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Rescue in Space - TDRS Flight 1

Emery I. Reeves

Vice President and General Manager, Spacecraft Engineering Division, TRW Space and Technology Group, Redondo Beach, California

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RESCUE IN SPACE — TRACKING AND DATA RELAY SATELLITE SYSTEM FLIGHT 1

Mr. Emery I. Reeves
Vice President and General Manager
Spacecraft Engineering Division
TRW Space and Technology Group
Redondo Beach, California

ABSTRACT

On 4 April 1983, the shuttle orbiter Challenger released the Flight 1 spacecraft of the Tracking and Data Relay Satellite System (TDRSS) and its Inertial Upper Stage (IUS) booster in low altitude orbit. Although perogee burn of the IUS was accomplished without incident, approximately three-quarters of the way through the orbital injection burn, the IUS lost control. At the completion of the IUS burn, the spacecraft-IUS stack was tumbling violently in an anomalous elliptic orbit. During the succeeding hours spacecraft separation was accomplished and the spacecraft was stabilized and placed under positive attitude control. After assuring spacecraft safety and analyzing the state of health of onboard equipment, firings of the spacecraft onboard attitude and velocity control engines were used to raise the spacecraft from its elliptic orbit into the desired circular synchronous orbit. Final orbit correction was accomplished on 29 June 1983, almost 3 months after initial launch. This paper describes the spacecraft and its mission, the sequence of events leading to and following its injection into anomalous orbit, a description of onboard propulsion and attitude control equipment, and how this equipment was used to correct the orbit.

INTRODUCTION

Figure 1 shows the TDRS spacecraft in deployed configuration. The spacecraft is characterized by two large solar panels, mounted on either side of a hexagonal equipment compartment. The individual panels are approximately 14 by 12 feet and give the spacecraft an overall length of slightly over 60 feet. On orbit, the solar array axis points in a north-south direction. Rotation of the solar array about this axis provides the 3 kilowatts of power required by the spacecraft through direct solar illumination. The hexagonal equipment compartment is 8 feet across flats and consists of three smaller modules. The axis of the hexagonal compartment is controlled to point toward nadir to provide the spacecraft antennas with a clear view of the earth. The elements of the multiple access antenna array are mounted on the nadir face of the equipment compartment.

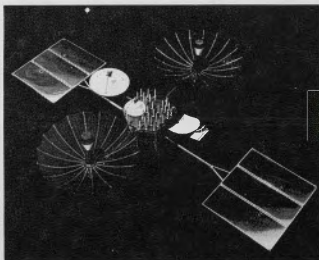


Figure 1. Tracking and Data Relay Satellite (TDRS)

Mounted adjacent to the equipment compartment are three solid antennas which provide communications between spacecraft and ground and implement K- and C-band links which were originally designed for commercial service. This spacecraft also has two boom-mounted parabolic reflectors, each 16 feet in diameter, which provide S- and K-band communications to user spacecraft. These antennas are gimbaled so that their pencil beams can track the users. Figure 2 depicts the TDRS

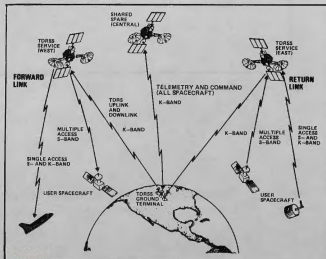


Figure 2. Tracking and Data Relay Satellite System (TDRSS) Mission



Figure 5. Spacecraft in Folded Configuration

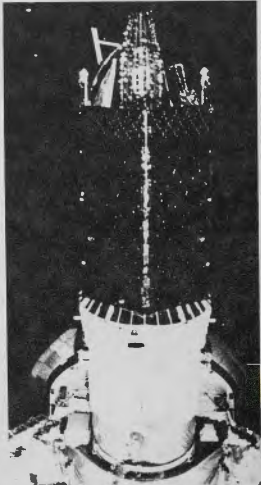


Figure 6. View of the Flight 1 Spacecraft from the Shuttle Cabin

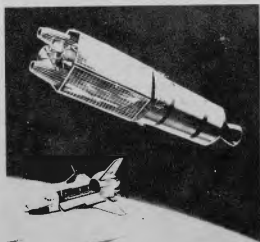


Figure 7. TDRS/IUS Prior to Ignition



Figure 8. TDRS/IUS Stack

ASCENT OPERATIONS

The mission plan for TDRS launch involved use of a conventional Hohmann transfer orbit to move the spacecraft from the 150-nautical mile parking orbit to geosynchronous altitude. In parking orbit the spacecraft is traveling at approximately 25,000 ft/s at an

inclination of 28.5 degrees. The IUS first stage boosts the stack velocity to approximately 33,000 ft/s sending the stack along the elliptic transfer orbit. Approximately 6 hours after injection into the transfer orbit, the IUS was programmed to reorient the stack and burn a second time to add approximately 6,000 ft/s to the spacecraft

