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# Telecommunications Analysis for "Faster, Better, Cheaper" Deep Space Flight Planning and Operations: The Deep Space 1 (DS1) Experience

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*In the "faster, better, cheaper" era, the Jet Propulsion Laboratory (JPL) continues to develop smaller and more frequent missions. The Deep Space Network (DSN) must track many spacecraft simultaneously. With ground tracking resources limited and with NASA moving into an era of full cost accounting, the need for an efficient and well-coordinated multimission telecommunications analysis service is apparent. This service is now provided as part of the Telecommunications and Mission Operations Directorate (TMOD) Deep Space Mission System (DSMS). Deep Space 1 (DS1) is the first mission to subscribe to TMOD's services. This article describes the DS1 telecommunications link analysis service scenarios, including the DS1 safing incident on July 28, 1999, the day of the asteroid Braille flyby. The aim of this article is to demonstrate that good people, efficient processes, and effective tools are key elements that enable (1) a wide range of cost-effective telecommunications analysis support and (2) timely detection and anticipation of unforeseen situations.*

## I. Introduction

The Jet Propulsion Laboratory (JPL) continues to develop and fly smaller spacecraft in more frequent missions in this "faster, better, cheaper" era. Consequently, the Deep Space Network (DSN) must track more spacecraft simultaneously. Also, project flight teams are smaller. With ground tracking resources limited and NASA moving into an era of full cost accounting, it is a luxury for each flight mission to fund telecommunications analysts individually. The need for efficient and well-coordinated telecommunications analysis among many projects and the DSN is apparent. The Telecommunications and Mission Operations Directorate (TMOD) at JPL meets this need by providing a telecommunications analysis service as one part of its Deep Space Mission System (DSMS). Deep Space 1 (DS1) is the first project managed by JPL to subscribe to some TMOD services. This article describes the meshing of a TMOD telecommunications analyst into the project pre-launch development and the subsequent telecommunications analysis activities in flight. During the 9 months leading up to the DS1 flyby of the asteroid Braille on July 28, 1999, both TMOD and project-funded telecommunications analysis played a significant role in day-to-day mission planning, sequence development, data monitoring and interpretation, technology

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[1] Communications Systems and Research Section.

validation (tech val) activities, and anomaly identification and resolution when needed. The aim of this article is to demonstrate that good people, efficient processes, and effective tools are key elements that enable (1) a wide range of cost-effective telecommunications analysis support and (2) timely detection and anticipation of unforeseen situations.

The broad challenge given to TMOD telecommunications analysis by DS1 was: "Tell us how to command our spacecraft." This challenge became more specific in terms of the three components of telecommunications analysis: prediction of link performance, comparison of reported link performance with predictions, and telecommunications model or parameter updating that leads to subsequent prediction. Telecommunications analysis service also can be generally classified into (1) pre-launch planning and development and (2) in-flight prediction, comparison, and planning. Pre-launch activities for DS1 included a telecommunications tools adaptation effort, the planning of telecommunication's role in flight operations, and the estimation of uplink and downlink data rate capability based on published station capabilities and ground testing of the spacecraft. Post-launch support has been provided to DS1 with a combination of expertise, processes, and tools. The in-flight telecommunications analysis includes sequence planning and pre-pass link prediction, post-pass trend analysis and coordination of corrective action, and spacecraft anomaly identification and resolution.

Telecommunications analysis for flight operations has become much more software intensive in the 1990s. Telecommunications analysis for DS1 made use of four major tools.

### A. Telecommunications Forecaster Predictor (TFP)

Adapted to include DS1 spacecraft models, the TFP is a multimission tool for communication link prediction [1]. It is built upon the commercial software Matlab, a technical computing environment for high-performance numeric computation and visualization. The TFP has a graphical user interface (GUI) to allow the analyst to input information and select link configuration and parameters. The TFP allows users to generate a wide variety of plots and tables for display, hard copy, or file input to a spreadsheet.

### B. Unified Telecommunications Predictor (UTP)

The UTP is the batch-mode counterpart of the TFP that generates telecommunications predicts to configure and operate the Deep Space Communications Complex (DSCC) telemetry subsystem. For DS1 and future missions, UTP has been adapted to generate data rate capabilities as a file (the DRCF) to facilitate mission planning and sequence generation. Figure 1 is a sample of one form of a DS1 DRCF. The UTP uses the same models as the TFP for tracking stations and the spacecraft to compute prediction values of link performance for a specific flight project.

### C. Service Package Writer (SPW)

New for DS1, the SPW uses pre-defined link configuration templates to generate both service packages (an input to the project sequence generation process and the DSCC's Network Planning and Preparation Subsystem) and UTP-mode files (an input to the UTP).

### D. Derived Channel Processor (DCP)

Also built upon Matlab, the DCP provides capabilities for comparing actual link performance with predicted performance. The DCP accepts input files from a standard multimission JPL software tool, Telemetry Retriever (TelRet).[2] Adaptation of the DCP for DS1, which occurred after launch, consisted of minor updates for data channel numbers. Figure 2 is a sample DS1 TelRet–DCP link performance comparison plot.

