raise boom, pull umbilical, deploy satellite, etc.), and 2) detailed control of an individual function (e.g., commanding a single relay) in a backup, or contingency mode. The backup feature of the design was invaluable during the recovery activities.

Anomaly 1: Deployer to Satellite U2 Connector Did Not Disconnect by Preplanned Means - During the first attempt to demate the U2 umbilical, there was no indication from the separation monitor (two connector pins shorted together on the satellite-side connector) that the umbilical had demated (refer to Figures 8 and 10). Subsequent TV views provided by the crew showed the connector still mated. The plot in Figure 9 shows a history of the multiple attempts to separate this connector. This plot shows the outboard (UTCM) and inboard (LTCM) tether tension variations which serve as a useful indicator of system behavior. After eleven unsuccessful attempts were performed, the U2 connector was successfully separated during the twelfth attempt.

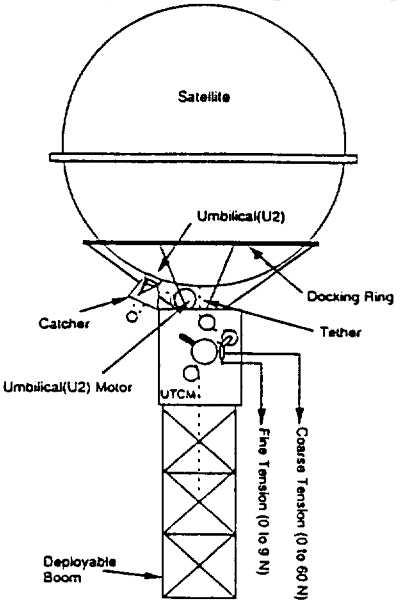

Figure 8. Deployer Configuration During U2 Separation Attempts

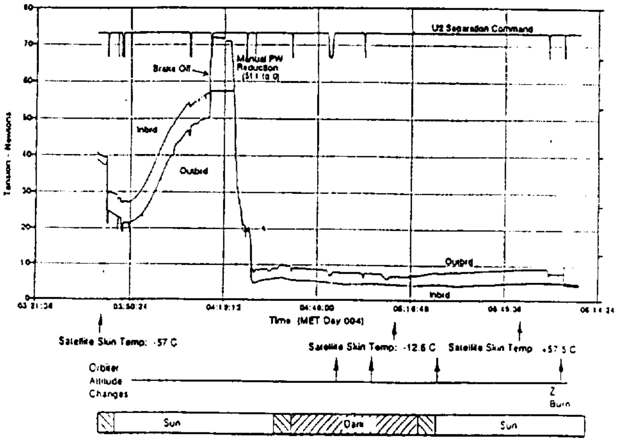

Figure 9. Tether Tension During U2 Separation Attempts

The subsequent attempts to separate U2 after the first unsuccessful try included use of: standard malfunction procedures (developed pre-flight), warming the connector with increased solar exposure, increasing tether tension to seat the connector closer to the motor, relaxing tension in the tether to let the satellite shift or float, stalling the umbilical drive motor for extended periods, and "hammering" the umbilical by turning the drive motor on and off.

The operational flexibility of the Deployer was put to use to recover from this anomaly. Initially, the Reel Motor control system was used to adjust tether tensions with the intent of aiding separation. The normal mode for U2 separation makes use of a single command to the control system (DACA), which then triggers an automatic sequence of events (see Figure 10). The DACA activates a specific relay which powers the U2 motor until the separation monitor indicates that U2 is separated, or until a timing sequence runs out. At this point, the DACA will cut power to the motor by commanding the relay to open. The final step in this sequence increases tether tension to assure the satellite remains seated in the Docking Ring.