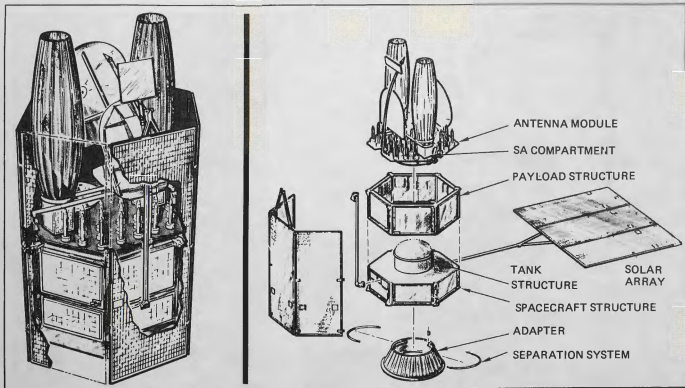


Figure 3. TDRS Launch Configuration and Exploded View

mission which is to relay S- and K-band signals between user spacecraft and the ground terminal located at White Sands. In its final configuration the TDRS system will consist of two operating spacecraft and provide near continuous communication between user spacecraft in low altitude orbit and the ground terminal. Data and communication signals received at the ground terminal are relayed to other users by alternate communication links.

Figure 3 shows the TDRS spacecraft in folded configuration and provides an exploded view of the equipment compartment. As shown in this figure, the equipment compartment consists of a spacecraft module, a payload module, and an antenna module. In the folded configuration the 16-foot parabolic antennas are folded, umbrella-like, on top of the nadir surface of the antenna module; and the fixed antennas occupy the space between the large parabolas. The solar array booms are double-folded, and the solar arrays surround the spacecraft to provide a compact hexagonal shape suitable for storage in the shuttle bay and boost by the IUS. The spacecraft is attached to its IUS booster by a conical adapter and a marman clamp.

Figure 4 shows the actual spacecraft hardware with fixed antennas deployed and rib mesh antennas folded. Elements of the multiple access antenna can be seen on the flat surface of the antenna module.

Figure 5 is a photograph of the spacecraft in the folded configuration showing the position

of the solar arrays relative to the antennas and the separation plane. Cutouts in the solar array, approximately a third of the way up from the base, provide for operation of 1-pound hydrazine thrusters which are mounted around the periphery of the equipment compartment. Figure 6 is a photograph taken from the shuttle cabin of the Flight 1 spacecraft, in the shuttle bay. The spacecraft-IUS stack is erected ready for release. The conical attached structure and the IUS are the lower white objects. The spacecraft solar arrays and antennas are clearly visible. Figure 7 is an artist's conception of the spacecraft-IUS stack after release from the shuttle prior to IUS first burn. Figure 8 is an actual photograph of the stack.

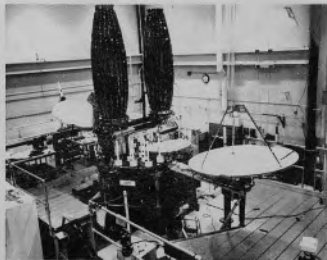


Figure 4. Spacecraft Hardware

velocity for circularization of the orbit. The mission plan then called for the IUS to orient the spacecraft toward the earth, allow the TDRS to release its solar arrays and fire the spacecraft separation ordnance. The design specifications for the TDRS attitude control system called for it to capture attitude from an initial rate of less than 0.5 deg/s. Once captured in attitude, the TDRS antennas could be deployed and the spacecraft oriented for mission operations.