[2] TelRet is one of the software utilities provided to the DS1 project by the Multimission Spacecraft Analysis Subsystem (MSAS) software development team. TelRet queries station data; the DCP allows the telecommunications analyst to compare telecommunications predicts produced by the TFP with actual station data.

| | | | |
|---|---|---|---|
| Produced by DS1 TFP V5.0a 04/19/1999 | | | |
| Data start date | 1999-348T22:15:00 | | |
| Data end date | 1999-349T02:45:00 | | |
| U/L Station | 34 Meter BWG | | |
| D/L Station | 34 Meter BWG | | |
| Uplink band | X | | |
| S/C Antenna | High Gain | | |
| Downlink band | X | | |
| Cmd Modulation | Off | | |
| U/L Rng modulation | 44.9 | | |
| Cmd supp due to Rng | -3 | dB | |
| D/L Rng modulation | Lo | | |
| Tlm supp due to Rng | NaN | dB | |
| Tlm Modulation | On | | |
| Diplexer | On | | |
| Attitude pointing | EarthPointed | | |
| Weather/CD | 25 | | |

| | Gold | Gold | Gold | Gold | Gold | Gold | Gold | Gold | Gold | Gold | Gold | Gold | Gold | Gold | Gold | Gold | Gold |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| date/time yyyy-doyThh:mm:ss | range km | range AU | one way light time sec | elevation angle deg | lgax to station deg | lgaz to station deg | lgaz- to station deg | s/c antenna | max cmd bit rate bps | supp due to cmd dB | max tlm bit rate bps | tlm mod index DN | doppler error mm/sec | ranging 3-sigma m | dl carr loop bw Hz | ul Pt/No m-3s dB.Hz | dl Pt/No m-2s dB.Hz |
| 1999-348T22:15:00 | 2.46E+08 | 1.646 | 821.28 | 35 | 0 | 90 | 90 | High Gain | 250 | -3.5 | 1422 | 38 | 2.16258 | 4.889 | 7 | 43.68 | 35.2 |
| 1999-348T22:30:00 | 2.46E+08 | 1.646 | 821.29 | 35.4 | 0 | 90 | 90 | High Gain | 250 | -3.5 | 1422 | 38 | 2.16158 | 4.886 | 7 | 43.68 | 35.2 |
| 1999-348T22:45:00 | 2.46E+08 | 1.646 | 821.29 | 35.5 | 0 | 90 | 90 | High Gain | 250 | -3.5 | 1422 | 38 | 2.16129 | 4.885 | 7 | 43.68 | 35.2 |
| 1999-348T23:00:00 | 2.46E+08 | 1.646 | 821.3 | 35.4 | 0 | 90 | 90 | High Gain | 250 | -3.5 | 1422 | 38 | 2.16169 | 4.886 | 7 | 43.68 | 35.2 |
| 1999-348T23:15:00 | 2.46E+08 | 1.646 | 821.3 | 35 | 0 | 90 | 90 | High Gain | 250 | -3.5 | 1422 | 38 | 2.1628 | 4.89 | 7 | 43.68 | 35.19 |
| 1999-348T23:30:00 | 2.46E+08 | 1.646 | 821.31 | 34.4 | 0 | 90 | 90 | High Gain | 250 | -3.5 | 1422 | 38 | 2.16465 | 4.896 | 7 | 43.68 | 35.19 |
| 1999-348T23:45:00 | 2.46E+08 | 1.646 | 821.31 | 33.6 | 0 | 90 | 90 | High Gain | 250 | -3.5 | 1422 | 38 | 2.16732 | 4.905 | 7 | 43.67 | 35.17 |
| 1999-349T00:00:00 | 2.46E+08 | 1.646 | 821.32 | 32.6 | 0 | 90 | 90 | High Gain | 250 | -3.5 | 1422 | 38 | 2.17092 | 4.916 | 7 | 43.67 | 35.15 |
| 1999-349T00:15:00 | 2.46E+08 | 1.646 | 821.32 | 31.4 | 0 | 90 | 90 | High Gain | 250 | -3.5 | 1422 | 38 | 2.17557 | 4.931 | 7 | 43.67 | 35.13 |
| 1999-349T00:30:00 | 2.46E+08 | 1.646 | 821.33 | 30 | 0 | 90 | 90 | High Gain | 250 | -3.5 | 1422 | 38 | 2.18151 | 4.951 | 7 | 43.66 | 35.1 |
| 1999-349T00:45:00 | 2.46E+08 | 1.646 | 821.33 | 28.4 | 0 | 90 | 90 | High Gain | 250 | -3.5 | 1422 | 38 | 2.18901 | 4.975 | 7 | 43.66 | 35.06 |
| 1999-349T01:00:00 | 2.46E+08 | 1.646 | 821.34 | 26.7 | 0 | 90 | 90 | High Gain | 250 | -3.5 | 1422 | 38 | 2.19847 | 5.006 | 7 | 43.65 | 35.02 |
| 1999-349T01:15:00 | 2.46E+08 | 1.646 | 821.34 | 24.8 | 0 | 90 | 90 | High Gain | 250 | -3.5 | 1422 | 38 | 2.21049 | 5.044 | 7 | 43.64 | 34.96 |
| 1999-349T01:30:00 | 2.46E+08 | 1.646 | 821.35 | 22.8 | 0 | 90 | 90 | High Gain | 250 | -3.5 | 1422 | 38 | 2.22589 | 5.094 | 7 | 43.63 | 34.88 |
| 1999-349T01:45:00 | 2.46E+08 | 1.646 | 821.35 | 20.6 | 0 | 90 | 90 | High Gain | 250 | -3.5 | 1422 | 38 | 2.24593 | 5.158 | 7 | 43.62 | 34.79 |
| 1999-349T02:00:00 | 2.46E+08 | 1.646 | 821.36 | 18.4 | 0 | 90 | 90 | High Gain | 250 | -3.5 | 1050 | 38 | 2.27251 | 5.244 | 7 | 43.61 | 34.66 |
| 1999-349T02:15:00 | 2.46E+08 | 1.646 | 821.37 | 16.1 | 0 | 90 | 90 | High Gain | 250 | -3.5 | 1050 | 38 | 2.30866 | 5.359 | 7 | 43.59 | 34.49 |
| 1999-349T02:30:00 | 2.46E+08 | 1.646 | 821.37 | 13.6 | 0 | 90 | 90 | High Gain | 250 | -3.5 | 1050 | 38 | 2.35948 | 5.521 | 7 | 43.56 | 34.26 |
| 1999-349T02:45:00 | 2.46E+08 | 1.646 | 821.38 | 11.1 | 0 | 90 | 90 | High Gain | 250 | -3.5 | 1050 | 38 | 2.43419 | 5.76 | 7 | 43.52 | 33.93 |

