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Deep Space Terminal Demonstration

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The Deep Space Terminal (DS-T) was a task that validated the concept of a fully automated, autonomous deep-space ground station. The DS-T successfully demonstrated "lights out"-mode ground-station operations using a Deep Space Network 34-meter beam-waveguide antenna that tracked a NASA deep-space probe orbiting Mars. The DS-T receives, processes, records, and distributes telemetry data to the project, without operator intervention. The DS-T task was a cooperative effort between JPL and industry, leveraging JPL's specialized knowledge with industry's fast implementation cycle.

I. Introduction

In 1996, the Deep Space Terminal (DS-T) task began with the object of demonstrating the proof of concept of a fully automated and autonomous "lights out" ground station by implementing a prototype terminal in the Deep Space Network (DSN) environment. A series of successful demonstrations in 1998 documented the achievement of this objective. To counter the increasing operational cost of the DSN, the Network Simplification Plan's (NSP's) target is to reduce the daily operating cost by a significant percentage via automation. The successful realization of the DS-T confirms that ground-station automation is a practical goal for the NSP.

This article documents the DS-T's capabilities and the corresponding demonstrations. Section II describes the demonstration concepts and approach; Section III covers the DS-T in detail; Section IV describes the demonstration with Mars Global Surveyor (MGS); and the final sections contain the task conclusions.

The DS-T task used a fast prototyping approach to create the fully automated terminal based on commercial off-the-shelf (COTS) components when appropriate. The station was successfully demonstrated with a single spacecraft (S/C), single-track capability in April 1998 and with multispacecraft and multitrack capability in lights out mode over several days in September 1998.

The DS-T concept is built around the autonomous, unattended operations concept of the Low Earth Orbiter Terminal (LEO-T). The DS-T task leveraged on the earlier LEO-T task's success in automating a low Earth satellite ground terminal in the DSN. Some modifications were necessary to address the

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inherent differences between requirements for ground-station support of deep-space missions as compared with low Earth orbiting (LEO) spacecraft. They include

(1) The longer track times for deep-space missions allow for more complex sequences of events during a track.

(2) While COTS could be used for almost all of the LEO-T subsystems, DS-T has a number of non-COTS subsystems specially designed for deep-space applications.

(3) The custom-built deep-space subsystems work much closer to the theoretical limits than do the LEO subsystems. Also, these are built-in limited numbers and generally do not enjoy trouble-free operations to the extent available with COTS equipment in the LEO-T. This necessitated a more capable error-detection and -recovery algorithm at the ground-station level.

(4) JPL subsystems have DSN-specific interfaces that would have encumbered the contractor if DS-T were to be built as a turnkey procurement.

These constraints suggested a teaming arrangement between JPL and industry to leverage on the strengths of each party. The team achieved DS-T autonomous operations by leveraging COTS ground-station-operations software (S/W) complemented with a JPL scheduling component and dynamic script generation, resulting in cost-effective prototype development.

II. Demonstration Concept and Approach

The Telecommunications and Mission Operations Directorate (TMOD) Technology Office's directives drove the demonstration concept and implementation approach. These were for a low-cost, quick demonstration of the proof of concept using a DSN antenna and NASA deep-space spacecraft, fully automated and autonomous operation, and the use of COTS components when appropriate. The demonstration was to cover all activities associated with the execution of a track, from track scheduling to delivery of telemetry (TLM) and monitor data to the mission.

The following concepts were defined as goals to be demonstrated:

(1) Fully autonomous, automated operations over several days

(2) Schedule-driven operation (only a high-level request input is necessary); automated scheduling and conflict resolution within the DS-T

(3) Self-generated predicts for antenna pointing and receiver frequency information

(4) Expandable, service-based operation

(5) Automatic pre-track configuration and self-test

(6) Autonomous operation, with active monitoring of the track and with built-in error recovery

(7) Automatic post-track telemetry and monitor-data delivery to the mission

(8) Use of COTS and/or existing JPL (DSN) components when appropriate

(9) Treatment of ground terminal as network computer node

A. Demonstration Concept

The proof-of-concept demonstration's goal was to operate the DS-T station in automated, unattended mode for several days at a time. Remote access was used to enter the service request (SR) to track a spacecraft. Based on the SR, the DS-T configured the station, tracked the spacecraft, received telemetry, processed the data, and developed track quality information. The telemetry data were sent to JPL for storage. For the duration of the demonstration, the connection between the equipment at Deep Space Station 26 (DSS 26) (located at Goldstone, California) and the remote-control position at JPL in the Telecommunications Systems Research Laboratory (Building 161-113) was via secure link over the NASA Science Internet (NSI) connection using network encryption units. Figure 1 shows the DS-T demonstration concept.

B. Mission Selection

The selection of candidate missions for the demonstration was based on

(1) Availability in 1998 for field testing and demonstration, preferably with a regular active downlink

(2) A mission normally supported by a 34-meter beam-waveguide (BWG) antenna in the DSN

(3) A NASA mission preferably managed by JPL, for access to ephemeris and sequence of events (SOE) data.

Discussions with mission operations and projects resulted in an agreement with the Mars Global Surveyor (MGS) project to support the DS-T task with ephemeris data and SOE updates. Comparing the number of frames received and decoded at the Consultative Committee for Space Data Systems (CCSDS) transfer frame level (Level 0) with the theoretical number of frames possible for the same time period validated the telemetry data quality. The existing MGS mission database did not allow the delivery of telemetry data from an experimental source; therefore, in the DS-T Principal Investigator (PI) workstation, a temporary database was set up as a mission data sink.

DS-T testing plans with the MGS spacecraft covered the December 1997 to September 1998 period. The original flight plan had the aerobraking completed by February 1998 and MGS positioned in the mapping orbit. Due to a mechanical failure, the spacecraft had to execute a much longer braking sequence, which extended into February 1999. The final 6-day unattended DS-T demonstration was planned from September 14 through September 21. At 3:30 Pacific Daylight Time (PDT) on September 17, 1998, the consequence of an error in the spacecraft's command (CMD) sequence put the spacecraft in safe-hold mode, and normal operations were suspended. The 6-day unattended demonstration had to be terminated after the first 3 successful days.

The DSN attempted to schedule the 34-meter high-efficiency antenna (HEF) for MGS telecommunication support and used the BWG antennas when schedule conflicts occurred. Figure 2 shows the link margin for MGS orbiting Mars in the 1998 time frame, via the high-gain antenna and BWG. MGS telecommunications subsystem specifics are given in Table 1.

The DS-T implementation plan included support for the Deep Space 1 (DS1) mission's beacon mode experiment (BMOX) that uses tones to communicate the spacecraft health status to Earth. The BMOX uses the full-spectrum recorder (FSR) with special software as the downlink receiver, operating at a very low signal level. The mission was to evaluate the received spacecraft health information. Similarly to the MGS support, the DS-T implemented fully automated, SR-driven track support for DS1 also. The mission planned to use the DS-T's automated uplink function for commanding during the BMOX, using the demand access capability of the DS-T. Due to DS1 launch delay, BMOX support with the DS-T-controlled ground equipment was canceled. The complete DS1 support capability was tested in the laboratory at JPL.

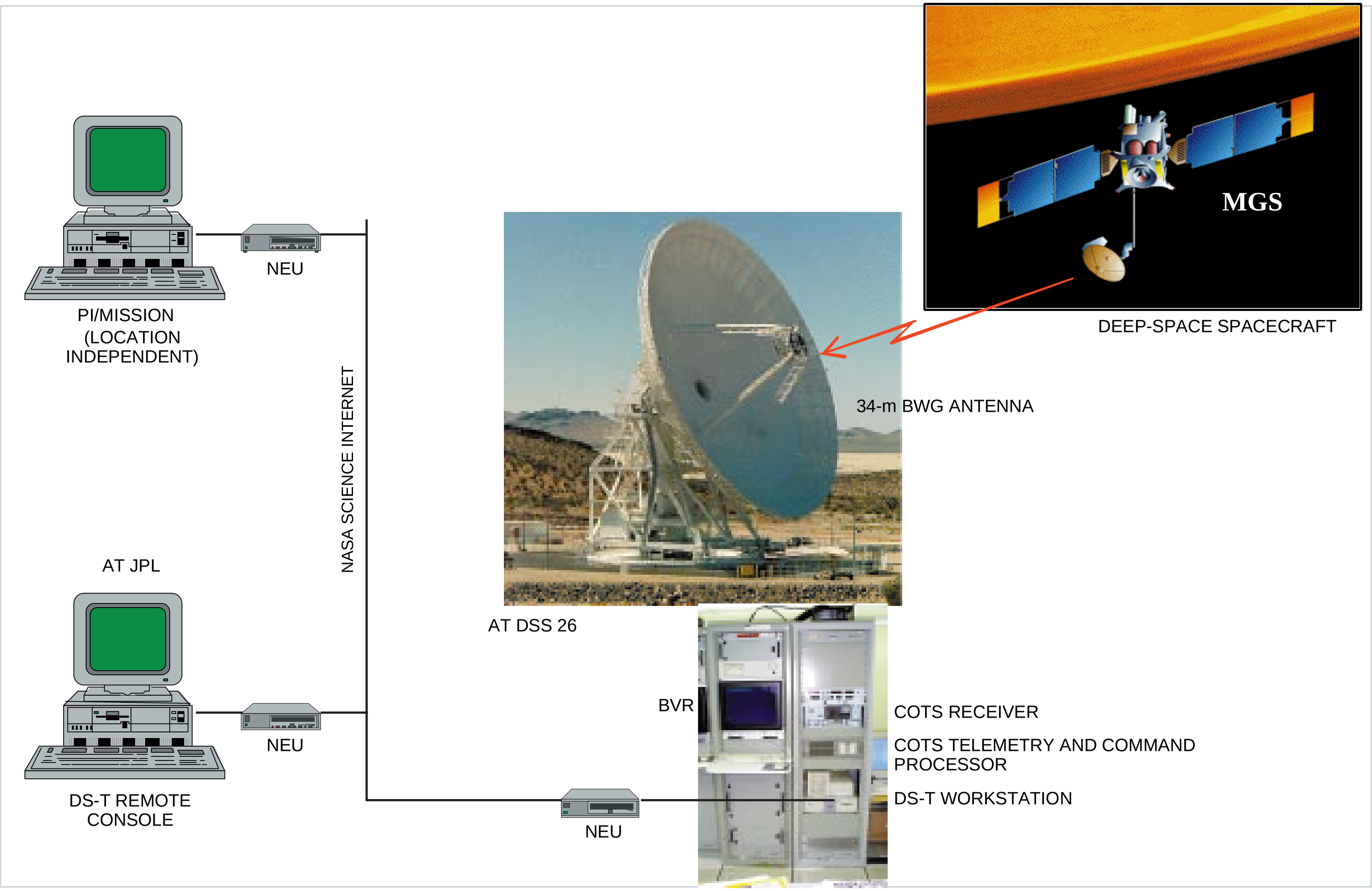

Fig. 1. The DS-T demonstration concept.