The targeted velocities and actual events are shown pictorially in Figure 9. The targeted attitude for the apogee burn was horizontal and 23 degrees south of east, i.e., of the equatorial plane. At the initiation of the IUS burn the spacecraft was traveling at a velocity of slightly over 5,000 ft/s and an angle of 26 degrees to the equatorial plane traversing from south to north. Initial IUS burn was accomplished without incident; however, at approximately 80 seconds into burn the vehicle lost control, probably due to a failure of the nozzle to respond to steering commands, and the stack tumbled. At the completion of the IUS burn the achieved velocity was slightly over 9,000 ft/s at an angle of approximately 2 degrees to the equatorial plane (the targeted velocity was some 1,000 ft/s higher and in the equatorial plane). In addition to the velocity deficit, the spacecraft-IUS stack was left spinning at 180 deg/s.

Figure 10 provides a timeline of events surrounding the IUS second burn and spacecraft separation. The TDRS telemetry system is a PCM system which, during launch, operates at 1 kb/s. At this telemetry rate, mainframe information is provided every 1/2 second, and subcom data is provided approximately every 30 seconds. Due to the violent tumble of the spacecraft-IUS stack, telemetry lock was difficult to maintain and telemetry

SRM-2 BURN INITIATION	95/10:47:04
LOSS OF TDRSS TELEMETRY	10:50
NOMINAL SEPARATION TIME	10:55
SCF INITIATED SEPARATION COMMANDING	11:21:45
COMMAND INERTIAL MODE ENABLE	12:50:34
COMMAND YAW OUTPUT ENABLE	
SEPARATION	12:50:50
COMMAND ROLL, PITCH, YAW INERTIAL MODE OUTPUT ENABLE	12:58:58 ↓ 13:33:38

Figure 10. Separation Events

indication of the spacecraft state of health was not available at the ground station. Shortly after 11:20 GMT on 5 April, the Air Force Satellite Control Facility started initiating separation commands. As indicated earlier, separation of the TDRS from the IUS is accomplished by ordnance release of the marman clamp. This ordnance is powered and controlled from the IUS side only. At approximately the same time commanded separation was being initiated by the SCF, TDRS ground operations at White Sands was queried regarding steps that could be taken on the TDRS side to slow down the tumble. Rapid analysis of spacecraft structural capabilities coupled with estimates of spin conditions obtained from signal strength measurements indicated that the only feasible maneuver for the TDRS to perform was control system initiation using gyros for attitude sensing and the yaw thrusters which operate through solar array cutouts. These commands were sent to the spacecraft slightly before 1:00 p.m. GMT, and subsequent commands to the spacecraft were sent to enable the thrusters. Postflight analysis indicated that separation actually occurred at 12:50:50.

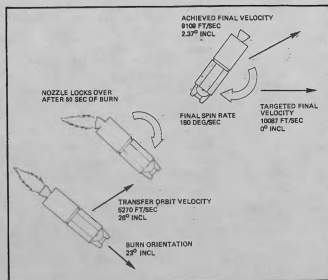


Figure 9. IUS Second Stage Performance

SPACECRAFT ATTITUDE CONTROL AND PROPULSION

The attitude control system for TDRS is shown schematically in Figure 11. The control system includes a series of sensors which provide attitude information. A micro-computer housed in the control electronics assembly selects and processes sensor information and provides signals to actuate torquers and control the articulated antennas. Control torques on the spacecraft are produced by reaction wheels during normal on-orbit control and by a series of 1-pound hydrazine thrusters during initial acquisition and navigation maneuvers.

The attitude control computer uses a pair of 2901-bit slice processors. Its operating system and principal software elements are programmed in firmware. The 8K ROM computer program routines are summarized in Figure 12.