**Fig. 1. A sample intermediate DRCF file.**

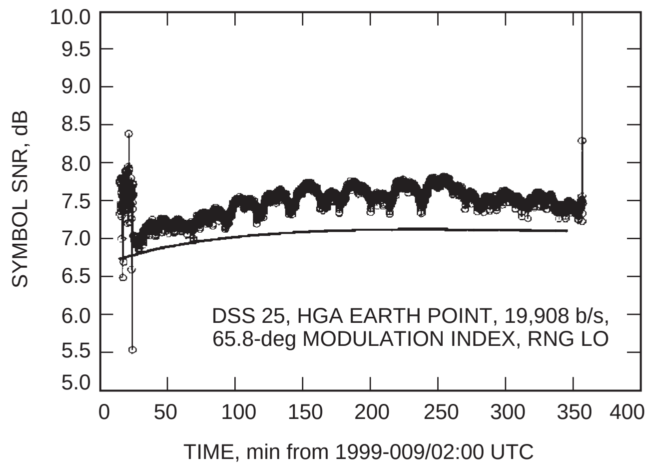


**Fig. 2. A sample TelRet/TFP/DCP output. Note that the actuals data were queried via TelRet; the predicted signal level was produced by the TFP (the smooth plot); and the DCP synchronized both data streams and plotted them. The residual appears graphically as the difference between the actual level and the predicted signal level.**

The rest of this article is organized as follows. Following this introductory section, Section II briefly describes the statistical nature of telecommunications link design, as incorporated into the TFP models. Section III discusses the key attributes and standard components of the multimission telecommunications analysis service. Section IV describes the adaptation of the standard service and the specific application of its processes through the DS1 project life cycle. Section V provides a detailed account of the role of telecommunications analysis in the DS1 safing incident on July 28, 1999, the day of the spacecraft flyby of the asteroid Braille. Section VI documents the lessons learned from our experience throughout the several phases of telecommunications analysis support for DS1. Section VII gives our conclusions about the degree of success of DS1 use of the TMOD telecommunications analysis service.

## II. Statistical Approach for Telecommunications Link Analysis

A typical spacecraft communications system performs three basic functions: telemetry, command, and tracking. The telecommunications link encompasses the entire communications path, from the information source through all the encoding and modulation steps, through the transmitter and the channel, through the signal-processing steps in the receiver, and terminating at the information sink. Most link parameters are neither constant nor precisely known. The communication channel, which is the propagation medium connecting the transmitter and receiver, introduces random noise that is unpredictable except in a statistical sense. Some link parameters vary with spacecraft environment, others with ground station configuration and the communications channel conditions. Some are associated with link components that have manufacturing tolerances.

Through the experience of many deep-space missions, telecommunications system designers found they could not state link performance simply by assigning conservative values to each link parameter. It was found that actual link performance was almost always several dB better than that predicted by the combining of adverse values. A better tool for modeling the performance of a system with many parameters (which are modeled as independent random variables) was needed in order to avoid over-designing the telecommunications system or under-predicting the data rate (and hence the achievable science data return).

Telecommunications link analysis is a statistical estimation technique for evaluating communications system performance. It calculates and tabulates the gain and loss parameters in terms of statistical link.