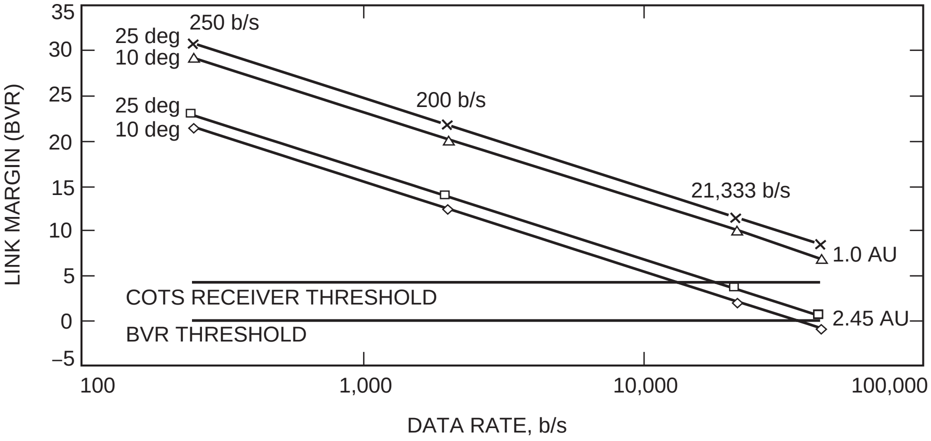

Fig. 2. The DS-T–MGS link margin in Mars orbit.

Table 1. MGS telecommunications subsystem specifics.

Item	Design value
Transponder	
Low-gain antenna EIRP	49.0 dBm (downlink)
High-gain antenna EIRP	81.42 dBm (downlink)
TWTA output	+44.2 dBm
Uplink frequency, Channel 16	7164.624299 MHz
Downlink frequency, Channel 16	8417.716050 MHz (one way)
Channel 20	8423.148147 MHz (two way)
Telemetry	
Modulation index	42.5 to 80 deg (selectable)
Modulation type	PCM (NRZ-L)/PSK/PM
Subcarrier (square wave)	320 kHz or 21333 Hz (10 and 250 b/s only)
Coding	Convolutional $K = 7, R = 1/2$ Reed–Solomon (255,223)
Data rates	
Engineering	10, 250, 2000, 8000, 32,000 b/s
Science (real time)	4000, 8000, 16,000, 32,000, 40,000, 64,000, 80,000 b/s
Science (playback)	21,333, 42,666, 85,333 b/s
Format	CCSDS packet telemetry
Command	
Modulation index	51.6 to 74.5 deg (selectable)
Modulation	PCM/PSK/PM
Subcarrier (sine wave)	16 kHz
Bit rates	7.8125, 15.625, 31.25, 62.5, 125, 250, 500 b/s
Format	DSN CMD 4–6

III. The DS-T

A. Requirements and Component-Selection Approach

To be useful for the DSN, the prototype terminal's antenna gain-to-total system temperature ratio (G/T) performance had to be similar to the regular DSN 34-meter BWG antenna's performance. For the long-term use of testing and demonstrations, the DSS-26 BWG antenna was made available to the task. The task implemented a new microwave feed and low-noise amplifier (LNA) design based on an experimental, tested, four-port junction and waveguide combiner from JPL and a JPL-designed LNA that was built by a subcontractor. Table 2 presents the RF performance of a 34-meter BWG antenna for a 7145- to 7190-MHz forward link and an 8400- to 8450-MHz return link (X-band) using the DS-T components compared with two antennas equipped with standard DSN components.

Table 2. BWG RF performance with DS-T versus DSN components.[a]

Parameter	Low-noise path			Diplex path		
	DS-T[b]	DSS 24[b]	DSS 54[b]	DS-T[b]	DSS 24[b]	DSS 54[b]
G, dBi	68.15	68.05	68.10	68.15	67.95	68.00
T_{op},[c] K	27.5	26.5	24.8	27.5	33.5	32.5
G/T	53.8	53.8	54.2	53.8	52.7	52.9

[a] All measurements were taken at a 45-deg antenna elevation.

[b] DSS 24 and DSS 54 are masers; DS-T is a high-electron mobility transistor (HEMT). The cost of the HEMT is about 30 percent of the cost for a maser.

[c] The T_{op} for the DS-T antenna/feed/four-port diplexer/LNA/atmosphere is 27.5 left circular polarization (LCP) and 26.4 right circular polarization (RCP)—significantly better than the design value of 29.2 K. The LNA noise temperature can be further reduced by about 4–5 K for less than 8 percent increment in cost.

The DS-T Design Team took into account the available COTS components and shaped the overall design to maximize the use of the COTS components while maintaining the necessary performance level. The result is a ground station that maps well into the DSN.

B. Terminal Characteristics

Figure 3 presents a block diagram of the DS-T. The DS-T uses the DSS-26 BWG antenna. The movement and pointing of the antenna are controlled by the antenna-pointing controller (APC) assembly, a standard DSN component used without any modification.

The safety plan developed for automated, unattended operation required a systematic evacuation of the antenna site and the activation of a perimeter-monitoring circuit. An interruption of the perimeter circuit had to stop the antenna immediately. The APC has a built-in perimeter-security control port; the DS-T used this port to stop the track execution if a person entered the antenna site during the demonstration period. Necessary antenna maintenance was performed during scheduled time periods.

All microwave-component configurations are controlled by the microwave generic control (UGC) assembly, a standard DSN component used without any modification. Both the APC and UGC are controlled by the DS-T via ethernet using the 820-19 DSN protocols.[5]

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[5] *DFL-1-2 DSCC General Data Flow Standard*, 820-19 (internal document), Jet Propulsion Laboratory, Pasadena, California, November 30, 1994 (formerly Document 890-131).

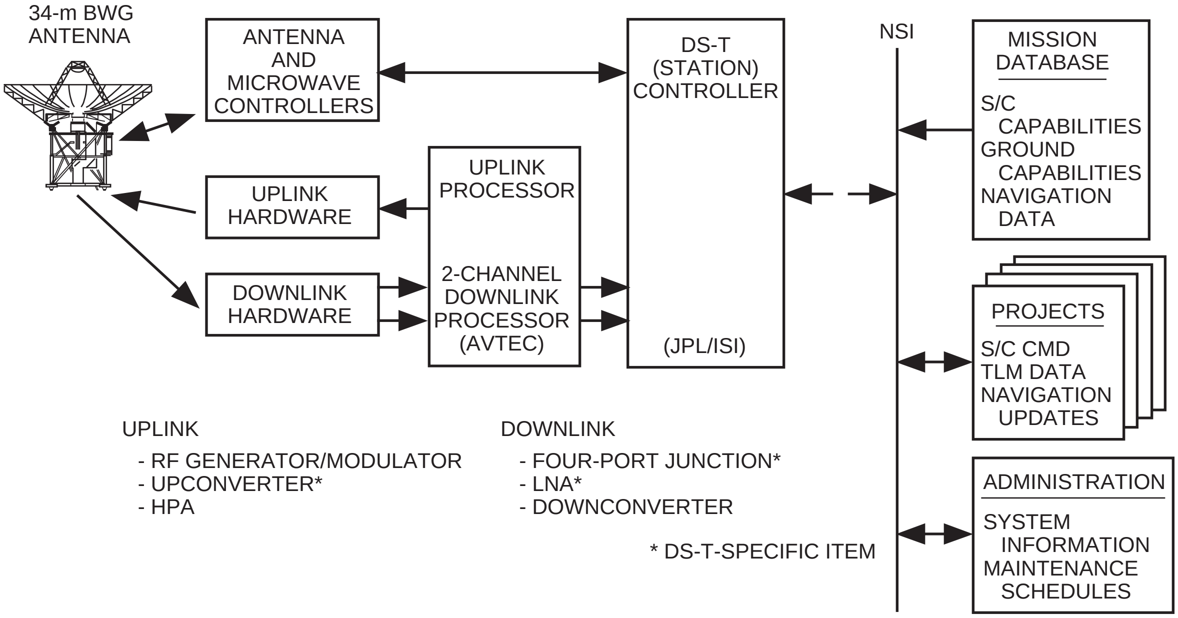

Fig. 3. The block diagram of the DS-T.

In regard to the front-end components, the antenna feed, four-port junction, and LNA are DS-T-specific components as described in Section III.A. A new low-cost downconverter was built for the DS-T with a specific IF frequency to enable use of both the COTS receiver and the block V receiver (BVR) simultaneously [local oscillator (LO) = 8150 MHz]. This downconverter was tested; the performance was comparable to the standard DSN unit. Due to limited resources, this downconverter was not installed at DSS 26 because a standard DSN loaner unit was installed earlier. Figure 4 shows the DS-T front-end equipment.

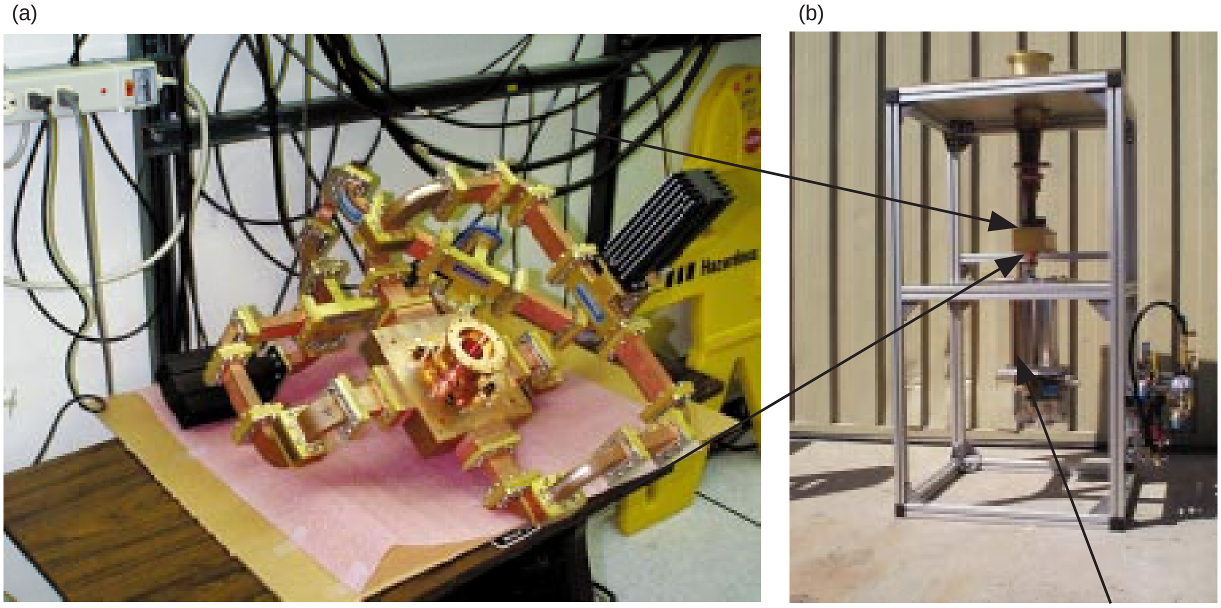

Fig. 4. The DS-T front-end equipment: (a) the low-loss feed diplexer, developed at JPL, before insertion between the feed and the cryogenic HEMT LNA package and (b) the cryogenic HEMT LNA and filter, fabricated by Berkshire Technologies.