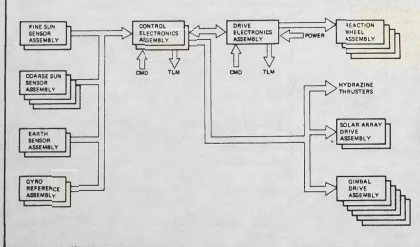


Figure 11. Attitude Control System (ACS) Equipment Block Diagram

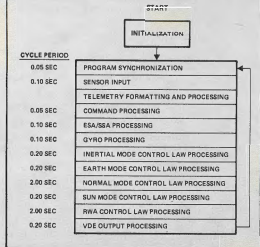


Figure 12. Attitude Control System Software

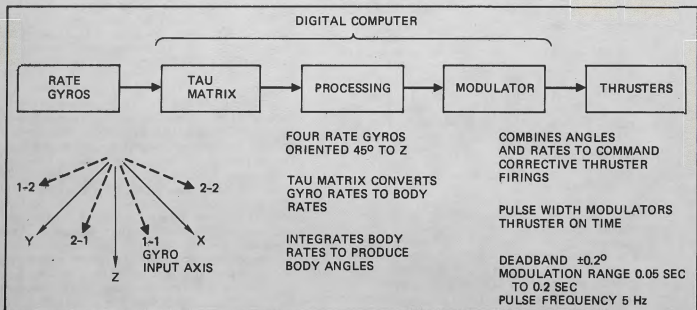


Figure 13. Attitude Control Subsystem Inertial Mode

This menu allows ground control to select control routines. Computations are accomplished sequentially by axis by routine. The ROM program is supplemented by 2K of RAM which is used to control connectivity and for programmable constants.

The inertial mode of control system operation couples rate gyroscopes to the hydrazine thrusters as shown diagrammatically in Figure 13. The spacecraft has four rate gyros oriented with their input axis in a rectangular pyramid centered about the Z body axis. Any three gyros can provide complete attitude information. The selection of gyros is accomplished by uplinking appropriate constants to a 3x4 matrix operationally inserted between the rate gyro output and the attitude processing algorithm. The attitude processing integrates the body rate output from the gyros to produce body angles and combines angle and rate information to produce control

signals. These control signals pulse-width modulate the 1-pound propulsion thrusters.

The principal attitude control thrusters are oriented as shown in Figure 14. Single thrusters provide for torque about the X and Y axes, and a set of four thrusters located on the spacecraft equatorial plane provide for torque about the Z or downpointing axis of the spacecraft. The Z thrusters can also be used in combination to produce horizontal velocity increments. In addition to the prime orientations shown in Figure 14, the Z thrusters are canted about the Y axis by approximately 15 degrees and produce small crosscoupling torques about the X axis. The thruster cant angle ensures that the thruster line of action passes through the spacecraft CG; and, although this cant angle was not basic to the design, the presence of the XZ crosscoupling proved quite beneficial to the

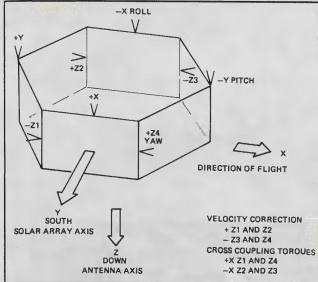


Figure 14. Thruster System

eventual rescue of the spacecraft. Each of the thrusters shown in Figure 14 actually consists of two thrusters, a prime and back-up, to provide equipment redundancy. The prime thrusters are plumbed together as are the backup thrusters. Each bank is connected to the hydrazine manifold through an isolation valve thus providing for the command isolation of either/or both banks of redundant thrusters.

Figure 15 is a photograph of the basic spacecraft structure showing the hydrazine tanks

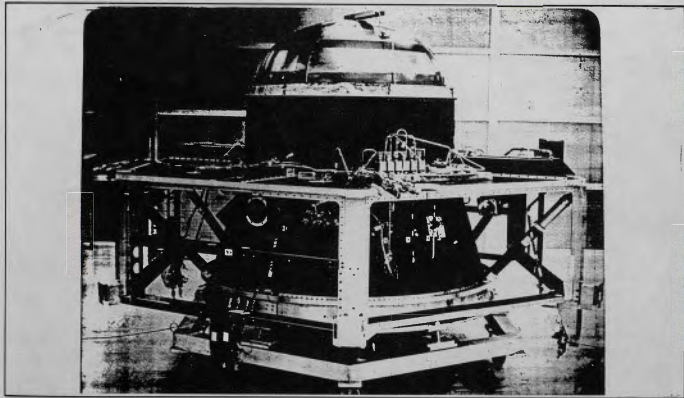


Figure 15. Spacecraft Structure

in the center. The hydrazine manifold is slightly to the right of the tank centerline and one of the yaw dual thruster modules may be seen on the horizontal spacecraft platform. The pitch and roll dual thruster modules are also evident at the base of the spacecraft structure.

The 1-pound thruster, shown in Figure 16, was developed by TRW on the FLTSATCOM program. It consists of a solenoid-actuated control valve which meters liquid hydrazine through a capillary tube to a catalyst bed which is electrically heated. In this catalyst bed the hydrazine decomposes, and the hot combustion products exit through the thruster nozzle. The electric heaters preheat the catalyst bed to assure decomposition of the hydrazine during intermittent or pulsed operation. Under continuous operation the thruster bed is heated by the combustion process. In fact the heat of this combustion process flowing back to the thruster solenoid proved to be a limiting factor in the on-time to which we could subject the thruster assemblies.