A detailed discussion of this technique is given in [2]. This technique, which has been standard at JPL since 1970, is used in the prediction of both pre- and post-launch telecommunications performance for all JPL deep-space missions, including DS1.

## III. Telecommunications Analysis Service

Telecommunications link analysis service provides the means (which may include tools and their adaptation, and the people to use the tools and interpret the output) for a flight project to plan the communications configurations, capabilities, and operation strategies between a spacecraft and the tracking stations of the Deep Space Network. This service also assesses the resulting tracking performance against the plans.

The kind and extent of telecommunications analysis that a mission needs varies from mission to mission and also is different for each phase of a mission. The challenge of a multimission telecommunications analysis service is to develop the right combination of expertise, processes, and tools to meet a wide range of customer needs, which may be

(1) Minimal, due to simple mission operations and/or large link margins

(2) Occasional, due to infrequent tracking

(3) Significant, due to mission-critical events

(4) Detailed, due to complicated mission operations and/or low link margins

(5) Intensive, due to telecommunications involvement in anomaly resolution

In an 18-month pre-launch development, an 11-month prime mission flight, and a planned 2-year extended mission, the DS1 project's telecommunications analysis needs have varied with mission phase and have ranged from level (2) to level (5).

The effectiveness and timeliness of the service depends strongly on the software tools. A detailed description of the Telecommunications Forecaster Predictor (TFP) tool is given in [1].

The standard telecommunications link analysis services are as follows:

(1) *Prediction Tool Configuration:* Incorporate mission- and spacecraft-specific parameters into the database of the standard TMOD telecommunications prediction tool. Verify the applicability of standard communication link and station models and auxiliary data interfaces to the project requirements. Standard interfaces with ephemerides, station view periods, spacecraft-pointing, and station-scheduling data are available.

(2) *Long-Range Prediction Generation:* Provide long-range uplink and downlink data-rate capability predictions for project planning.

(3) *Analysis Environment Setup:* Provide data displays, data analysis tools, documentation and training, and access to spacecraft telemetry and station monitor data for telecommunications link performance analysis.

(4) *Telecommunications Link Documentation:* Provide or generate spacecraft and station parameters and descriptions. The parameters are those required to complete a design control table (DCT) for each required uplink and each downlink mode and frequency band. The DCT, also called a link budget, is used to validate a new or updated model as well as to predict link performance for one configuration at one point in time. A DCT assumes a fixed geometry, such as range, station elevation angle, antenna gain, etc. Tabulations or plots describing the variation of specific link parameters with time can augment the DCT.

(5) *Service Package Preparation:* Starting with uplink and downlink capability predictions and a statement of project telecommunications activities, a set of service packages for the next mission phase is prepared. Services are provided by the Deep Space Station (DSS) and include such functions as Doppler, telemetry, command radiation, and ranging. A service package contains a set of spacecraft and station parameters and their values that enables the station to provide that service to the project.[3]

(6) *Real-Time Monitoring:* Observe, assess, and report on-line to project personnel the spacecraft telecommunications subsystem telemetry and the station performance data during station passes.

(7) *Post-Pass Analysis:* Acquire and analyze (compare against the predictions) the spacecraft telemetry and station monitor data for RF signal power, system noise temperature, telemetry and ranging channel signal-to-noise ratios (SNRs), and telemetry data frame decoding corrections. Store the analysis results in the project database.

(8) *Trend Analysis:* Analyze and provide reports on telecommunications performance trends, including recommendations to avert impending problems with spacecraft or station equipment. DS1 telecommunications reports range from brief oral statements of onboard subsystem health at daily project meetings to e-mail documentation of the station performance of one or more passes to the formal technical validation (tech val) reports at the end of the prime mission.

(9) *Flight Team Participation:* Provide telecommunications analysis support to team planning and status meetings, reviews, and reports. Respond to telecommunications capability "what if?" (planning) and "why did it?" and "is this a serious problem?" (performance) questions.

## IV. DS1 Telecommunications Analysis Process

This section does not present a perfect or fully mature process. Rather, it shows the functions and tasks that have been performed by telecommunications analysis for the DS1 mission. This section describes how the telecommunications analysis people and tools worked together to meet various project needs. We believe the functions described below have to be performed on any typical deep-space mission, so this will serve as a reference to users who are planning to do a mission.