1. Downlink Equipment. A DSN standard BVR was used as the primary receiver in order to be compatible with the DSN, and it provided the necessary performance. The COTS receiver was tested in the DS-T environment but not used during demonstrations because the MGS link-budget analysis showed insufficient link margin at higher data rates. To help the automated operation, the BVR was used via a TCP-IP connection through the BVR's maintenance terminal. JPL had to design a custom IF to the COTS TLM-processing equipment to feed the BVR-generated soft symbols into the COTS short constant-length (K7, R1/2) convolutional decoder, mapping from the BVR's 8-bit linear output to the decoder's 3-bit optimized input.

Telemetry processing was implemented in a COTS package, without modifications, supplied by Avtec with the programmable telemetry processor with NT interface (PTP-NT) control software. The dedicated hardware (H/W) is housed in a rack-mounted industrial PC, with two identical telemetry channels, one command channel, and one test-data source-channel hardware. A dual-channel disk controller with two 4-Gbyte SCSI hard disks was available for buffering the processed telemetry data. For the processes listed below, the maximum rate was 25 Mb/s except for the Viterbi decoder. Each of the following processes generates real-time-quality information and annotation of the telemetry data:

(1) Viterbi decoder and PCM decoding is interfaced through a DS-T specific card in the BVR, which maps soft-symbol quantization from 8 bits to 3 bits. The decoder input is up to 25 Msym/s. The NRZ-M and NRZ-S bit streams can be output as NRZ-L.

(2) Programmable frame synchronizer parameters include synchronization pattern, synchronization pattern mask, frame length, error threshold, check frames, flywheel frames, and bit-slip window. The frame synchronizer performs automatic polarity correction and optional CCSDS derandomization and cyclic redundancy check (CRC-16) virtual channel data unit (VCDU) error detection.

(3) Reed–Solomon (R-S) error correction performs R-S (255,223) VCDU error correction with an interleaving depth of from 1 to 8 and R-S (10,6) VCDU header error correction. Shortened code blocks also are supported.

Figure 5 presents a block diagram of the DS-T downlink. The COTS-supplied software implements the MGS mission-specific standard format data unit (SFDU) formatting as defined in 820-13 TLM 3-20.[6] All processing and formatting aspects of the output data packets are held in the DS-T database and can be modified without impact on the application software. The data delivery to the mission is guaranteed delivery, based on the distributed database concept. The processed SFDUs are buffered on the local disk until the receiving mission database acknowledges the delivery.

2. Uplink Equipment. Command file-to-radiated bit stream conversion was done in the DS-T workstation by software supplied by the I B + M A de Lande Long Software + Consultancy (deLL). This software, the Telecommand Encoder Shell, was developed for the European Space Agency (ESA) in Germany and implements the complete CCSDS telecommand protocol stack. The DS-T had a temporary license for this product. The test-signal output of the uplink at X-band was used extensively to exercise the downlink string. Figure 6 shows the block diagram of the DS-T uplink.

Because no block V exciter (BVE) was available for use at DSS 26 in the required time period, the DS-T implemented a simple replacement from COTS components. Testing of the DS-T uplink string showed excellent stability and overall performance matching the BVE.

The command subcarrier generator is the Avtec PTP-NT processor, which includes a subcarrier generator card. This card uses the frequency and timing system (FTS) 10-MHz reference to synthesize a

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[6] *TLM 3-20 DSN Telemetry Interface With SFOC—Mars Observer*, 820-13 (internal document), Jet Propulsion Laboratory, Pasadena, California, November 1, 1991.

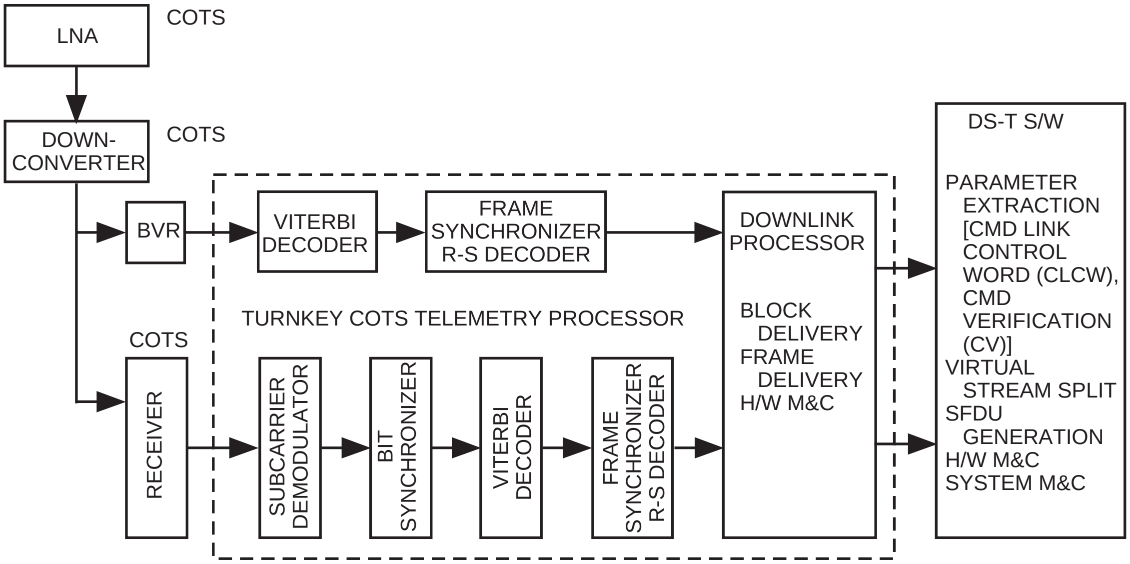


Fig. 5. The block diagram of the DS-T downlink.

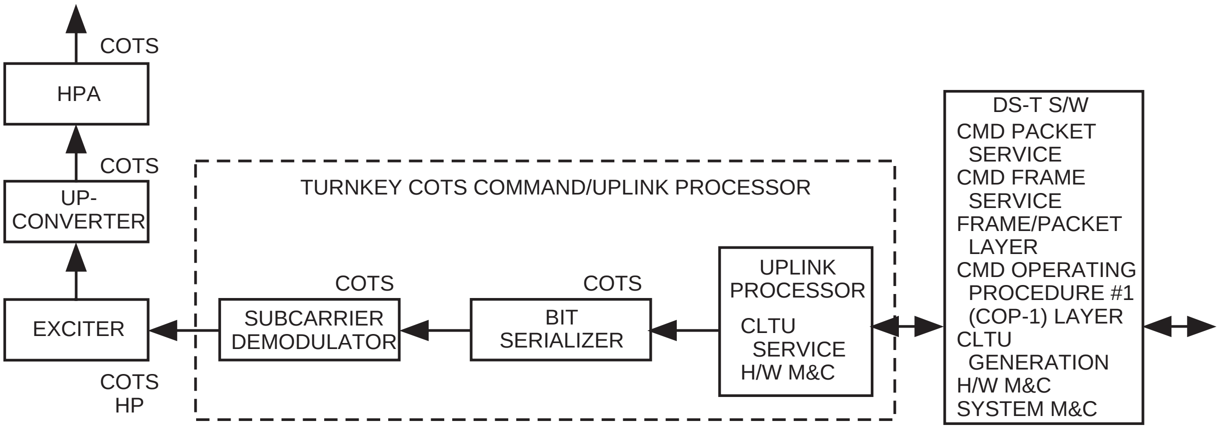


Fig. 6. The block diagram of the DS-T uplink.

sine-wave- or square-wave-modulated subcarrier in the range of from 100 Hz to 1 MHz in 0.01-Hz steps. A bit/symbol clock is available and is used to drive the serializer function for synchronous modulation. Optionally, the input data can be encoded to NRZ-M or -S.

For the exciter, the DS-T uses a Hewlett Packard (HP) 8663A signal generator with a phase-modulation option. Accurate modulation index adjustment is available from the signal generator without need to adjust the modulating signal's amplitude. The HP 8663A is controlled via the IEEE-488 interface from the Avtec box.

The DSN standard 4-kW X-band high-power amplifier (HPA) was partially installed at DSS 26. Due to DS1's launch delay to a date after the task end date, the HPA installation at DSS 26 was not completed.

C. Control Workstation

A Sun Ultra-2 computer, running the Solaris operating system, is used for the DS-T control workstation at DSS 26. Lower performance workstations are used for the remote controller position in

Building 161-113 at JPL and for the PI/mission position. All workstation connections are via standard protocols, such as TCP/IP, FTP, etc.

The largest software element in DS-T is the commercial EPOCH 2000 software (on the order of 120,000 lines of code) that provides the monitor and control (M&C) platform for the workstation. It provides database-driven functionality for the automation in the DS-T environment and allows M&C from multiple locations. This software is highly stable, well documented, and supported by the vendor. The same software is used daily in over 100 operational LEO ground stations.

About 150,000 lines of existing debugged code developed at JPL through technology development programs/Network Consolidation Plan (NCP) were reused by DS-T. The first major block of reused code is the predict generator. Second, both the network-level and terminal-level schedule-automation engines are a version of the Demand Access Network Scheduler (DANS), and, third, a modified version of the Automated Scheduling and Planning Environment (ASPEN) was used for dynamic control-script generation. The CCSDS command software, supplied by DeLL, an ESA contractor, is approximately 60,000 lines. This software is used in ESA ground stations and was made available to JPL for evaluation.

Customized software for the DS-T demonstration is estimated to be from 25,000 to 30,000 lines of code at the completion of DS-T downlink demonstrations, and about 50,000 lines of code for a fully operational system that includes the uplink.

1. Software Layers. To provide autonomous operating capability, the DS-T applies tightly coupled software and hardware in the DS-T. This coupling is established during the script-generation phase of the track execution. The generalized script generator uses spacecraft, ground-equipment, and track-specific information to create a track-unique script to be executed in real time. The models of the spacecraft, ground equipment, and service (to be provided during the track) are held in a database. Changes in any of the models do not change the application software. Similarly, by populating the necessary database records, new services can be provided.

To correctly demonstrate the DS-T in the future automated NSP environment, the automated resource allocation process had to be modeled. For this, an additional layer was implemented, representing the DSN network capabilities, such as processing the SRs into a format representing the planned network planning and preparation (NPP) activity service request (ASR), which is the input to the DS-T. The network layer stores all information necessary to support the tracking services. Three functional layers can be found within the DS-T. From the top, these are the automation layer, the application layer, and the subsystem layer. The software layers are shown in Fig. 7.

The automation layer is responsible for the high-level control and execution monitoring of the DS-T station. This layer comprises all of the automation software. The automation layer also provides the user interface to the autonomous station/terminal. From the network layer, it is through the automation layer that ASRs are submitted to the system and then scheduled for execution.

The application layer is for monitor and control and is responsible for low-level control of the antenna track as well as for the logging and archiving of relevant monitor data. It also provides the real-time operator interface, if requested, which displays monitor data and accepts low-level operator directives. Use of real-time operator directives is not necessary for the execution of a track, but it is available in the event of an operator override. This layer is comprised of the control software used in commanding the subsystems in the hardware layer and monitoring the status of these systems.