Figure 17 shows the location of the dual thruster modules relative to the separation plane and the folded solar array. Figure 18 is a more detailed picture of the roll dual thruster module located at the base of the spacecraft. The location of this equipment relative to the conical adaption section and the solar array is shown in Figure 19.

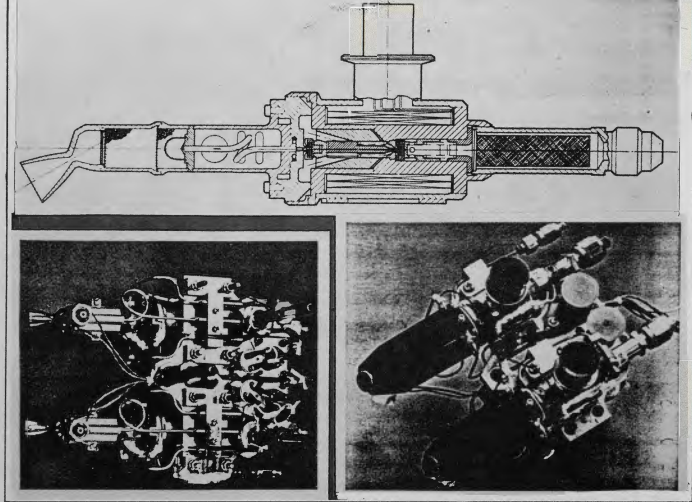


Figure 16. One-Pound Thruster

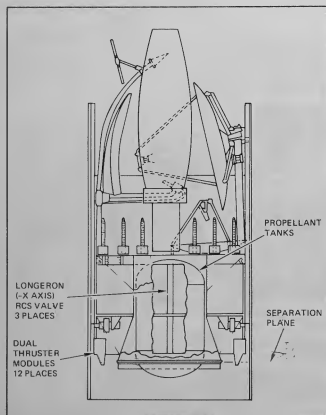


Figure 17. TDRS-IUS Adapter

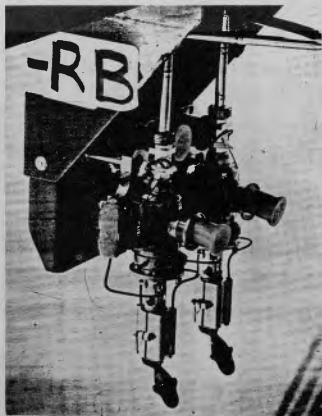


Figure 18. Roll Dual Thruster Module

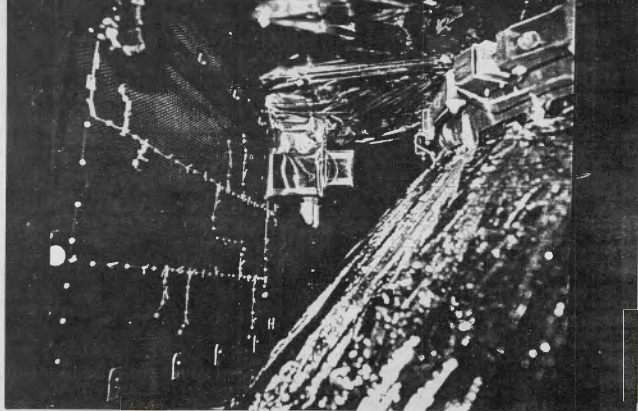


Figure 19. Location of Roll Dual Thruster Module

SEPARATION AND STABILIZATION

As indicated earlier, separation of the spacecraft from the spent IUS second stage occurred at approximately 12:50 GMT on 5 April. Immediately after separation the spacecraft attitude control system slowed the spacecraft to 0.44 rev/s. It should be noted that this rate is over 300 times the design value of 0.5 deg/s. During the time interval from 12:50 to 13:40 various command sequences were attempted by both the satellite control facility to the IUS and by White Sands to the TDRS via the Spacecraft Tracking and Data Network (STDN). These command sequences initially involved enabling the yaw axis of the control system and subsequently involved commands to enable all three axes. At approximately 13:40 all three axes were enabled and the spacecraft stabilized itself in approximately 20 minutes as shown in Figure 20. Once attitude capture of the spacecraft had been achieved and the spacecraft orientation placed under active control, the deployment sequence was initiated. As shown in the pictures of the folded spacecraft, the solar arrays are mounted with cells exposed so that the solar array is capable of producing partial power even in the folded configuration. However, once the spacecraft was fully stabilized the operational sequence called for array deployment. Once deployed,