### A. Telecommunications Subsystem Description

The heart of the DS1 telecommunications subsystem is a small deep space transponder (SDST) that includes the functions of a 7.2-GHz (X-band) receiver, an 8.4-GHz (X-band) exciter, a 32-GHz (Ka-band) exciter, telemetry modulation for X-band and Ka-band, command detection, and ranging demodulation and modulation. The subsystem has a total of five antennas: the Ka-band horn antenna (KHA), the

[3] The service package is a text file intended to be readable by both computers and people. The format of the file and the syntax of the service parameters within are as defined in an internal JPL TMOD interface document, OPS-6-24. The service package includes the names of the services (Doppler, telemetry, command, and ranging were used by DS1), the start and end times of the service (beginning of track and end of track were used by DS1), and numerous technical parameters to define the particulars of the services. These parameters include such things as which spacecraft and station antennas are involved and antenna polarizations; whether the whole pass will be via one spacecraft antenna or two successive antennas; the spacecraft and station transmitter band and power output; command modulation bit rate and uplink carrier suppression; telemetry modulation symbol rate, subcarrier frequency, modulation index, and coding type; and ranging modulation index. As a file, the DS1 service package is used by the sequence engineer to generate both a spacecraft sequence of commands file and a DSN keywords file (DKF). The DS1–TMOD plan was for telecommunications analysis also to submit service packages to TMOD as a statement of the required start and end times for each service in each pass and the overrides to the mission service tables (which contain default parameter values for DSN services). The agreement changed such that the project sequencing process would generate from the service packages a DKF to submit to TMOD as a time-ordered list of station actions for the passes in the sequence.

X-band high-gain antenna (HGA), and three X-band low-gain antennas (LGAX, LGAZ, and LGAZ-), where the X, Z, and Z- refer to those coordinate axes.

The X-band uplink carrier is at 7168 MHz and can be modulated at the station with a command subcarrier or ranging modulation or both. The X-band downlink carrier is at 8422 MHz and can be modulated in the SDST with a telemetry subcarrier or ranging modulation or both. The Ka-band downlink carrier is at 32,157 MHz and similarly can be modulated with telemetry or ranging or both. The downlink from the SDST X-band exciter goes through the X-band power amplifier (XPA) to either the HGA or one of the LGAs. The downlink from the Ka-band exciter goes through the Ka-band power amplifier (KAPA) to the KHA. The uplink from the station goes through the same antenna (HGA or LGA) as the X-band downlink.

None of the telecommunications subsystem elements are redundant (duplicated), although there is some functional redundancy. For example, with an appropriate uplink command rate and spacecraft pointing accuracy, commands can be received via either the HGA or an LGA. Similarly, telemetry can be transmitted on either the X-band or Ka-band downlink.

## B. Pre-Launch Activities

**1. Subsystem Testing and Parameter Documentation.** The prime mission of DS1 was technology validation. Rather than the gathering of science data, the main emphasis of the mission was to demonstrate the performance of new technologies for use in future missions. New telecommunications technologies aboard DS1 included the SDST and the KAPA. Telecommunications analysts, together with the hardware developers, planned and conducted in-flight tests of the SDST and KAPA in which performance prediction was an important factor.

The pre-launch development of the DS1 telecommunications system was done on a very tight schedule (1-1/2 years, versus 3 years for previous JPL missions). Tests were performed at Motorola (the SDST contractor), at JPL in different laboratories, and at the DS1 launch site and were documented in electronic form. Performance characteristics such as the non-linearity of the phase modulator of the SDST X-band exciter were analyzed and modeled for use in link prediction software.

**2. Project Requirements and Plans.** About 1-1/2 years before launch, the DS1 project contracted with the Telecommunications and Mission Operations Directorate (TMOD) at JPL to be provided a telecommunications analysis service. TMOD initially assigned one telecommunications analyst who worked side-by-side with the project telecommunications designers to develop operational aspects of the system.

As the project developed its mission operations system (MOS) plans, the requirements on telecommunications analysis for flying the mission became more specific. At the top level, telecommunications analysis consists of three activities: prediction of telecommunications link performance for planned sequences or known configurations, comparison of obtained performance against predicts, and updating of telecommunications prediction models. Together, these support the generation and review of new command sequences to continue the mission.

Planned telecommunications characterization tests included five major areas:

(1) *Telemetry:* The in-flight verification of 19 data rates (from 10 b/s to 19,908 b/s) at both X-band and Ka-band

(2) *Modulation Linearity:* The interaction of telemetry and ranging modulation at both the low and the high ranging modulation index

(3) *Carrier Frequency Stability:* The stability of the downlink carrier in both the two-way coherent mode frequency driven by the station's uplink and the one-way mode driven by an onboard oscillator

(4) *X-band Compared with Ka-band:* Modulated and unmodulated X-band and Ka-band downlinks

(5) *Characterization of the SDST Receiver:* Accomplished through the routine uplink acquisition and tracking of the RF carrier, modulation of the carrier by ranging modulation, and the command activities that occurred with every pass

**3. Telecommunications Parameter/Model Development (Excel).** Early in the design process, the telecommunications analysts used a link performance spreadsheet produced by the Microsoft Excel program. A similar spreadsheet had been used successfully for designing telecommunications links for many missions, including Cassini. The spreadsheet is a very versatile tool for developing new link models based on test data. DS1 examples include modeling the X-band phase modulator, which was highly nonlinear, and modeling the ranging and command performance. We also used the spreadsheet for performing numerous design-phase "what if" performance trade studies.

