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Paper Session II-B - The Tracking and Data Relay Satellite System

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THE TRACKING AND DATA RELAY SATELLITE SYSTEM

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ABSTRACT

The Tracking and Data Relay Satellite System (TDRSS) is a multi-satellite operational system which both uses the Space Transportation System (STS) as a launch vehicle and provides key tracking and data communications services to STS flights. Since the Tracking and Data Relay Satellite (TDRS) was originally designed for an Expendable Launch Vehicle (ELV) launch, the STS requirements provided many difficult challenges both technically and programmatically. The time span of the TDRS development was roughly in the same time span as the development of STS operations, and, being one of the first STS payloads, the TDRS and the STS matured together, pioneering many of the features incorporated into this launch system today.

This paper describes the history of the TDRS and STS relationship, the unique considerations which were required of the TDRS Program, and the design drivers which were imposed on the TDRS as the program matured and subsequently as the STS was re-evaluated as a consequence of the Challenger accident. The in-advance preparations and coordination is detailed as are the pre-launch and launch activities required to fly on an Orbiter. The advantages as well as disadvantages of flying on a manned launch vehicle are detailed, and the paper ends with advice and recommendations based on lessons learned. It is hoped that this paper will give some insight into how yesterday’s vision of a reusable launch vehicle evolved into today’s operational launch system, and how yesterday’s vision of a space-based Tracking and Data Relay System has replaced the Ground Spaceflight Tracking and Data Network (GSTDN) Stations, providing markedly improved data rates and orbital coverage for today’s users including the STS.

INTRODUCTION

The TDRSS provides the primary means that NASA has to communicate with and gather data from most of its low Earth orbiting missions. This includes the great observatories, Hubble Space Telescope (HST), Gamma Ray Observatory (GRO) and Upper Atmosphere Research Satellite (UARS), as well as the STS, Landsat and the Cosmic Background Explorer (COBE). Indeed, the TDRSS is an integral part of most of NASA’s near-Earth missions now and for the foreseeable future. The Earth Observing System (EOS) and Space Station Freedom missions will rely on TDRSS for the bulk of their two-way communications and orbital tracking needs.

The TDRSS is a series of geosynchronous satellites maintained and operated by a ground station located at White Sands, New Mexico. These satellites relay data from the White Sands Ground Terminal (WSGT) to user spacecraft. Since the TDRS’s are in a geosynchronous orbit, they maintain constant contact with the ground station and have direct line-of-sight communication with user spacecraft throughout most of their orbit. These communications are implemented through either one of the two TDRS Single Access Antennas, which are steered in the direction of a user, or by using the Multiple Access array which electrically forms a beam to a user. The Single Access system is operated at either K-Band or S-Band while the Multiple Access system is restricted to S-Band only. Another vital part of the operational TDRSS is the Network Control Center (NCC) at the Goddard Space Flight Center (GSFC). The NCC is responsible for scheduling the services provided by the TDRSS and for providing a two-way data and operations interface to the TDRSS users.
The history of the TDRSS goes back to the early 1970’s when the communications and data gathering services for low-Earth orbit missions were provided by a world-wide network of ground stations which would track user spacecraft as they went overhead in their orbits. In the early days of NASA, these ground stations, which provided low data rate transmission capability over about 15% of a typical users orbit, were adequate in meeting user needs. As data transmission rates grew substantially and requirements for extended contact times with users also grew, the existing network of ground stations was no longer up to the task. Additionally, since these ground stations were necessarily located in sovereign foreign countries, political and economic problems in supporting and maintaining these stations were exponentially increasing. Today, the TDRSS provides coverage of about 85% of a typical users orbit at data transmission rates exceeding 300 Mbps. In fact, each TDRS has the capability of transmitting the data equivalent of a 24-volume encyclopedia in less than six seconds. The original contract for the TDRS required the spacecraft to be designed to support a dual role. In addition to the TDRSS mission, a commercial K-Band and C-Band communications capability was required. However, due to programmatic considerations, the commercial mission was terminated prior to the launch of the first TDRS.