the panels could be pointed at the sun for full power generation. This was accomplished approximately an hour after attitude capture, and the arrays were slewed to point to the sun. This array orientation also provides a solar attitude reference to augment gyro information. Shortly after solar array deployment the fixed antennas were deployed and single access antenna deployment was initiated. These events and their appropriate times are shown in Figure 21.

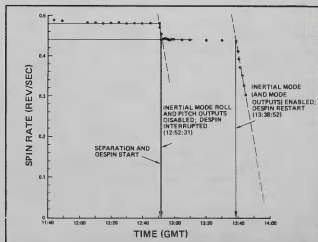


Figure 20. Separation and Stabilization

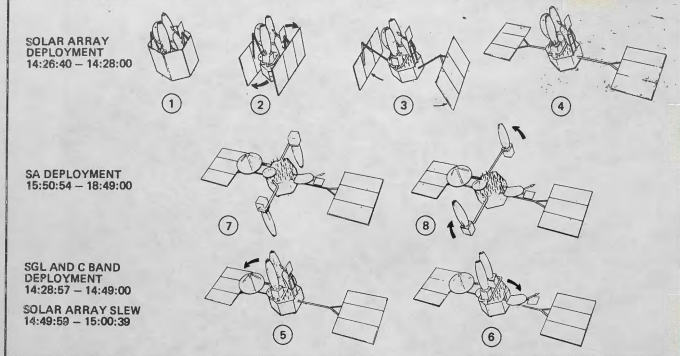


Figure 21. Appendage Deployment

Having completed principal deployment of the appendages, the spacecraft passed through its first eclipse which lasted almost an hour. Since the spacecraft was controlled by gyros, attitude was maintained during the eclipse. After emergence the spacecraft was commanded to sun mode. In the sun mode the spacecraft X axis is pointed toward the sun and a roll rate of 0.1 deg/s is induced. Under these conditions the earth sensors which point out along the Z axis are swept through a plane at right angles to the sun line. Orbital motion of the spacecraft carries this plane through space until it intersects the earth. At earth intersection the spacecraft attitude control system can acquire earth control, thus completing the signal triad necessary for normal on-orbit control. Even though TDRS was in an anomalous orbit ranging from apogee at geosynchronous attitude (19,300 nautical miles) to perigee altitude of slightly over 11,000 nautical miles, it was felt that normal mode control could be used. Figure 22 provides a timeline for the first orbit which indicates that earth control was entered at 7:30 GMT on 6 April. After establishing earth control the single access antenna reflectors were opened and routine monitoring of spacecraft operation was initiated. At 10:13 GMT attitude and propulsion telemetry indicated a gross anomaly. Command activity was initiated to correct the situation. The observed data shown in Figure 23 included violent pressure spikes in the propulsion system and abrupt cooldown of the negative roll thrusters from approximately 300°F to the telemetry limit of 0°F. Although the changes in these telemetered signals were abrupt and violent, each of

these signals is subcommanded at one sample in 30 seconds and so fine grain of the actual transients was lost.

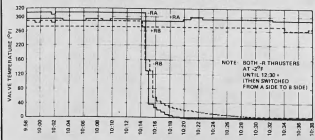
These propulsion indications were accompanied by a loss of attitude control. From 10:13 GMT until 12:56 GMT on 6 April analysis of the telemetry data was conducted and command sequences were synthesized to reestablish spacecraft control. At approximately 12:56 GMT control of the spacecraft was reestablished using the B thruster set and sun mode. Subsequent analysis of the telemetry data has indicated that the negative roll A thruster, operating in an abnormal duty cycle, became overheated and subsequently detonated, opening either a propellant line

DEPLOYMENT COMPLETE	95/18:49
ECLIPSE	22:07-23:04
SUN MODE	96/03:09
EARTH MODE ATTEMPT	07:31
EARTH MODE PITCH ONLY	07:46
SA REFLECTORS OPENED	07:59-08:11
EARTH MODE PITCH AND ROLL	09:15
ROLL THRUSTER ANOMALY	10:13
CONTROL REGAINED - SUN MODE	12:56