**4. Design Control Document (First Mission With a DCD On the Web).** The pre-launch development team assembled all the relevant performance data and analyses into a design control document (DCD) on the Internet[4] for two reasons: (1) to transfer knowledge between the pre-launch and the operations team and (2) to provide an easy-to-access reference for any telecommunications analyst on DS1. (Traditionally, flight projects such as Cassini and Mars Global Surveyor have published and maintained the DCD as a paper book.)

**5. Prediction Tool Development for Flight Operations.** Development (adaptation) of the TFP for DS1 began pre-launch but has continued well into the prime DS1 mission. Both phases are described here.

For setting up the TFP pre-launch, telecommunications analysts used an Excel spreadsheet program to evaluate link performance when developing the subsystem design and making performance trade-offs. But the very strengths of the Excel tool for development make it not well suited to the operations environment. While a developer wants flexibility in use, in operations the analyst wants all the link calculations to be done using the same, validated model (so once the model is validated, one does not need to continually re-check the results). In other words, flight operations requires configuration control of the parameter values and models that are to be used.

For DS1, the telecommunications analysis development group recommended the Matlab-based Telecommunications Forecaster and Predictor (TFP), which was already used by Cassini and was being used to support several other missions (like Mars'98). The correctness of the TFP models was verified extensively by comparing TFP outputs with Excel outputs. The Excel models and output values, already checked out, provided a benchmark for the TFP.

## C. Post-Launch Activities

**1. Fine-Tuning the TFP: Parameter Updates and Addpath.** The modeling and use of the TFP was an iterative process due to changing mission needs. The TFP was designed pre-launch with a baseline set of capabilities. Planning in-flight activities, such as technology validation tests or spacecraft pointing maneuvers, revealed the need for more flexibility. Fortunately, the TFP developers gave us a very robust and flexible tool, so all these changing needs could be met.

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[4] The DCD is available within JPL through JPL internal Web space.

The TFP had one capability that became very valuable to the analyst—the addpath. The name addpath is an abbreviation of the phrase "add and use a directory path." The TFP link models exist in the form of files that are in a standard hierarchical computer file directory structure. The "path" to a particular model is via the top-level directory in the hierarchy, then via a second-level directory, and so forth. If the telecommunications analyst wants to use an alternate model at the time of a TFP run, the analyst can store the alternate model in a subdirectory and reference a path to that subdirectory with the addpath function. The models in the addpath supersede those of the standard, officially delivered TFP version. We still used almost the entire set of well-tested models, but a needed set of TFP model changes or output format updates could be included in an addpath file directory without having to wait for another official release. The addpath is an example of good balance between configuration control and flexibility. It allowed the telecommunications analyst to provide quick turnaround support to the DS1 project's many "what if" questions.

**2. Telecommunications Involvement in Spacecraft Sequence Development.** Sequences of spacecraft commands are reviewed for consistency with flight rules and to ensure that they accomplish the intended activities without harming the spacecraft. Generally, sequence generation and review is iterative because of interaction between subsystems, evolving mission needs, and results of ground testing of the sequences.

The sequence-development process ends with a command approval meeting. Upon approval, sequence files and individual commands are placed in a secure file repository at JPL, the distributed object management subsystem (DOM). Some of the individual commands will activate, deactivate, or delete sequences that are already stored onboard the spacecraft. Subsequent command activity is through command forms signed by the project's mission director. The emphasis of the DS1 command process is to ensure correctness and accountability. During a station pass, the project's real-time mission controller (known by the on-net call sign "ACE") uses a workstation to move ("stage") the commands from the DOM to temporary storage at the DSS, and to initiate transmission ("radiation") to the spacecraft of the commands stored at the DSS. The ACE is the project interface with the operating personnel at the station. The ACE works under the authority of the real-time Flight Director. The ACE documents in a log the times of radiation of each command or command file.

The telecommunications analyst is responsible for the correct use and parameter values of all telecommunications subsystem commands integrated into sequences stored onboard or radiated to the spacecraft individually. The telecommunications analyst reviews sequence file printouts and attends the command conferences. The telecommunications position in the MSA is next to the ACE, and telecommunications verifies the condition of the uplink before and during commanding, comparing the signal levels with those previously generated with the TFP. Telecommunications also reviews telecommunications parameters in the telemetry from the spacecraft and the station monitor data, either in real time or from a data query after the pass.

**3. Telecommunications Software Input/Output Fileflow.** Generation of telecommunications configuration sets and signal level predictions does not take place in isolation. Operational predictions require the input of data files for spacecraft trajectory and antenna pointing. In turn, the predictions themselves are organized into files that follow a specified format.

A significant pre-launch development on DS1 was to plan what sets of data were the responsibility of each group, when the sets would be created and updated, and the means by which they would be delivered and announced. The fileflow plan of trajectory and DS1–DSN file interfaces has been formally documented and is maintained by the project. The fileflow diagram shown in Fig. 3 identifies the project teams, the TMOD services, the formally delivered files, and the expected frequency of file updates. Figure 3 is intended to convey an idea of the complexity of interfaces between different teams.