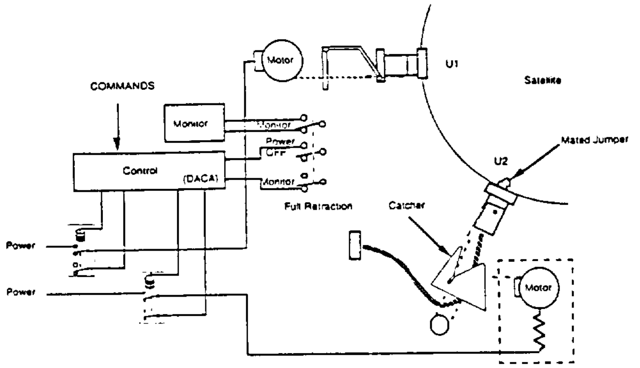

Figure 10. Umbilical System Configuration and Commanding Technique

The normal action described above was completely bypassed after the initial U2 separation attempt failed. The first recovery attempt (a standard malfunction procedure) sent separate relay commands to start and stop the motor. A subsequent attempt was made to increase solar exposure (by rotating the docking ring) on the connector, with the hope that warming the connector would free the "sticking" mechanism. The resultant temperature increase was approximately 100 °C, however no separation occurred after the separation command was repeated. Additional attempts were made by increasing and decreasing the tether tension to produce relativement movement between the U2 connector and satellite. The U2 motor was then commanded on for an extended period with the hope that continual motor force would slowly pull the connector loose. None of these methods were successful.

The final operation that successfully separated the connector involved relieving tether tension, pulsing the umbilical motor (using manual commands built into the Deployer control system), and firing the Orbiter thrusters to maneuver the Orbiter away from the satellite. This approach made use of the satellite inertia to add separation force to the connector.

It should be noted that no specific cause for the U2 separation anomaly has been found following an exhaustvie post-mission investigation. The U2 connector has subsequently been removed from the Deployer for the TSS-1R mission. This design modification will be discussed further in Section IV.

Anomaly 2: Satellite Did Not Deploy During the Initial Flyaway and at 224 Meters - The control system in Figure 3 is referenced again for explanation of this anomaly. This control system, as has been discussed, generates a commanded tether length, and uses closed loop feedback to control the reel motor such that the length error is removed. This process starts after the crew sends a single command to the DACA to activate the control laws.

The planned flyaway sequence, developed prior to flight included: activation of control laws, vernier motor power-on and activation of one set of satellite thrusters, with a thrust capability of 2 N. When this sequence was attempted on orbit, the correct commands were issued, but the satellite moved only a very small distance (refer to Figure 11).

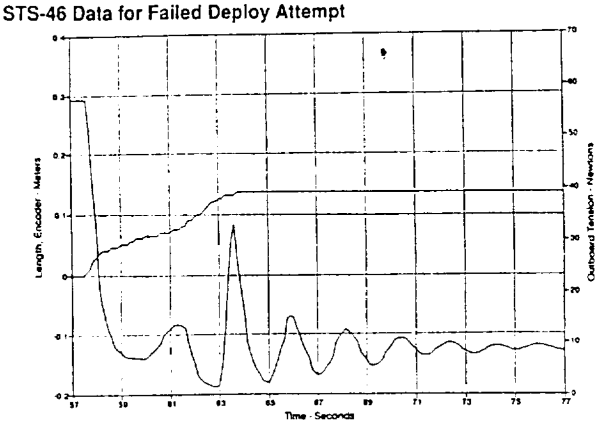

Figure 11. Flight Data for First Failed Flyaway Attempt

The second attempt to deploy used a modified sequence: activation of both sets of satellite thrusters (4 N thrust total), powering of vernier motor before starting control laws, while there was high tether tension. This method achieved a successful flyaway, and the satellite deployment proceeded as planned for 179 meters.

The second time the tether jammed was during an attempt to start up from a deployed length of 224 meters. The tether had been held in this position for a time which allowed an inboard slack tether condition due to the thermal expansion/contraction movements of the boom. When the vernier motor was energized to set the clutch, a jam occurred. Indications at the time were that the vernier motor was not supplying the required force to deploy the tether (refer to Figure 12 for tension plots). A 16 N tension level was observed, compared to the expected 35 N value. A technique known as "popping the clutch" was employed to maximize the vernier motor output. This was accomplished by powering the vernier motor using individual relay commands and then engaging the clutch with the motor running. This maneuver worsened the situation, since the tether could not be deployed or retrieved afterward. The conventional solution at this point would be the use of the pyrotechnic circuits to cut the tether at the boom tip and release the satellite, likely losing the satellite.