Presently, the TDRSS on-orbit constellation consists of five spacecraft. The F-1 was launched in 1983 and is about to be retired from general TDRSS service and will be dedicated to special support for the GRO mission. In this capacity, the F-1 will be moved out of view of the WSGT and will be operated remotely through its own unique and dedicated mini-terminal located in Australia. The F-4 and F-5 Spacecraft, launched in 1989 and 1991, respectively, are presently carrying the bulk of the TDRSS workload and are augmented on occasion by the F-3. The F-3 Spacecraft, launched in 1988, is only partially operational due to an on-orbit failure of one of the high data rate K-Band links. The F-6 Spacecraft, which was just launched in January of this year, is being stored on-orbit as a ready reserve spacecraft should something happen to either F-4 or F-5. These spacecraft were all built for NASA by TRW of Redondo Beach, California.

The TDRSS ground station located in White Sands, New Mexico, is operated and maintained by GTE and provides the functions of controlling the on-orbit spacecraft as well as relaying data to and from user control centers to on-orbit user spacecraft. The ground station is operated 24 hours a day, 365 days a year. A contingent of about 300 persons, 5 civil servants and 295 contractor personnel working for GTE, Bendix and TRW, man the station to maintain operations. Presently, the station operates the system with an efficiency in excess of 99%. That is, more than 99% of user requests for services which have been accepted by the NCC scheduling system, are actually provided to the user. Scheduling of TDRSS service to users is usually done weeks in advance although some limited amounts of quickly scheduled service, to accommodate user spacecraft emergency needs, are also available.
Since the TDRSS is an integral part of most other NASA missions, plans are in place to maintain and even augment the system through the foreseeable future. In the near term, an F-7 TDRS is being readied at TRW for a mid-1995 launch. A few years from now, when the EOS and Space Station Freedom are on orbit, the TDRSS is planned to operate four active geosynchronous spacecraft with a fifth spacecraft on orbit in ready reserve. To achieve this expanded capability, the Agency is now building a Second TDRSS Ground Terminal (STGT), also located at White Sands, New Mexico, and is planning a procurement of several new TDRS's. The STGT is expected to be operational in 1994 and additional spacecraft of a new design are expected to be available for launch in the late 1990's.

All of the present generation of TDRS were designed to be launched by the STS and taken into geosynchronous orbit with a Boeing-built Inertial Upper Stage (IUS). As of this date, five spacecraft have been successfully launched using the STS. The remainder of this paper expands on the development of the relationship between the STS and the TDRS.

**HISTORY - A STORY OF FIRSTS**

The original contract specified that the first three TDRS's would be launched on Atlas-Centaur which were fully developed operational vehicles. The final three of the original buy of six was planned to be launched on the STS/Space Shuttle Upper Stage-A, later changed to the STS/IUS, all of which were still under development at the time of the contract start.

Sometime after the preliminary spacecraft design had been developed, but still relatively early in the contract, it became clear that the spacecraft design was outgrowing the Atlas-Centaur load capability. Spacecraft weight growth was driven by a change in requirements in the K-Band and C-Band commercial services and made necessary a shift of the first three TORS to the STS/IUS. Although STS/IUS requirements and parameters were not yet firm, the fixed price nature and system development schedules of the TDRSS mandated a continuation of design and implementation efforts of the TORS. By the time the STS/IUS requirements were firmed up, the TORS design was frozen and implementation of the F-1 and F-2 Spacecraft was well on its way. Since the TORS F-1 was only the second payload of the STS, it was very difficult to anticipate the kinds of problems which would develop.