The subsystem layer is made up of an interface and the subsystems themselves. In conjunction with the hardware mentioned above, additional peripheral subsystems, such as a weather station, make up the lowest layer of the architecture. The subsystem layer provides a uniform interface to the various subsystems to facilitate modular software design and reduce the effort needed to interchange and upgrade hardware.

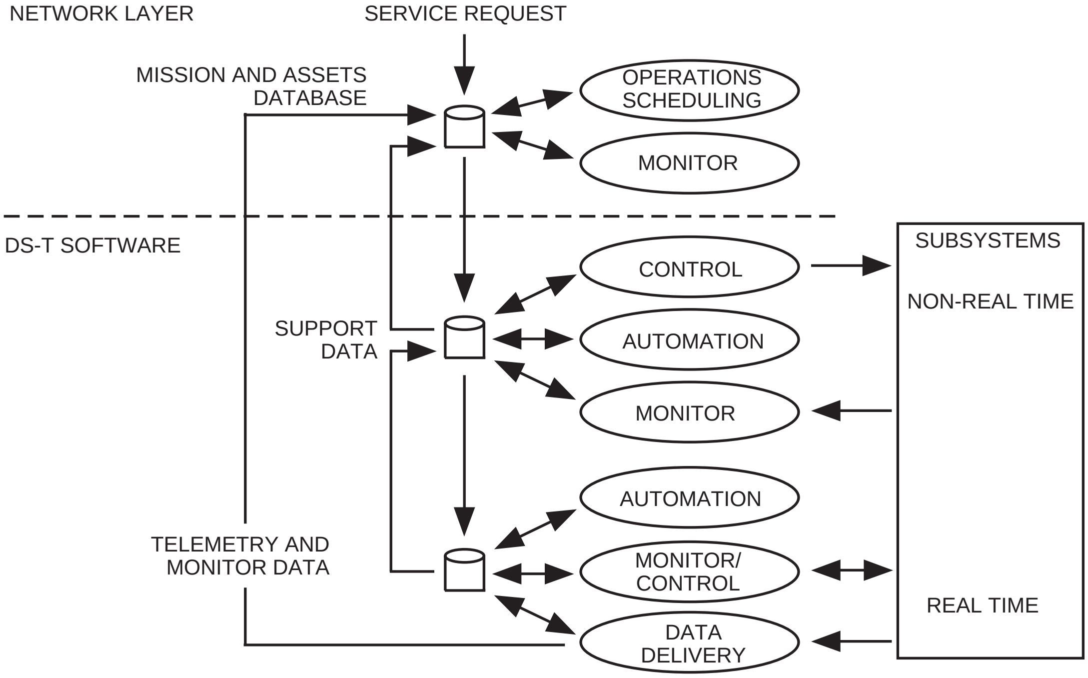


Fig. 7. The software layers.

The layered approach to the architecture provides several benefits. First and most importantly, it provides clean boundaries between different functionalities within the system. This, combined with the proper abstraction levels, makes division of the system simpler, aiding in division of development and testing responsibilities.

Each software layer is discussed in detail below.

2. Network Layer. This layer, show in Fig. 8, accepts track and service requests from flight projects and produces a local schedule for the DS-T. The input is spacecraft identification (ID), track start and stop times, and the required service. Output is a high-level activity list that has sufficient data for the station automation layer. Once the track information is transmitted to the station, the station can operate in a stand-alone mode. (The network-layer service-request processor and the terminal service-request processor applications work at different levels, reusing the same code.)

The network layer has three principal interfaces to the DS-T automation software. In addition to the track activity list, the network layer is responsible for storing information on the tracking services required by the spacecraft, current spacecraft configuration, planetary and spacecraft ephemeris, and telecommunications models. This information (as well as the current schedule) is stored in a globally accessible database called the mission and assets database (MADB). The MADB is a major interface point from the network layer to the automation element of the station layer; the architecture uses a local copy of the MADB data if the connection to the network layer is temporarily lost. Last, the network layer accepts and appropriately distributes the DS-T real-time monitor data and the processed telemetry for delivery to the mission/PI, and generates near-real-time performance summarization.

3. Automation Layer. The automation layer performs several functions within the DS-T workstation, all relating to automation and high-level monitor and control for the DS-T station. This layer consists of six components: the terminal service-request processors, the schedule executive, the configuration engine, predict generators, the script generator, and the station controller. Figure 9 shows the automation layer.

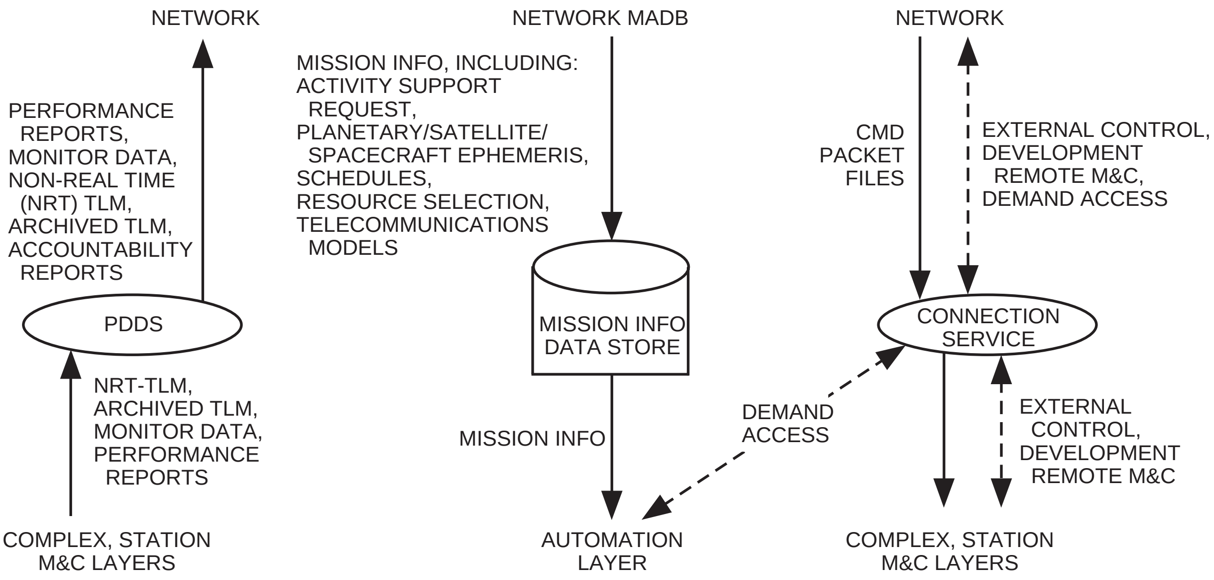


Fig. 8. The network-layer data flow.

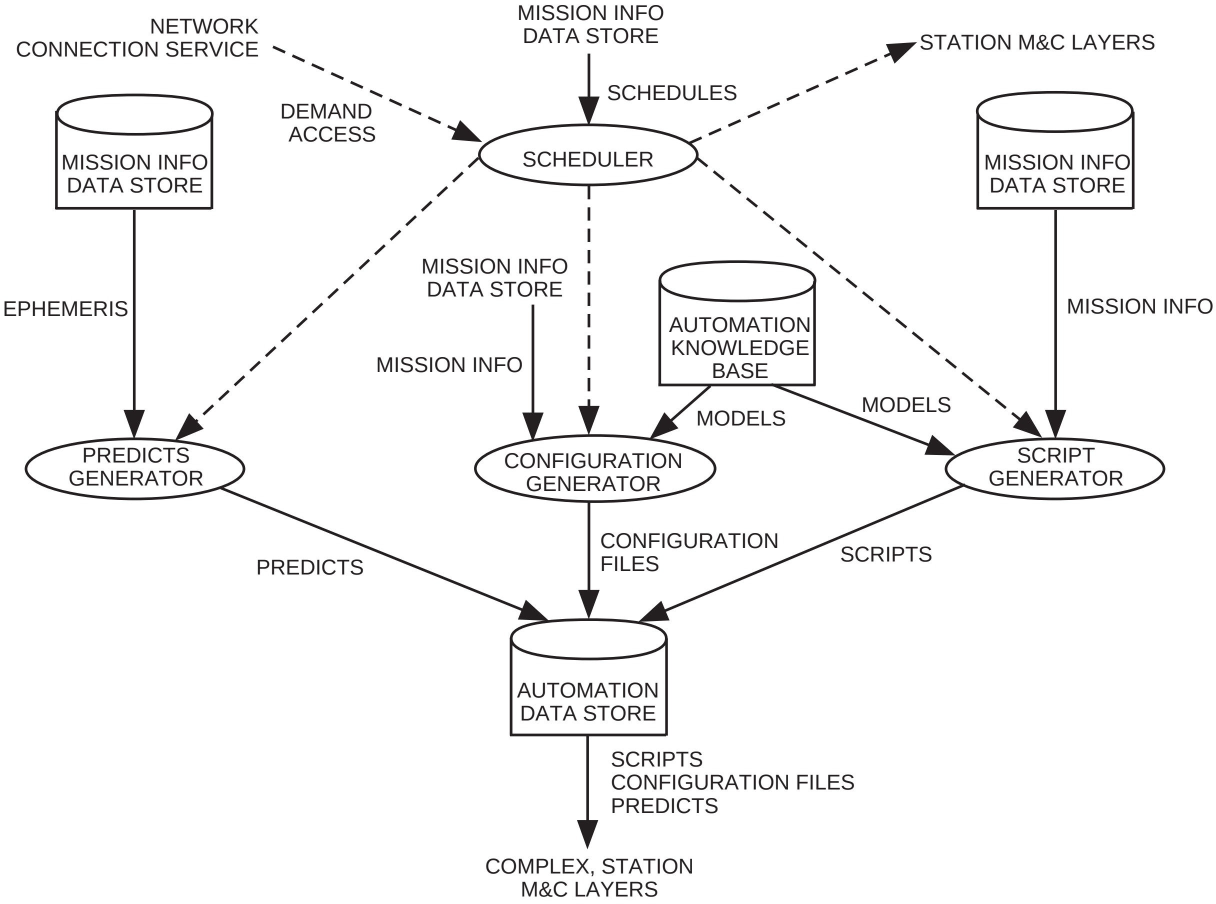


Fig. 9. The automation layer.

The DS-T's service request (SR) processor takes in an ASR from the network layer, generates the first-cut configuration files needed to produce a scheduling request, and defines the request to be performed. From these files, the request is passed to the DANS system to produce the network schedule.

The schedule executive (SE) takes the network schedule and sets up the station schedule for execution and provides the means for automated rescheduling and/or manual schedule editing in the event of changes to the master schedule. Parsing the schedule and scheduling the subtasks that need to be performed in order to accomplish the originally scheduled activity set up schedule execution. Each subtask is placed into the crontab (a cron configuration table for the cron application) file with the appropriate time stamp relative to the acquisition of signal (AOS). In this manner, each of the remaining components of the automation layer are invoked at the appropriate times by the UNIX crontab facility.