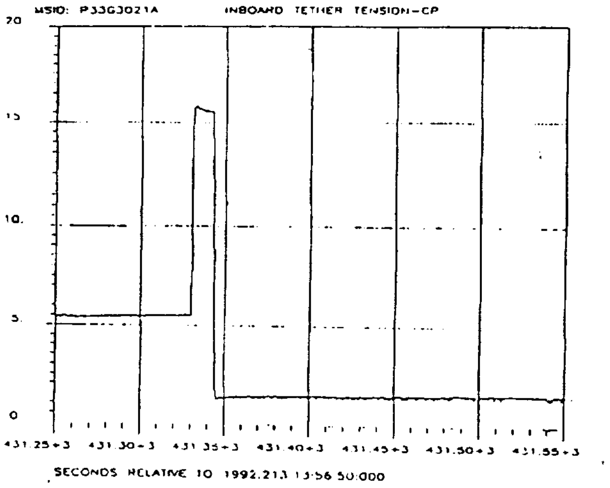

Figure 12. Tether Tensions During Vernier Motor Checkout at 224 Meters

Extensive discussions on the ground focused on other options which would still enable satellite retrieval. It was decided to attempt using the boom to free the jam, since all indications were that the tether was jammed in the UTCM. The plan was to lower the boom by one bay (about 18 inches in length) and then use the force of the boom extension motor to reextend the boom, with the reel brake applied, to free the jam. This effort was deemed acceptable by the Deployer engineering team since the boom had a large structural safety factor and its normal mode during extension included pulling tether off the reel with the brake applied. The boom extension was ultimately successful in clearing the jam, allowing a safe retrieval of the satellite under manual control.

Post-flight investigations identified four contributing factors to the tether jam anomaly. The first cause was the slack tether condition found to exist immediately after control law activation. When tether tension is lost, the jamming potential in the UTCM increases significantly (see Figure 13 for typical jam locations). A second cause was the full force application of the vernier motor upon start-up. This creates higher tether acceleration in the UTCM as compared to the satellite, thereby creating a jam.

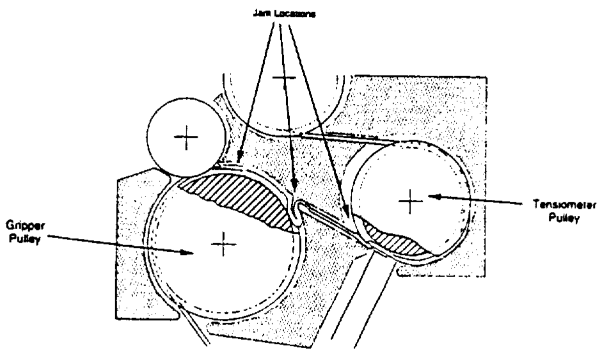

Figure 13. Tether Jam Locations in UTCM

The third cause was the increased stiffness of the tether eyesplice which is used to secure the tether end to the satellite interface. This stiff section of tether extended down into the UTCM, and acted as a stiff "column" during the initial flyaway attempt, and increased the potential for jamming (reference Figure 14). The fourth cause was an improper ground test method (pre-mission) which did not accurately simulate the satellite acceleration in a zero-g environment. The ground test had made use of suspended weights simulating the satellite thruster force (1.7 N). However, the acceleration of the weights in the ground tests was equal to the acceleration of gravity (9.8 m/sec 2), which was far greater than the satellite acceleration in flight. All four of these conditions contributed to the problem; fixing any one did not guarantee a proper system solution, but addressing all four was seen to solve the problem during post-flight ground tests (a further discussion is presented in Section IV).