In order to lay down a baseline for TDRS/STS/IUS activities, a Payload Integration Plan (PIP) and nine annexes were written and rewritten many times. A special Interface Control Document (ICD) had to be developed in order to interface the TORS with the IUS and subsequently with the STS. The ICD effort was very difficult since there were so many new players and no guidelines for such an integration effort. Changes were continuous. Now, standards exist and the changes are relatively few.
Since the TORS was originally designed to fly on an ELV, minimal attention was initially paid to the stringent man-rated safety requirements. After signing on with the STS, we found that safety policy and requirements of the STS were being constantly revised, making necessary significant and expensive design changes to spacecraft already being built. Today, the requirements are well developed and quite firm so that new users know up front what their safety design goals are. In particular, in the original design, the TORS Spacecraft ordnance firing circuitry did not have the necessary two-fault tolerant safety inhibits as required by STS safety considerations. This problem required extensive redesign of TORS circuitry, permeated through several fixed-price contracts and subcontracts and required physical rework of much of the in-process hardware. Integrated Test Procedures, now called Operations and Maintenance Instructions (OMI’s), had to be developed without any existing standards for content or format; in addition, basic test philosophy was still evolving. Customer stand-alone test procedures which were necessary to support the OMI’s needed to be written but could not because the format of the OMI, which the stand-alone test procedure interfaced with was not defined. On F-1/STS-6, the procedures were written over and over again. Additionally, many deviations were written during the actual launch Integration and Test flow. Today, very few procedural changes occur.

Early on in the program for F-1, extensive effort was required in order to convince the management of both the launch vehicles and the TORS that, prior to launch, an end-to-end test was required to verify that the spacecraft and the various ground terminals and networks played together. It was argued that this type of testing was unnecessary and too costly. It was finally agreed that the community would support the tests providing that the user pay the costs. Today, no one would think of launching a primary spacecraft without end-to-end tests.

F-1 was the first payload to be processed through the Vertical Processing Facility (VPF) and launch pad. The VPF facilities were in fairly good shape, the operations well planned, and the clean room cleanliness met the user requirements. The launch pad and specifically the Payload Changeout Room (PCR), which is part of the Rotating Support Structure (RSS), required extensive redesign in order to maintain cleanliness specifications after F-1 was launched. During the time when F-1 was on the Pad, a severe storm passed through. The movement of the tower was not in sync with the movement of the Orbiter; as a result, seals designed to maintain a positive pressure within the PCR did not do their job. Moisture and particulate matter entered the PCR and contaminated the TORS. TORS was cleaned on the Pad and subsequently launched. Today, after extensive modifications to the PCR and the implementation of good clean room procedures, the PCR is really an excellent clean room.

There were a lot of firsts with the launch of the TORS:

- The first to use the VPF, particularly the transfer of a 47,000 pound payload into the transportation canister.
The first to run end-to-end tests, the first test revealed such severe problems with the supporting communications network elements that, had we launched without the end-to-end test, there would have been serious on-orbit problems communicating with the spacecraft through the launch vehicle communications links.

The first to move to the launch pad in a canister, be erected at the PCR, transferred into the PCR and subsequently into the Orbiter cargo bay. These operations were pretested by KSC using a dummy load. However, when the 47,000 pound load of the TDRS/IUS was transferred into the Payload Ground Handling Mechanism (PGHM), it revealed misalignments in the PGHM which caused the load to shift several inches. This caused some major excitement.

F-1 was the first spacecraft to be fueled in the PCR at the Pad.

F-2 was the first spacecraft to experience a flight hardware problem on the Pad that would necessitate removing the spacecraft from the Pad for repair. No one had ever backed out of a launch flow before; consequently, procedures to accomplish the tasks were either not prepared or were not in a usable state. Essentially the entire forward going flow from the VPF to the Pad had to be reversed. Procedures were written under severe pressure because there was another payload waiting in the wings and KSC needed to clear the Pad.

- The spacecraft had to be defueled on the Pad.
- With the tanks still wet with a small quantity of residual fuel, the payload was removed from the PCR and moved to the VPF.
- Once in the VPF work stands, the TDRS was demated from the IUS and transported to an explosive/safe area where considerable disassembly of the spacecraft was required to accomplish the repair.
- Once repaired, the spacecraft was stored under purge for more than six months waiting to re-enter the launch flow. The Reaction Control System was stored with minor residual fuel in the system during the entire time.