The configuration engine (CE) is the first to be started up by the cron (a standard UNIX program that executes other programs based on the crontab) facility. This component is responsible for retrieving from a collection of data stores all the data/data files necessary for station operations. These files contain information about the spacecraft trajectory needed to calculate antenna-pointing predicts; spacecraft view periods; models of planetary orbits, to determine if the spacecraft view is obstructed; precise location of the ground station; and activity service packages (ASPs). The ASPs contain the service request that defines the type of activity desired by a mission/project and activity details like carrier frequency, symbol rate, and project mission profiles. The CE examines this large collection of data and extracts the relevant information into configuration files for the remaining modules of the automation layer.

After the CE creates the needed configuration files for the predict generators (PGs) and the script generator (SG), the cron facility invokes the SG processes with its appropriate configuration files.

The SG is where the majority of the control autonomy comes from. The SG uses artificial intelligence planning techniques to perform a complex software module reconfiguration process. This process consists of piecing together numerous highly interdependent smaller control scripts in order to produce a single script to control the operations of the DS-T station.

The core engine used in the SG is the Automated Scheduling and Planning Environment (ASPEN). The ASPEN system is a reusable, configurable, generic planning/scheduling application framework that can be tailored to specific domains to create conflict-free plans or schedules. It has a number of useful features, including an expressive modeling language, a constraint management system for representing and maintaining antenna operability and/or resource constraints, a temporal reasoning system, and a graphical interface for visualizing plans and states. ASPEN has been adapted to input antenna-tracking goals and to automatically produce the required command sequence to create the requested link.

The control script produced by the SG (1) sets up the track by configuring the station during pre-track, (2) provides the requested track service by commanding the antenna and subsystems to acquire and maintain lock on the signal throughout mode changes, and (3) cleans up and shuts down the station at the completion of the track.

It is during the pre-track that the predict generation (PG) process takes place. The PG functionality consists of three predict generators used to calculate antenna-pointing predicts (AP-PDX), radiometric predicts (RAD-PDX), and telemetry predicts (TEL-PDX). Another requirement of the DS-T was to provide the means of generating predicts on demand for the pass or to use provided predicts. This provides another example of how the DS-T SG reconfigures the pre-track by selecting which predicts (xx-PDX) are to be generated.

The station controller (SC) spans both the automation layer and the application layer. As such, the explanation of the SC functionality is left for the next section.

4. Application Layer. The station monitor and control process in the application layer acts as an agent for the automation layer, executing the generated scripts. Figure 10 shows the application layer. The underlying engine of this layer is the EPOCH 2000 software that executes the track-specific script based on the reported subsystem status. The monitor and control process expands the high-level directives of the script into subsystem-dependent directives, isolating the automation layer from the lower levels. By using the monitor information from the station monitor process, the script execution path is altered as necessary to accommodate external events. The EPOCH 2000 software provides the optional real-time operator display and low-level directive input for the subsystems in bypass mode for debugging and experimental use.

All subsystem-generated monitor information (monitor data packets and event notices) is processed in the station-monitor process. The monitor data are recorded in a local data store, and condensed performance reports are generated for the higher-level processes. The collected monitor data are sent to all subscribing workstations.

The uplink/downlink process handles the spacecraft command and telemetry data flow. The command data are accepted as command link transmission units (CLTUs) or as command packet files and processed according to CCSDS standards. Telemetry data are formatted in the subsystem into frames or packets. These are archived until the data are delivered to the mission or the product data deliver system (PDDS).

5. Subsystem Layer. The subsystem interface layer handles the interfaces to the DS-T assigned subsystems, all the communication-protocol and connection-related work. This is necessary because the DS-T is a mix of COTS and custom JPL-designed equipment using a variety of protocols. The inherited JPL equipment uses a proprietary communication protocol, while some COTS units use TCP/IP, and others use either the IEEE-488 or RS-232 low-level protocols. The JPL protocol also requires the equipment "be assigned" to a track, requiring some hereditary connection management. Figure 11 shows the subsystem layer data flows.

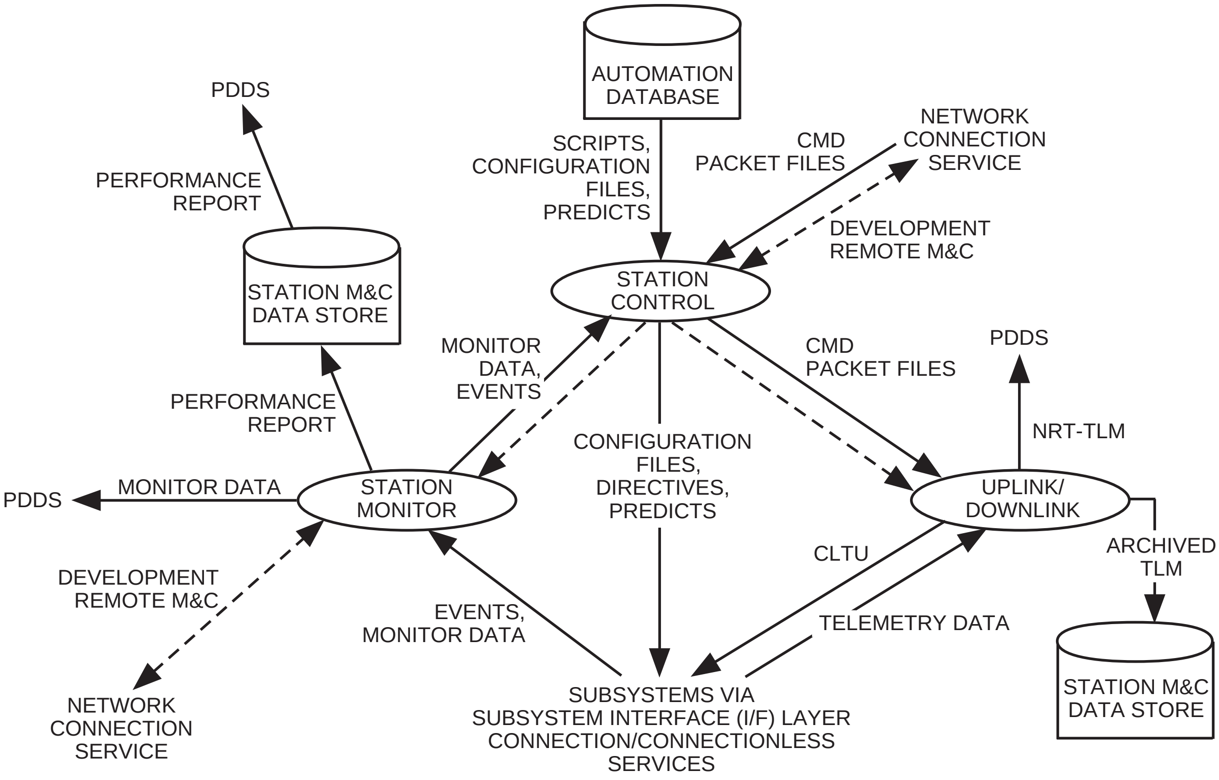


Fig. 10. The application layer.

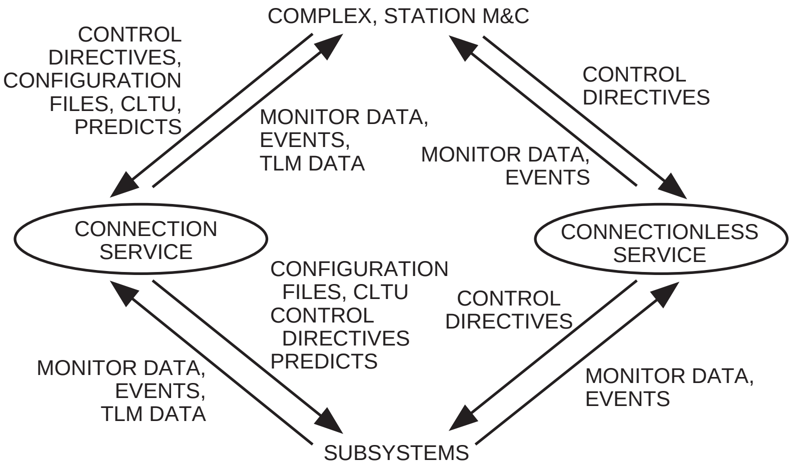


Fig. 11. The subsystem-layer data flows.

D. Remote Control and Communications Interface

For safety and security reasons, the DS-T Team had to implement secure links over public networks linking the physically different locations. A COTS product was selected and installed, and the configuration is shown in Fig. 12. The communications between the DS-T at the antenna site, the DS-T remote console for operational control, and the PI/mission workstation are implemented using network encryption units (NEUs) that provide highly secure hardware-based encoding and decoding. Each workstation had an IP address assigned, and the NASA Science Internet connectivity provided the link. The NEU control computer (C.C.) was set up in a restricted-access location, co-located with the DS-T remote-console workstation.

The NEU control computer periodically queries each NEU for proper operation and provides a new encryption key for the next interval. The product allows the control of interconnections between workstations; for example, the PI machine was not permitted to send directives to the DS-T at DSS 26.

The built-in capabilities of the EPOCH 2000 product allowed real-time monitoring of the DS-T from any of the other locations running the EPOCH 2000, which greatly helped the development effort.

E. The DSS-26 Environment

While the DS-T task resided at DSS 26, the antenna was not in operational status in the DSN due to budgetary constraints. The antenna and its subsystems were complete although not fully calibrated. This is the reason for some antenna-pointing residuals being high. The frequency and timing subsystem (FTS) was available for timing and frequency reference signals at a slightly reduced accuracy, while the weather-station information was provided from the nearby DSS-25 site. The Goldstone Deep Space Communications Complex (GDSCC) personnel maintained the antenna and all other equipment in DSS 26 on a best-effort basis.

IV. Demonstration With MGS

A. The MGS Spacecraft

The MGS spacecraft, fabricated at Lockheed Martin, was launched in November 1996 and reached Mars in September 1997. The primary mission is the mapping of Mars' surface, atmosphere, and external fields with the six main scientific instruments over 1 Martian year (687 Earth days). After mapping finishes, the spacecraft will function as a communication satellite to relay data back to Earth from follow-on surface landers.