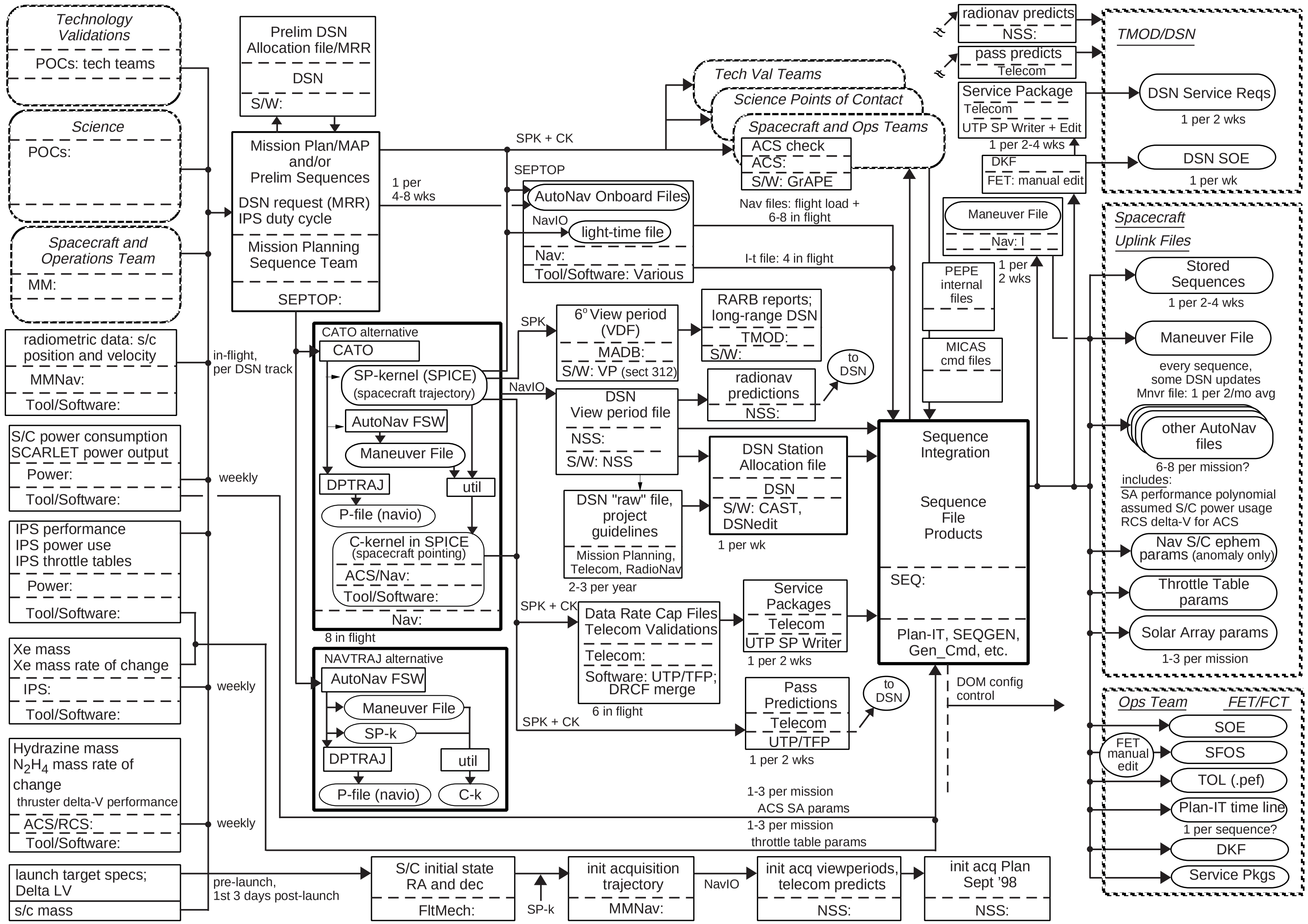


**Fig. 3. Fileflow diagram.**

**4. Testing of Analysis Software.** A major telecommunications analysis challenge on DS1 has been to develop, learn to use, and debug several tools that required fine-tuning. It definitely was not a "turn-key" environment. Although this process has made the DS1 telecommunications prediction software reliable and the link models mature, there is no such thing as a software tool that becomes bug-free and no longer requires any updating.

After launch, a second powerful way of checking the trajectory and telecommunications prediction software correctness became available—the direct comparison between a predicted quantity, such as a signal-to-noise ratio, and the value reported by the spacecraft or station receiving system. Errors in modeling spacecraft pointing and telecommunications parameters as well as typos in data tables were made evident by this kind of checking. The usual result of such checking, small residuals, showed that the models were done correctly.

**5. Procedures and Memory Aids for Standard and Repetitive Tasks.** DS1 procedures[5] are approved (maintained under configuration control) by a team chief. A telecommunications memory aid is a small or informal procedure not under configuration control. Use of procedures and memory aids created by the DS1 telecommunications analysis lead made the training of other analysts possible in a limited time environment. They also serve as checklists for an experienced analyst when there is no time to rediscover how to use a computer process used a month previously but not thought about until suddenly needed again. The procedures and memory aids show how improvements might be made to streamline a process. Ours was a workable system. It captured knowledge so that the lead analyst would not be the only one who knew what data were where and what to do with them.