After learning all of the pioneering lessons before and during the F-1 launch and the education which was obtained as a result of the F-2 stand-down, things have gone very well from the launch integration standpoint. Presently F-3, F-4, F-5 and F-6 have all been launched using techniques and procedures largely developed for the F-1 and original F-2 efforts. (After the original F-2 stand-down, the F-2 came back and went through a smooth launch re-integration flow. Unfortunately, that spacecraft was subsequently lost in the Challenger accident.)
DESIGN DRIVERS

As a launch system, the STS offers a rather benign ride to its customers imposing relatively mild structural and thermal engineering requirements. However, since it is a man-rated system, the safety requirements on the design and implementation of a user spacecraft are enormous and, as a result, are significant cost drivers. For the TDRS, when the initial contractual launch vehicle was switched from an ELV to the STS, we took on some major upgrade activities within several spacecraft subsystems. The TDRS pressure vessels (containing hydrazine at about 340 lbs/square inch pressure) although designed with ample margin for an ELV launch, needed to be proof-tested and, in one case, needed to be subjected to an ultimate burst test to adequately demonstrate their man-rated qualification. The commanding system and its operations especially in the way that on-board ordnance commands were processed, had to be re-designed. All systems which could have an impact on STS safety must be two-fault tolerant. On the TDRS, certain ordnance and propulsion subsystem commands are hardware inhibited during the time that the TDRS is on-board the STS. While in the STS payload bay, inadvertent radio frequency radiation, especially since it may impact ordnance safety, is also of great concern. The hydrazine fueling, always a high profile safety operation, now came under new scrutiny because of the planned fueling on the launch pad. Fracture control was imposed on every one of the structural members of the spacecraft, its appendages and the launch vehicle adapter. Fracture control is a process whereby each individual part on each individual flight spacecraft is subject to analysis, testing, or a combination thereof to verify that it was manufactured in a way which will not allow it to fail under launch or launch abort loads. (For the TDRS launch on the STS, the abort or return from orbit loads are the driving condition. These loads are significantly greater than the predicted launch loads.) All of these items collectively had a huge impact on TDRS schedules and costs.

PREPARATIONS AND COORDINATION

Perhaps the greatest lesson learned from the many TDRS launches on the STS is the need for early coordination through preparation and a continued dialogue between all responsible entities. As in virtually all other complex technical and programmatic matters, the first definitions of TDRS/IUS/STS interface problems and their early solutions were found to be inadequate. Early understandings developed into misunderstandings which required large expenditures of resources and energy to resolve. Only tight coordination and constant preparations allowed the eventual resolution of all problems prior to the first launch. Our present method of preparation and coordination is to designate specific interfaces within the three organizations and maintain life in those interfaces through scheduled meetings on a semi-annual basis even when launch is not imminent. When we get within nine months or so of a launch, interface meetings or teleconferences are held on a monthly basis even when major problems do not exist. If major concerns develop, daily teleconferences and meetings can be common.
PRE-LAUNCH ACTIVITY

The pre-launch activity for a TDRS starts with the arrival of the spacecraft via a C-5A aircraft 90 days prior to the scheduled launch date. Upon arrival, the spacecraft is set up in the VPF where it receives a mechanical look-over and is then electrically connected to its test set. Those spacecraft subsystems which are normally activated during the actual launch are then checked out to verify their continued readiness. Upon a complete checkout of those subsystems (the TDRS Communications Payload cannot be activated in the launch configuration and remains off until the spacecraft has been deployed on orbit) the spacecraft is mechanically and then electrically mated to the IUS. This activity also takes place in the VPF. After mating IUS/TDRS interface testing is performed with both the TDRS and the IUS in nearly launch-ready configuration, tests of data flows are made to the controlling centers of each system and a final review to determine readiness to proceed is also held. After the TDRS/IUS combination is tested, the entire stack, at this point weighing in at nearly 47,000 lbs., is transported vertically to the launch pad. At the Pad, the stack is lifted to the PCR and, when the Orbiter is moved to the launch pad, the TDRS/IUS combination is placed into the payload bay of the Orbiter. Hydrazine fueling, a final pre-launch battery reconditioning, and trickle charging are done on the Pad.