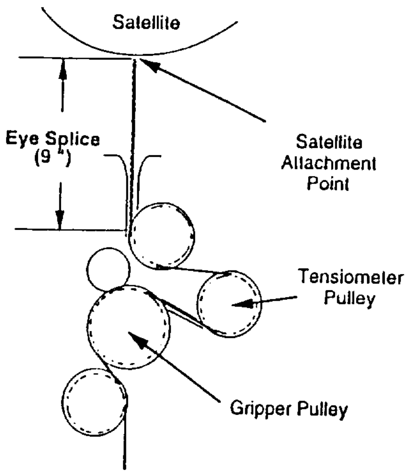

Figure 14. Tether Eyesplice Configuration

Anomaly 3: System Stopped Deployment and Would Not Proceed Past 256 Meters - The last anomaly that occurred involved tether stoppages at the 179 m and 256 m deployed distances. The first recovery attempt after the stop at 179 m used a manual pulse width deployment scheme, in the event the automatic control system was at fault. The manual pulse width control did not enable deployment past this point either. Since the system would not move forward, the tether was retrieved 10 m with manual pulse width control to setup a new starting position. An additional amount of tether was subsequently retrieved so that a "running" start could be achieved to get past the unknown obstruction in the reel.

This was attempted and the deployment proceeded to the 256 m distance, with significant unexpected tension changes and erratic tether velocity readings. It was not apparent that the pulse width commands available to the crew could maintain a proper deployment, so it was decided to use the automated deployment method which has higher granularity and control of pulse width. This method used commands never intended for use during flight, however, did save about two hours valuable flight time. The mechanical interference in the level wind, however, prevented any further deployment.

During the last stress analysis before the TSS-1 flight, it was noted that part of the structure holding the reel would be stressed past its allowable margin. This was fixed by the addition of a wedge block which was installed after the final tether deployment/retrieval testing had taken place. A bolt used to hold the wedge block in place, inadvertently stuck out into the path of the level wind (see Figure 15). The system was able to move past the 179 m mark, with the "running" start due to chain slippage past the gears on the reel. A hard stop was eventually reached at the 256 m distance. The post-flight modification which eliminated the interference is described in the next section.

IV. Design Modifications for the TSS-1R Reflight Mission

Deployer design modifications have been implemented to correct the anomalies observed during the first TSS mission. The design modifications have been successfully tested during the Deployer system level tests conducted at the Kennedy Space Center in July - September 1994.

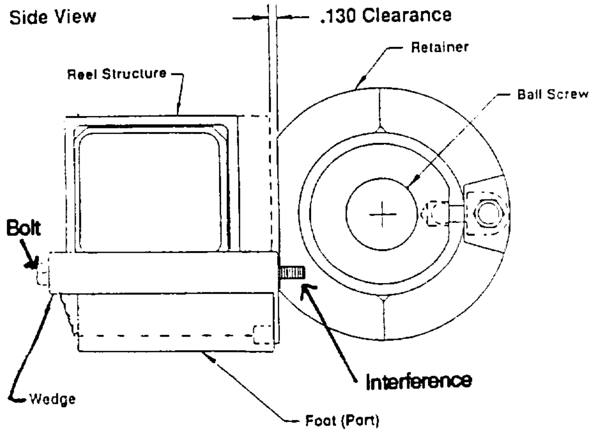

Figure 15. Level Wind Interference with Wedge Block Bolt

Since no specific cause was found for the U2 connector separation anomaly, the U2 connector has been removed from the Deployer. This recommendation was made by a post-flight investigation team consisting of government and contractor personnel. Critical U2 functions have been transferred to the existing U1 connector. In addition, the pull force on the U1 umbilical motor has been increased to provide additional margin in separation capability. The increased pull force was accomplished by descreasing the control circuit resistance for the U1 motor.

The tether jam anomaly required multiple concurrent solutions, and was demonstrated through extensive ground testing with the Martin Marietta System Test Bed facility in Denver, Colorado. Two specific design recommendations were made based on the test results. First, the vernier motor controller was modified to include a voltage ramp-up circuit, which allowed a gradual force application to the tether. The second recommendation was to develop a shorter eyesplice length at the end of the tether. This removed the stiff splice section from the UTCM, and provided additional tether compliance outboard of the Deployer (refer to Figure 16). As an item of interest, three operational recommendations were made in response to the tether jam problem: activate both sets of satellite thrusters before flyaway, turn on vernier motor before control law activation, and uplink an initial tether length parameter which will force the control system to maintain a high tether tension. A modification of the ground test setup included a flywheel which simulated satellite inertia to more accurately reflect satellite acceleration on-orbit. This flywheel was used to verify flyaway capability during ground tests in Denver and at KSC.