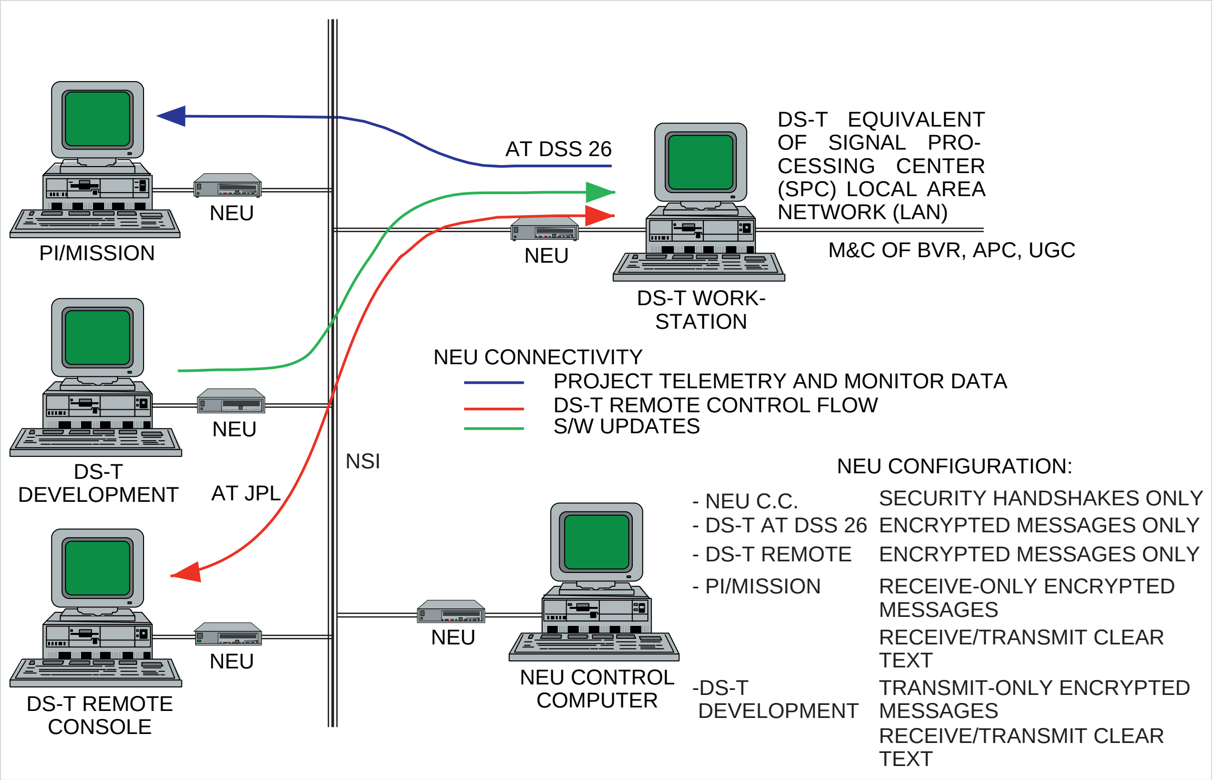


Fig. 12. The DS-T secure internal network configuration.

The actual testing of the DS-T with the MGS spacecraft covered the March to September 1998 period. Due to a mechanical failure, the spacecraft was executing the aerobraking sequence during this period. Because of the solar conjunction in May 1998, the extended aerobraking was broken into two phases. At the start of DS-T testing, MGS was in the first aerobraking phase until the end of March 1998. Three weeks around the solar conjunction, communications with the spacecraft were less reliable and, for 5 days prior to and after the conjunction, the DS-T did not track MGS due to concern about overloading the LNA. After this point, until September 1998, the spacecraft was in the science phasing orbit, operationally a relatively repetitive period. On most orbits at periapsis, MGS turned to Mars to perform science investigations. Communication was interrupted with the spacecraft since the HGA is in a stowed position until the end of aerobraking. The collected data were played back when the spacecraft turned back to Earth.

Due to the changed flight plan, and to maximize the science-data return, on occasions the mission flight controllers used downlink configurations (data rates) that were not in the original telemetry parameters during solid-state recorder playbacks. For flexibility, the DS-T configuration is held in a database; to enable tracking with the “new” rates, only one record item had to be updated with new values.

MGS started the second aerobraking phase in September 1998. The final 6-day DS-T test was planned from September 14 through September 21. At 3:30 PDT on September 17, 1998, an error in the spacecraft’s command sequence set the solar arrays to an incorrect angle, which caused significant discharge of the spacecraft’s batteries and subsequently sent it into “contingency” mode. In this mode, the spacecraft switches to Sun-pointing safe-hold mode and communicates via its low-gain antenna. The significantly ($\sim$32-dB) reduced signal level necessitated the use of the 70-meter antenna for ground support. Commands to return the spacecraft to normal operations were uplinked starting Sunday evening (September 21), with return to high-gain antenna operations on Monday evening. During the contingency period, the mission operated the ground stations via real-time voice updates, and the BWG antenna could not reliably acquire the downlink due to insufficient link margin.

B. The MGS-to-DS-T Link Margin

The DS-T testing occurred near the solar conjunction. DSN support for MGS usually was assigned to the BWG antennas; the maximum downlink data rate is limited to 21,333 b/s. Figure 13 shows the MGS downlink link margin, and Fig. 14 shows the MGS uplink link-margin calculations.

When the spacecraft is broadcasting data, without an uplink at the same time, it is in one-way mode (on Channel 17), and the downlink carrier frequency is derived from an onboard frequency source. When uplink and downlink are taking place simultaneously, the spacecraft is in two-way mode (on Channel 23), and the downlink carrier frequency will be different from the one-way frequency. In the case of two-way mode, the downlink carrier frequency is derived from the uplink frequency. If a station is communicating in two-way mode and another station is listening, that other station is in three-way mode. Because DS-T never operated the uplink with MGS, the DS-T operated either in one-way or three-way mode.

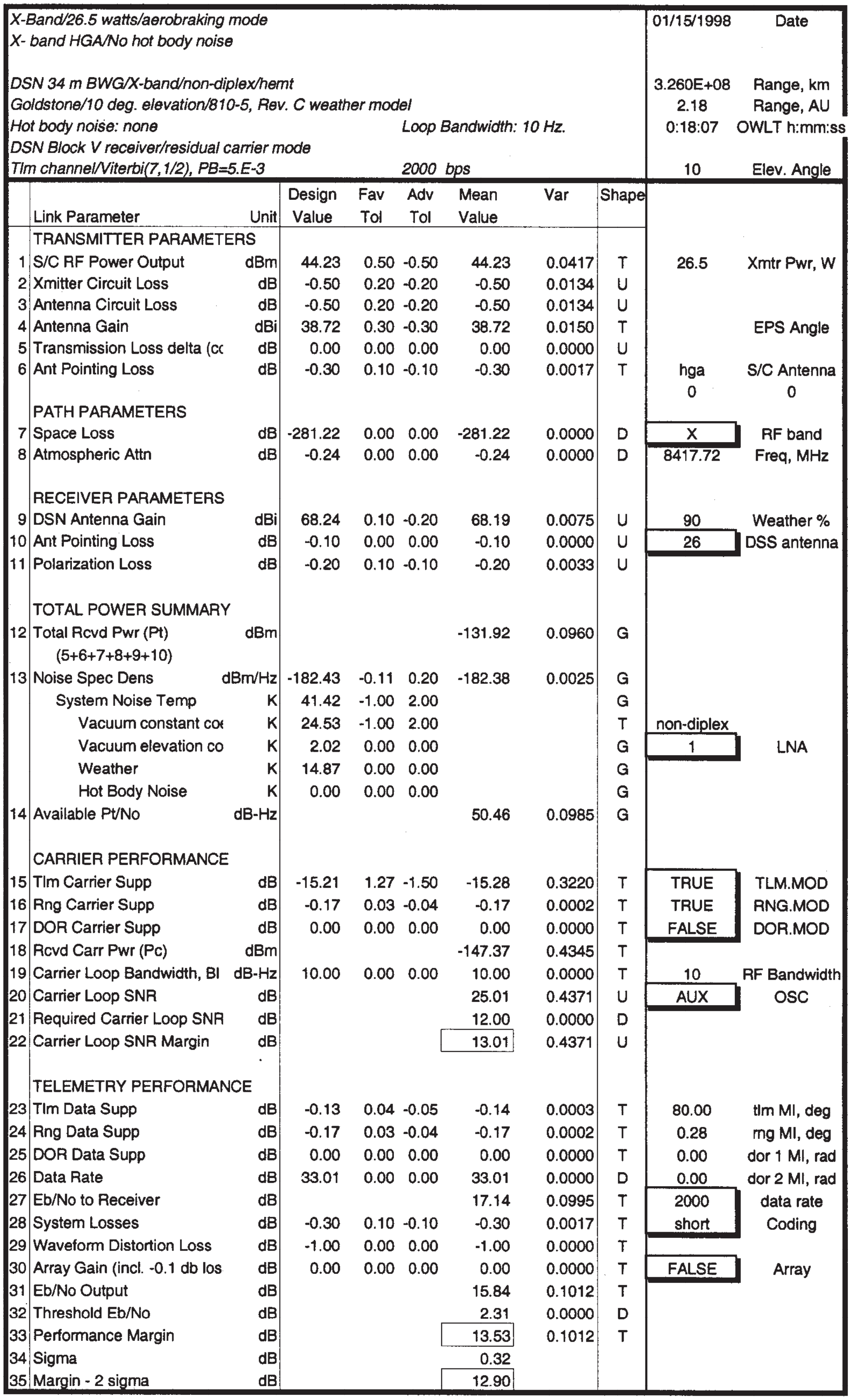
C. The Demonstration Operational Scenario

For the DS-T demonstration, those tracks that were tracked by the DSN with the primary antenna at GDSCC were classified as Class 1, and the DS-T performance was evaluated by the success of data collection on those tracks. Tracks when the primary antenna tracking MGS was not located at GDSCC were classified as Class-2 tracks. Due to the low elevation angle at DSS 26, data collection was at times less then optimal, because the downlink data rate was set up for the better elevation at the other station. In order to increase our total test and demonstration time, the DS-T tracked MGS when it was in view, even if no DSN support was scheduled. These tracks were designated as Class-3 tracks; when operating in this mode, the team had to extrapolate information from the SOE to generate the SR. Several successful Class-3 tracks were executed.

During the science phasing orbit, the orbital period of MGS was almost 12 hours, and the DSS-26 view period only moved a few minutes per day, starting in the early morning.

On the night before the track, the latest SOE was scanned and the MGS downlink segments extracted and classified. The SRs were generated and entered at the remote terminal. During the demonstrations, the PI/mission workstation acted as the mission database, and the monitor data and received telemetry were collected there. The received telemetry data were analyzed to establish performance figures. Day of year (DOY) 245 is shown in graphic form in Fig. 15. DS-T tracked MGS through the 10 track segments indicated in the figure. Track segments 7 and 10, labeled LOS, indicate that there was a scheduled loss of signal (LOS), so during this segment, no frames were collected. As shown by the figure, during segments 1 and 9, the elevation of the antenna is low. Under these circumstances, there is considerably more atmospheric interference, which explains the lower percentage of frame collection. On the other hand, at segments 4, 5, and 8, when there are long segments with the spacecraft high in the sky, the data collection is good: 98, 99, and 99 percent, respectively. In segment 6, the value is a little lower due to the shortness of the segment. The reason is that some data are lost during a change in mode, a transition from three-way/DSS 25 to one-way mode. During our lights out, autonomous, unattended demonstrations, we collected above 90 percent of the transmitted frames. This performance is on a par with the operator-controlled stations.

The monitor data also were analyzed for receiver and antenna-pointing performance. During the demonstrations, the concentric scanning (conscan) feature of the APC was turned on, and the pointing residuals were plotted. The relatively high residuals are due to the status of DSS 26, as mentioned above.