When mechanically and electrically installed in the payload bay of the Orbiter, a series of end-to-end tests involving the STS, the IUS, and the TDRS is performed. The controlling centers of each system are brought on line and all launch-required systems are checked out. This portion of the pre-launch activity can bring about unwelcome surprises even with good pre-coordination. Generally on the STS, two or more payloads can be co-manifested and at this point in the launch flow these payloads start coming together for the first time. Since the processing is done with the payloads and the STS in a vertical attitude, those payloads closest to the STS cabin will be physically directly above the other payloads in the PCR. This can bring about many concerns such as the accidental dropping of material or tools. For the TDRS, we have insisted upon and received custom-manufactured debris shields which are affixed directly above the delicate TDRS Spacecraft and its stowed appendages and protect the TDRS from activities physically above the spacecraft.

LAUNCH ACTIVITY

The TDRS launch window starts in the morning hours and is limited to be less than three hours in length. The morning constraint is levied by a combination of STS preference (the transatlantic abort landing sites are in daylight) and thermal constraints of the TDRS (the sun look angles post launch and during deployment from the STS). The length of the window is limited by the STS crew-on-back time. (The launch crew is seated but is lying on their backs due to the vertical take-off position of the Orbiter.) For the TDRS launch, the STS follows a nominal orbit with an inclination of 28°. Although from lift-off, the communications are provided through two ground stations, Merritt Island Launch Area (MILA) and Bermuda, the TDRS soon takes over and provides real-time contact with the Orbiter as it goes over the Atlantic. The data from the IUS and the TDRS being launched that day is
combined with STS telemetry and relayed to the Johnson Space Center (JSC) via the TDRSS network. From JSC, the data is stripped and shipped to the various control centers. The IUS data goes to the Consolidated Space Test Center in Sunnyvale, California, and the TDRS data ends up at the WSGT in New Mexico and at the Back-up Operations Control Center at the spacecraft manufacturers plant in Redondo Beach, California. On a nominal launch, the TDRS data which gives a continuous look at the state of health and performance of those subsystems which are activated for launch, is continuously relayed to the WSGT and monitored. A sophisticated system designed to support mainly the TDRS launch is used to monitor, plot, compare and archive all spacecraft data. System and subsystem experts are responsible for viewing this data in real-time and reporting go/no-go or abnormal conditions to Project Managers. A major advantage of launching on the STS is the ability to meaningfully check the performance of the spacecraft being launched and return a spacecraft without placing it in orbit should a failure develop or even possibly correct a problem, on-orbit but prior to deployment, which might have developed during launch.

Once the STS has achieved a successful low-Earth orbit, and all of the TDRS and IUS systems have been checked and are nominal, the tilt table to which the TDRS/IUS is attached is tilted to 58° and the TDRS/IUS is released from the Orbiter. About one orbit later, after the Orbiter has backed away to a safe distance and the IUS has aligned itself to the proper altitude, the first stage of the IUS, a solid rocket motor, ignites and the TDRS is on its way to a geosynchronous orbit. The IUS thrusts for less than three minutes. The coast to a geosynchronous apogee then takes a little more than five hours. During this time the IUS performs a slow roll to help maintain thermal equilibrium. During this time, a preprogrammed IUS maneuver called a dipout is also performed five times at nearly equally spaced intervals. The dipouts re-orient the TDRS to point the TDRS communications antenna back towards Earth just in case commands are needed to be sent to perhaps reconfigure the TDRS. (TDRS telemetry is continuously sent down by being multiplexed on the IUS telemetry link.)

Upon reaching the proper altitude, the IUS second stage fires to circularize and place the spacecraft into the intended orbit. After holding on to the TDRS for a few more minutes to stabilize the spacecraft through the critical deployments of the solar arrays, the IUS second stage separates and the TDRS is on its own. Several additional complex deployments are then performed and the spacecraft is ready for on-orbit checkout and eventual operations.

**ADVICE AND RECOMMENDATIONS**

1. Take time to thoroughly understand STS operations and especially safety requirements.

2. Start and maintain interface activities as soon as it is known that the STS will be the launch vehicle.

3. Six months to a year prior to the actual launch date, establish a semi full-time presence or representation at KSC. GSFC has established a permanent office at KSC to perform this function for its launches.

4. Interface not only with STS but with co-manifested payloads.