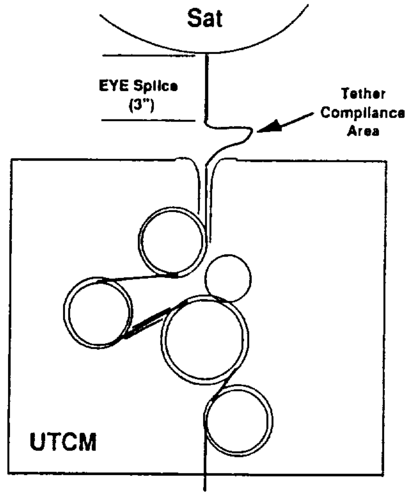

Figure 16. Modified Tether Eyesplice

The mechanical interference with the reel level wind assembly was eliminated. This design modification included a new collar on the linear drive ball reverser, which increased the clearance between the level wind mechanism and the wedgeblock. The new design is shown in Figure 17.

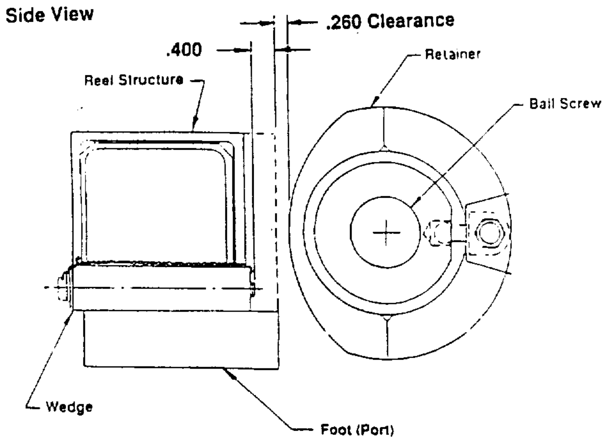

Figure 17. Modified Ball Reverser Collar

CONCLUSIONS

The TSS Deployer successfully demonstrated the proof-of-concept for deployment, control and retrieval of a tethered satellite during the STS-46 mission. The fundamental closed loop technique for controlling tether movement was proven. Deployer operational flexibility was also observed due to inherent design features which allow multiple methods to perform given functions. The Deployer avionics and majority of mechanisms were seen to operate successfully.

Hardware demonstrating successful operation included the Deployer flight computer (DACA) which received and processed commands and executed the tether control laws throughout the mission with no anomalies. Other avionics elements including the Motor Control Assembly, Motor Power Conditioner and High Voltage Relay Assembly were seen to function properly during all mission phases. Deployer mechanisms including the reel launch lock, brake, deployment boom, satellite restraint latches, docking ring and U1 umbilical operated successfully. Proper retraction of the boom and closure of the satellite restraint latches were critical activities for ensuring a safe landing configuration for the Orbiter. The boom mechanism was also successfully used to clear a tether jam during the mission (a previously unplanned application).

The problems occuring during the mission have been studied extensively and corrected. The tether jamming anomaly has been resolved with a combination of design modifications and operational changes. Tether jamming was not observed during pre-flight ground tests due to an improper setup in simulating satellite acceleration on-orbit. The satellite acceleration had been simulated using hanging weights, which were subject to the gravitational acceleration constant of 9.8 m/ s 2, much higher than the actual acceleration in flight. Post-flight test modifications have been made to include a flywheel which simulates the actual satellite inertia during flyaway.

The mechanical interference problem with the reel level wind assembly ultimately stopped the mission at a 256 meter deployment distance (vs the planned 20 km deployment). A late design modification created the interference, with no subsequent system testing prior to flight. The key lesson learned is that post-test modifications produce a significant risk in ensuring a successful mission. Ideally, testing should always be performed following hardware modification.

ACKNOWLEDGMENT

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