Figure 22. Events - First Orbit

- AT 06:10:14—RA THRUSTER EXPLODED HYDRAZINE DETONATION
- DRAMATIC COOLDOWN, 350°F → -36°F IN ONE MINUTE
- PROPELLANT PRESSURE SURGES
- CESSATION OF CONTROL AUTHORITY

DAY 096 ROLL THRUSTER TEMPERATURES



TANK PRESSURE VERSUS TIME

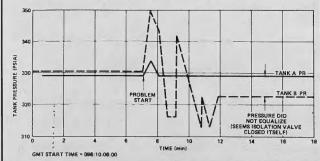


Figure 23. Roll Thruster Anomaly

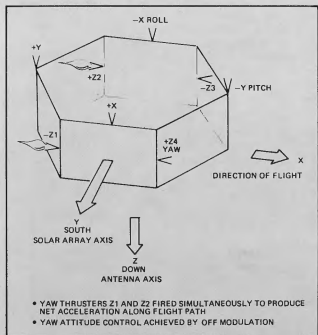


Figure 24. Delta V Technique

or the thruster assembly. This caused a rapid vacuum freeze of the liquid hydrazine which revealed the damaged thruster. Subsequent stabilization of spacecraft in the sun mode allowed control of the spacecraft attitude without using either negative roll thruster, and plans were made to conduct further maneuvers without recourse to a negative roll.

Four of the principal attitude control thruster assemblies are located on the aft face of the spacecraft and four on the spacecraft belt. The latter thrusters operate in couples to produce rotational torques about the Z axis and can be operated in pairs to provide velocity increment along the X axis. This velocity adjustment technique is shown diagrammatically in Figure 24. Although the orientation of the thrusters and their operation is designed to impart velocity to the spacecraft, the acceleration level of these thrusters is very small. Each thruster operates with approximately 1 pound of force, and the spacecraft at beginning of life weighs over 5,000 pounds. In order to impart the 1,000 ft/s deficit occasioned by the IUS failure, the thrusters were required to operate for over 40 hours. Since the velocity increment was required to be put in at apogee, the velocity correction was accomplished in a large series of short burns. To complicate the design of the velocity correction effort, the damage to the negative roll thruster implied that the spacecraft had to be controlled without recourse to negative roll torques.

The canting of the yaw thrusters about the Y axis so that the line of action passes through the center of gravity proved to be very beneficial because the Z thrusters could be used in combination to provide a small amount of negative roll torque. The thruster combinations capable of securing this roll torque are listed in Figure 25. As can be seen by this tabulation, appropriate combinations of the Z1, Z2, and Z3 thrusters can produce a positive acceleration on the spacecraft together with either positive or negative yaw torque for spacecraft yaw control and a negative roll torque for roll control if required. The attitude control system can control the thrusters in accordance with a wide variety of sensor signals. In addition, the computer can introduce bias firing of the thrusters in accordance with ground command. All of these features were used to control

Z1	Z2	POSITIVE ACCELERATION ZERO YAW TORQUE ZERO ROLL TORQUE
Z2	Z3	ZERO ACCELERATION ZERO YAW TORQUE NEGATIVE ROLL TORQUE
Z1	Z2-Z3	HALF ACCELERATION NEGATIVE YAW TORQUE NEGATIVE ROLL TORQUE
Z2		HALF ACCELERATION POSITIVE YAW TORQUE NEGATIVE ROLL TORQUE

Figure 25. Roll Control During Delta V

the spacecraft during its climb to synchronous orbit.