X-Band/26.5 watts/aerobraking mode	01/15/1998	Date
X- band HGA/No hot body noise		
DSN 34 m BWG/X-band/non-diplex/hemt	3.260E+08	Range, km
Goldstone/10 deg. elevation/810-5, Rev. C weather model	2.18	Range, AU
Hot body noise: none *Loop Bandwidth: 10 Hz.*	0:18:07	OWLT h:mm:ss
DSN Block V receiver/residual carrier mode		
Tlm channel/Viterbi(7,1/2), PB=5.E-3 *2000 bps*	10	Elev. Angle

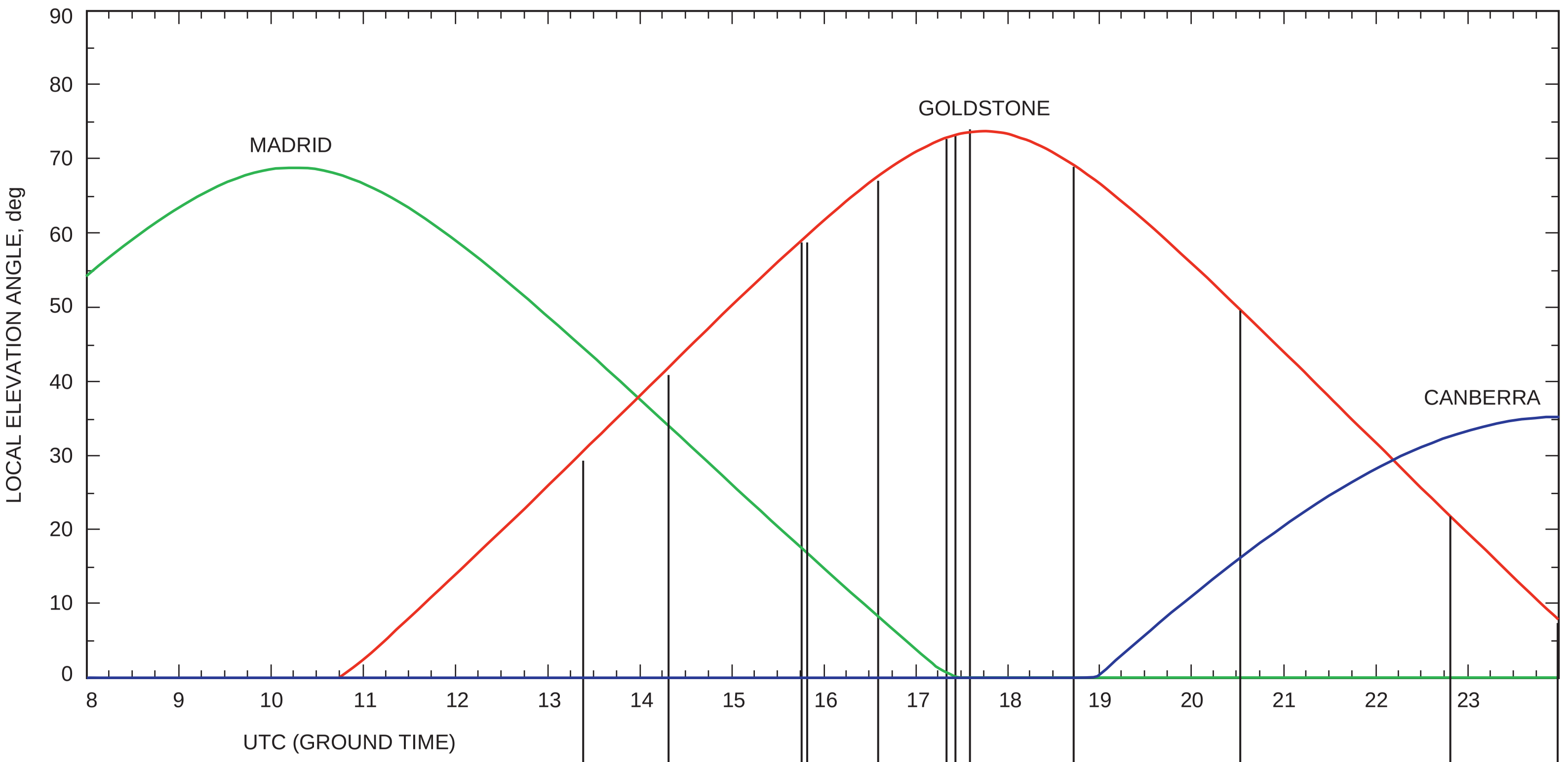
	Link Parameter	Unit	Design Value	Fav Tol	Adv Tol	Mean Value	Var	Shape		
	TRANSMITTER PARAMETERS									
1	S/C RF Power Output	dBm	44.23	0.50	-0.50	44.23	0.0417	T	26.5	Xmtr Pwr, W
2	Xmitter Circuit Loss	dB	-0.50	0.20	-0.20	-0.50	0.0134	U		
3	Antenna Circuit Loss	dB	-0.50	0.20	-0.20	-0.50	0.0134	U		
4	Antenna Gain	dBi	38.72	0.30	-0.30	38.72	0.0150	T		EPS Angle
5	Transmission Loss delta (cc	dB	0.00	0.00	0.00	0.00	0.0000	U		
6	Ant Pointing Loss	dB	-0.30	0.10	-0.10	-0.30	0.0017	T	hga	S/C Antenna
									0	0
	PATH PARAMETERS									
7	Space Loss	dB	-281.22	0.00	0.00	-281.22	0.0000	D	X	RF band
8	Atmospheric Attn	dB	-0.24	0.00	0.00	-0.24	0.0000	D	8417.72	Freq, MHz
	RECEIVER PARAMETERS									
9	DSN Antenna Gain	dBi	68.24	0.10	-0.20	68.19	0.0075	U	90	Weather %
10	Ant Pointing Loss	dB	-0.10	0.00	0.00	-0.10	0.0000	U	26	DSS antenna
11	Polarization Loss	dB	-0.20	0.10	-0.10	-0.20	0.0033	U		
	TOTAL POWER SUMMARY									
12	Total Rcvd Pwr (Pt)	dBm				-131.92	0.0960	G		
	(5+6+7+8+9+10)									
13	Noise Spec Dens	dBm/Hz	-182.43	-0.11	0.20	-182.38	0.0025	G		
	System Noise Temp	K	41.42	-1.00	2.00			G		
	Vacuum constant co	K	24.53	-1.00	2.00			T	non-diplex	
	Vacuum elevation co	K	2.02	0.00	0.00			G	1	LNA
	Weather	K	14.87	0.00	0.00			G		
	Hot Body Noise	K	0.00	0.00	0.00			G		
14	Available Pt/No	dB-Hz				50.46	0.0985	G		
	CARRIER PERFORMANCE									
15	Tlm Carrier Supp	dB	-15.21	1.27	-1.50	-15.28	0.3220	T	TRUE	TLM.MOD
16	Rng Carrier Supp	dB	-0.17	0.03	-0.04	-0.17	0.0002	T	TRUE	RNG.MOD
17	DOR Carrier Supp	dB	0.00	0.00	0.00	0.00	0.0000	T	FALSE	DOR.MOD
18	Rcvd Carr Pwr (Pc)	dBm				-147.37	0.4345	T		
19	Carrier Loop Bandwidth, Bl	dB-Hz	10.00	0.00	0.00	10.00	0.0000	T	10	RF Bandwidth
20	Carrier Loop SNR	dB				25.01	0.4371	U	AUX	OSC
21	Required Carrier Loop SNR	dB				12.00	0.0000	D		
22	Carrier Loop SNR Margin	dB				13.01	0.4371	U		
	TELEMETRY PERFORMANCE									
23	Tlm Data Supp	dB	-0.13	0.04	-0.05	-0.14	0.0003	T	80.00	tlm MI, deg
24	Rng Data Supp	dB	-0.17	0.03	-0.04	-0.17	0.0002	T	0.28	rng MI, deg
25	DOR Data Supp	dB	0.00	0.00	0.00	0.00	0.0000	T	0.00	dor 1 MI, rad
26	Data Rate	dB	33.01	0.00	0.00	33.01	0.0000	D	0.00	dor 2 MI, rad
27	Eb/No to Receiver	dB				17.14	0.0995	T	2000	data rate
28	System Losses	dB	-0.30	0.10	-0.10	-0.30	0.0017	T	short	Coding
29	Waveform Distortion Loss	dB	-1.00	0.00	0.00	-1.00	0.0000	T		
30	Array Gain (incl. -0.1 db los	dB	0.00	0.00	0.00	0.00	0.0000	T	FALSE	Array
31	Eb/No Output	dB				15.84	0.1012	T		
32	Threshold Eb/No	dB				2.31	0.0000	D		
33	Performance Margin	dB				13.53	0.1012	T		
34	Sigma	dB				0.32				
35	Margin - 2 sigma	dB				12.90				

Fig. 13. The DS-T–MGS downlink link margin.

HGA Uplink	01/15/1998	Date
DSN 3.565 kW/34 m BWGstation/blind pointing/0.012 deg peak error		
Goldstone/10 deg. elevation/810-5, Rev. C weather model		
X-band HGA/3.14 mrad pointing error/No hot body noise	3.260E+08	Range, km
	2.18	Range, AU
X-band/Cassini DST/best estimates/8.75 Hz BLo	0:18:07	OWLT h:mm:ss
Command channel/uncoded, PB=1.E-5 *7.81 bps*		
Sine wave subcarrier/new model	10	Elev. Angle

	Link Parameter	Unit	Design Value	Fav Tol	Adv Tol	Mean Value	Var	Shape		
	TRANSMITTER PARAMETERS									
1	Total Xmitter Pwr	dBm	65.52	0.20	-0.20	65.52	0.0067	T	3.565	Xmtr Pwr, kW
2	Xmitter Waveguide Loss	dB	0.00	0.00	0.00	0.00	0.0000	T	FALSE	on-nominal p
3	DSN Antenna Gain	dBi	66.91	0.10	-0.20	66.86	0.0075	U	25	DSS antenna
4	Ant Pointing Loss	dB	0.00	0.00	-0.01	0.00	0.0000	T		
5	EIRP (1+2+3+4)	dBm				132.38	0.0142	U		
									X	RF band
	PATH PARAMETERS									
6	Space Loss	dB	-279.83			-279.83		D	7175.03	Freq, MHz
7	Atmospheric Attn	dB	-0.24			-0.24		D	90	Weather %
	RECEIVER PARAMETERS									
8	Polarization Loss	dB	-0.09	0.08	-0.06	-0.08	0.0017	U		
9	Ant Pointing Loss	dB	0.00	0.00	-1.00	-0.33	0.0556	T		
10	S/C Antenna Gain	dBi	37.43	0.30	-0.30	37.43	0.0150	T		
11	Lumped Ckt/Ant Loss	dB	-24.77	0.32	-0.41	-24.82	0.0445	U	hga	S/C Antenna
	TOTAL POWER SUMMARY									
12	Total Rcvd Pwr (Pt) (5+6+7+8+9+10+11)	dBm				-135.49	0.1310	G		
13	Noise Spec Dens	dBm/Hz	-170.23	-0.07	0.27	-170.17	0.0051	T		
	System Noise Temp	K	686.26	-10.22	43.33					
	Rcvr Noise Temp	K	159.16	-10.22	43.33					
	Rcvr Noise Figure	dB	1.90	-0.10	0.40					
	Loss Noise Contr.	K	289.03	-0.07	0.09					
	Hot Body Contrib.	K	0.01	0.00	0.00					
14	Rcvd Pt/No	dB-Hz				34.68	0.1362	G	(12-13)	
	CARRIER PERFORMANCE									
15	Cmd Carrier Supp	dB	-1.45	0.10	-0.10	-1.45	0.0017	T	TRUE	CMD.MOD
16	Rng Carrier Supp	dB	0.00	0.00	0.00	0.00	0.0000	T	FALSE	RNG.MOD
17	Rcvd Carr Power (Pc)	dBm				-136.94	0.1327	T	(12+15+16)	
18	Carr Noise BW, 2BLo	dB-Hz	12.43	1.00	-0.71	12.58	0.2443	U	17.5	Hz
19	Required Carrier Margin	dB	12.00			12.00		D		
20	Excess Carrier Margin	dB				8.65	0.3821	U	(17-13-18-19)	
	CHANNEL PERFORMANCE									
21	Cmd Modulation Loss	dB	-5.65	0.17	-0.18	-5.66	0.0051	T	0.8	cmd MI, rad
22	Rng Data Supp	dB	0.00	0.00	0.00	0.00	0.0000	T	44.9	rng MI, deg
23	Data Pwr to Rcvr (Pd)	dBm				-141.15	0.1361	T	(12+21+22)	
24	Data Rate	dB	8.93	0.00	0.00	8.93	0.0000	D	7.8125	data rate
25	Eb/No	dB				20.09	0.1413	T	(14+21+22-24)	
26	System Loss	dB	-1.60	0.28	-0.28	-1.60	0.0131	T	(includes radio loss)	
27	Threshold Eb/No	dB	9.60			9.60		D	BER = 1e-5, uncoded	
28	Performance Margin	dB				8.89	0.1413	T	(25+26-27)	
29	Sigma	dB				0.38				
30	Margin - 3 sigma	dB				7.77				