Figure 26 shows geometrical aspects of the earth, sun, and spacecraft during initial stages of velocity correction. The line of apsis was approximately at right angles of the sun line in mid-April, thus allowing the spacecraft to be pointed at the sun during velocity correction firings. During early burns the spacecraft was pointed at the sun using normal sun mode until apogee was approached. By timing earth sensor crossings, a measure of the roll attitude could be deduced and the spacecraft roll rate stopped at the appropriate point. A velocity increment could then be produced by firing the Z thrusters. The duration of firing was constrained by a combination of orbital geometry and thruster thermal performance. Red line temperatures were incorporated in the procedures to prevent the thrusters from overheating, and absolute time restraints were also incorporated to assure that velocity was accomplished at apogee. A variety of algorithms were employed to keep the thruster temperatures within bounds during velocity correction sequences. The thermal performance of the thruster is affected by duty cycle as well as absolute duration of operation. When operated in the pulse mode, heat from the catalyst chamber soaks back and tends to overheat the solenoid. At high duty cycles, sufficient liquid hydrazine flows through the valve to keep it cool, but at low duty cycles this is not the case and the thrusters can overheat. Notwithstanding these constraints almost half the required velocity was imparted to the spacecraft during the month of May. However, with the passage of time the orbital geometry changed as shown in Figure 27. With the sun line located closer to the line of apsis the sun could no longer be used as a primary reference for establishing the thrust direction in inertial space. It was therefore necessary

to devise a different attitude control sequence and algorithm for thrust direction control.

Again the flexibility of the computer controlled attitude control system allowed the spacecraft to be maneuvered to properly orient the thrusters. In the latter stages of orbit correction this was accomplished in a two-step attitude maneuver. The spacecraft was initially oriented toward the sun in the sun mode. Roll rate was stopped with the Y axis generally at right angles to the orbit plane. A yaw maneuver was accomplished using gyro reference to place the X axis in the orbit plane and subsequently a pitch maneuver was used to orient the X axis along the line of flight for thrust direction control. All of these maneuvers were accomplished by synthesizing negative roll control using the Z thrusters. With the attitude control sequence established, a second series of incremental velocity maneuvers was conducted during the last few days of May and June. The chronology of the maneuvers and resulting perigee altitude are shown graphically in Figure 28.

As synchronous altitude was approached, the sequencing of the velocity maneuver was modulated to allow the spacecraft to be flown to its targeted synchronous position. On 29 June the 39th burn of the Z thrusters placed TDRS in synchronous orbit at 67 degrees west longitude, and test of the spacecraft communications mission equipment was initiated.

CONCLUSIONS

The rescue of TDRS 1 has provided the United States with the first of the tracking and data relay spacecraft resources which are vital to the continued success and productivity of our nation's space program. The rescue required Herculean effort by a large

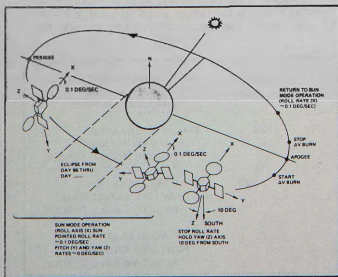


Figure 26. Delta V Sequence Initial Burns

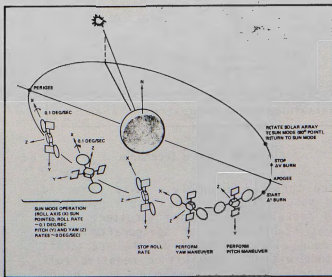


Figure 27. Delta V Sequence Final Burns

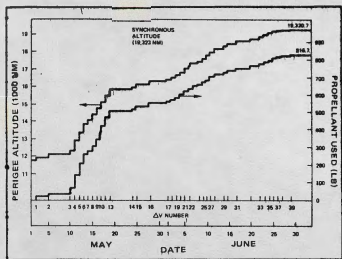


Figure 28. Climb to Synchronous Orbit

number of engineering and operations people from the spacecraft contractor, TRW; the spacecraft owner and operator, Spacecom; and the eventual spacecraft user and controller, NASA. The rescue effort also profited by a large amount of good fortune. The space-

craft, initially built for the dual function of data relay and commercial communications, incorporated very large propellant tanks. The extra propellant allowed spacecraft velocity to be corrected while still providing sufficient propellant for a full data relay mission. In addition, TDRS achieved separation with what was apparently the last gasp of the IUS battery. Assisted by these elements of good fortune, White Sands and Space Park personnel were able to effectively use the flexibility of the spacecraft and its ground station to maximum advantage. Careful planning and proper deployment of personnel assured that knowledgeable engineers were available at White Sands to render real time judgments to first protect the safety of the spacecraft and subsequently to posture the spacecraft for long term control until its eventual injection into final orbit. The design of the spacecraft attitude control system has proved to be particularly robust and flexible, accommodating non-nominal conditions and equipment failures while allowing ground operating personnel the control necessary to save the mission. Those involved in the rescue of TDRS are particularly proud to have been a part of this successful effort.