Fig. 14. The DS-T–MGS uplink link margin.



SEGMENT NUMBER	1	2	3	4	5	6	7		8	9	10
SEGMENT DURATION, min	59	90	0.8	49.5	49	3.7			93.7	138	LOS
WAY	3w 65	3w 65	3w 65	3w 65	3w 25	1w	LOS		3w 25	1w	
DATA RATE, kb/s	21.3	2	0.25	4	4	4			16	16	
SYMBOL SIGNAL-TO-NOISE RATIO (SSNR) (BEGIN/END), dB	–9.1 4.6	15 15.2		12.1 12	11.9 11.7	11.7 11.7			5.7 5.4	5.4 4.1	
BVR LOCK TIME, min	6.1	9.5	0.3	1.4	2	2			2	2	
FRAME RECEIVED	18,002	1174	4	1163	1169	83			8945	19,695	
PERCENTAGE RECEIVED	N/A	87	?	98	99	93			99	~97	

Fig. 15. DOY 245 performance figures.

DS-T used the published nominal carrier frequencies as an input to the frequency predict generation; when this was updated to actual mission frequencies, the residuals fell below ±100 Hz at X-band. The carrier power over noise per frequency unit (P_c/N_o) and signal-to-noise ratio (SNR) actuals followed the predicted values very closely.

The post-pass analysis also evaluated performance figures such as time to acquire the signal and the number of reacquisitions executed. The lock-up figures were similar or better than the operator-controlled stations, and the automatic process never lost data due to internal malfunctions.

V. Team Work

The DS-T implementation was carried out with extensive collaboration between JPL's Communications Systems and Research Section, Communications Ground Systems Section, Application Development Section, and Information and Computing Technologies Research Section, and with industry, including Allied Signal, Berkshire Technologies, Integral Systems (ISI), and Avtec. This allowed for effective implementation of DS-T by drawing on the best of JPL and industry in the following areas:

(1) Rapid fabrication of a microwave feed system and a high-performance cryogenic X-band RF system by Berkshire Technologies based on technologies developed by JPL for the Telecommunications and Mission Operations Directorate Technology Office (TMOT). The implementation was reduced from 1.5 years to about 9 months.

(2) Cost-effective collaborative development of terminal automation software by JPL and Integral Systems using Integral Systems EPOCH 2000 software. Each developer group focused on its area of specialty; tasks were assigned to the appropriate implementor. The use of high-level interfaces has freed the DS-T Team from doing mundane low-level coding; this allowed full concentration on high-level issues of automation and exception handling.

(3) Cost-effective integration of the Avtec telemetry system into the DS-T by close collaboration between JPL, Integral Systems, and Avtec. This enabled JPL engineers to focus on high-level issues, such as modeling, because the telemetry processor was seamlessly integrated into the EPOCH 2000.

(4) Effective DS-T system engineering facilitated through close collaboration between JPL and Integral Systems. The DS-T made use of the results of work done earlier in several cases, such as use of the experimental four-port junction and waveguide combiner and the use of artificial intelligence planning and scheduling software developed for other JPL tasks.

(5) The fast development and implementation of the safety plan for unattended operations, which was made possible only through the close collaboration between JPL and Allied Signal. The GDSCC personnel provided almost operational-level support in case of breakdowns and maintained DSS 26.

VI. Task Conclusions

The level of completeness of the DS-T implementation of the concepts as stated in the original task plan is discussed in the following paragraphs.

Fully autonomous, automated operations over several days. At the DSN station level, the DS-T fully implemented and demonstrated lights out operations. Real-time operator input was possible from two places only—the operator's terminal at DSS 26 and the remote terminal in Building 161-113. This capability was used once during the 6-day demonstration, when a real-time change occurred in the SOE.

During the demonstrations, DSS 26 was unattended and locked for safety reasons. Any person entering the station would have triggered an alarm and, for safety reasons, stopped the track.

Schedule-driven operation with only high-level-request input necessary. Automated scheduling and conflict resolution within the DS-T. Fully implemented, all tracks were activated by entering a service request into the DS-T scheduling component. The SR included the track start time, time information on downlink configuration changes, and the track end time. The automated scheduling did not cover the DSN network level; a different task was assigned to solve that problem. However, the scheduling and conflict-resolution engine used in the DS-T originated from that task.

Self-generated predicts for antenna-pointing and receiver-frequency information. Fully implemented, the DS-T generated all pointing and frequency predicts for all tracks. Predict generation and delivery activity took a little over 2 minutes during the pre-track period. Carrier frequency offset between the predicted and actual was less than 100 Hz, and the pointing predicts were able to acquire the signal consistently (i.e., without the use of conscan). Functionality was included for use of provided predicts as well.

Expandable, service-based operation. The DS-T fully implemented the telemetry downlink service and partially implemented the command uplink service. All tracks were using the telemetry service during the 6-day demonstration. New services could be added without disturbing the existing services; see the addition of DS1's beacon-mode service support. Since most operations are model/script driven, adding new capabilities does not require programmatic changes and does not increase complexity or risk.

Automatic pre-track configuration and self-test. DS-T configured all the subsystems required in the operation of the station. For the antenna-pointing subsystem, predicts were generated and loaded and several directives were issued to correctly configure the subsystem. All microwave switches were configured via directives. For the BVR, the predicts were generated and loaded and several directives were issued to correctly configure the receiver. The appropriate configuration tables were loaded into the telemetry subsystem.

Autonomous operation, active track monitoring, and built-in error recovery. A number of error-recovery routines, covering the most likely errors, are implemented in the DS-T. These are placed in the track-specific script. One of the lessons learned is that a more robust error recovery is possible by generating new error-specific recovery scripts as anomalies develop.

Post-track telemetry and monitor-data delivery to the mission. The telemetry data are formatted into SFDUs and recorded on the DS-T, but they were not sent to the mission in real time during the 6-day demonstration. As planned, a workstation at JPL was set up to be the mission-data receiver, and the telemetry data were transferred when the Goldstone NSI link was less loaded.

Use of COTS components when appropriate. The DS-T implementation used as many COTS components as possible. Only in cases when the COTS products could not deliver satisfactory performance were JPL-specific items used. The receiver is one example. For the overall control of the station, the EPOCH 2000 product from ISI was used; only the JPL-specific interfaces were developed at JPL. Telemetry processing was done on the COTS hardware platform using the supplied software. Much of the automation software already was developed at JPL; in this case, the DS-T Team reused this software. The DS-T Design Team took into account the available COTS components and shaped the overall design to maximize the use of the COTS components while maintaining the necessary performance level.

Treatment of the ground terminal as a network computer node that happens to have an RF peripheral. The DS-T is a node in the network using standard communication protocols; it could be moved to a different network without the need to change any software.

The following failures were excluded from the performance evaluation because they were considered external to the task's scope:

(1) Subsystem errors or sub-par performance if unquestionably due to subsystem internal errors. The DS-T development task did not attempt to correct any subsystem anomalies. DS-T used the subsystems "as is." However, in several cases, the DS-T was able to work around subsystem anomalies.

(2) Operator entry errors (such as an SR-entry typing error).

(3) Data losses due to an SOE real-time change. On the other hand, the DS-T was able to reschedule a track based on new SOE information quickly, and, by using operator intervention, the regular 15-minute pre-track period was reduced to 8.5 minutes.

VII. Lessons Learned

The lessons learned from the DS-T task are discussed in the following paragraphs.

DSN antennas can be safely operated in a schedule-driven mode—the state of the art in ground-station automation and reliability has reached and passed the point at which station operation can be left to autonomous unattended stations running on high-level directives. Utilizing automated procedure-generation techniques, the pre-track-generated dynamic scripts allow error recovery for a substantial class of real-time errors. Based on the DS-T experience, a better approach is to generate a success-oriented script with the ability to generate and transfer control to a new error-recovery script as anomalies develop. The overall script is simpler, and unplanned interactions between various error-recovery routines do not interfere, while the execution is limited to the routine that resolves the cause of the problem.

The best of JPL and industry together in partnership gets excellent results, returning high performance for low cost. JPL provides performance knowledge gained from extensive research and leading-edge development work. Industry knows how to do things quickly and efficiently from necessity; fast turnaround of new products is practiced daily.

Autonomous ground stations can be applied in the DSN. The DS-T operational concept is a natural extension of the NSP approach—operations based on a number of defined services with new services that can be added as needed. Through a schedule-driven design, stations can be controlled in a goal-oriented fashion wherein a high-level input is sufficient to perform a track. In this goal-oriented approach, the automation focus is on specifying what needs to be archived instead of how to control activities that are automated, whether the goal is to support regular spacecraft tracking or testing. Operator intervention is allowed but rarely would be needed. Monitor data are published as well as recorded for support of trend analysis and for post-track remote debugging by an analyst via a single point of contact for all M&C flows to the network layer.

The DS-T design isolates the subsystems from other layers during development, testing, and normal operations. DSN and external users need to have minimal familiarity with subsystems to operate in an efficient manner.

Partitioning of the system based on existing available industrial subsystems and interfaces was effective. The system design took into account the availability of fielded and debugged components in the satellite ground-support industry. The monitor and control platform is COTS, highly stable, well documented, and supported by the vendor. Cost-effective, complete uplink- and downlink-processing channels available off the shelf and meeting DSN operational needs were selected; again, they were stable and well supported by the vendors. We found that the industrial components have been developed for many commercial users who demand cost-effective solutions for most of the same problems encountered in the DSN.

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