**6. In-Flight Planning of Telecommunications Capability (DRCF).** When predicting communications link performance, the analyst (with the aid of the TFP) estimates the mean received total power-to-noise spectral density ($P_t/N_0$), as well as a measure of the uncertainty of it (characterized by its standard deviation, $\sigma$). Each flight project determines which level of risk or uncertainty it will accept when predicting link performance. Typically, the statistical mean of $P_t/N_0$ minus a multiple of the statistical standard deviation, $\sigma$ (e.g., two), is used when estimating the achievable command or telemetry data rate and other functions, such as Doppler and ranging.[6]

Performance predictions, based on $P_t/N_0$, are given in a data rate capability file (DRCF) for uniformly spaced points in time and different link configurations. A link configuration includes the kind of tracking station, the kind of spacecraft antenna, whether or not a simultaneous ranging channel is used, and the spacecraft-pointing assumption. The DRCF documents a profile of telecommunications link capability for each link configuration.

The mission planners are the primary users of the DS1 DRCF. The first use made of it is to judge the number of station passes per week and the type of tracking station that will be required during a particular mission phase to return the data that will be produced. Later, the telecommunications analyst uses the DRCF to specify the data rate commands to be placed in the sequence for each station pass. The analyst makes adjustments for special activities, such as a technology validation that requires the high-gain antenna (HGA) to be pointed a fixed number of degrees from Earth at a specific interval during a scheduled station pass.

Pre-launch, we planned a DRCF format for 28 specific configurations, each one of them requiring a run of the program to cover the whole mission daily at a fixed station elevation angle of 10 deg. While these 28-run products have been useful for long-range planning, our in-flight experience showed a need also to

[5] The procedures used by the DS1 Flight Engineering Team are all documented and available internally through JPL internal Web space.

[6] This "mean minus $2\sigma$" is given as an example; typically, pre-launch, when there is more uncertainty (the hardware has not yet been built and tested), an analyst will use 3 dB as a performance margin rather than $2\sigma$.

be able to make predictions for a smaller set of specific configurations over shorter periods of time and with smaller time increments with actual station elevation angles, corresponding to individual sequences. The software was updated accordingly, so that it could quickly generate a DRCF "intermediate file" for one specific link configuration. See Fig. 1 for a sample DRCF intermediate file.

**7. Pass Predictions.** Station pass predictions are tabulations in which the columns are quantities that can be monitored during one station pass, such as carrier power, symbol-signal-to-noise ratio, or system noise temperature. The rows are values of these parameters at successive time intervals, usually from 10 to 30 minutes. Even if time is short or the spacecraft configuration changes unexpectedly, the telecommunications analyst can produce valid predicts quickly. Pass predictions can be run and printed in one minute or so and, therefore, are often made shortly before a pass or even during a pass. For this reason, the pass predicts are often referred to as "just in time." The TFP takes care of the formatting and provides a log of the configuration at the top of each predict set. Pass predictions are needed by the ACE to brief the station on expected carrier signal level and telemetry signal-to-noise ratio. They also are referred to by the ACE or the telecommunications analyst during real-time data-monitoring sessions to confirm the spacecraft and the station telecommunications equipment are properly configured and operating.

**8. Real-Time Data Monitoring.** DS1 has a Mission Support Area (MSA) that provides the means for project analysts to see data and provide control of the spacecraft in a single location. Telecommunications analysis is one of about 15 positions in the MSA. The telecommunications position has a workstation for query, display, and processing of telemetry data and another for station monitor data, as well as a voice control box and headsets for communications with other MSA analysts. During real-time support, the flight team follows a procedure and sequence of events (SOE) for the activity.

A traditional science mission has a "quiet" early cruise period during which the flight team learns to fly the spacecraft, followed by a science period with intense activity. DS1 did the opposite because of its technology-validation nature. Many in-flight tests were conducted during the first few months after launch, requiring extensive real-time support.

**9. Daily "Health and Safety" Monitoring and Reporting.** It has been a telecommunications goal to review spacecraft telecommunications-performance telemetry (currents, temperatures, and RF power levels) using the project telemetry system to make a set of standard plots of the measurements versus time. For station data, sometimes called "monitor data," the telecommunications analyst uses a display system developed for the Deep Space Network real-time controllers. This system, Network Operations Control Center-Real Time or NOCC RT for short, has tabular and graphical displays from which hard copies can also be made. This system provides tabular and graphical displays. NOCC RT data are organized by station, data type (tracking, telemetry, command, and monitor), spacecraft, and start time.

**10. The "Telecom Book"—A Record of Day-to-Day Data.** There are two major sources of data for telecommunications:

(1) Spacecraft telemetry, which is stored electronically. All spacecraft data since launch are available to members of the flight team.

(2) DSN station-performance data, called monitor data. It is much more voluminous and is stored electronically for only the most recent month.

Both kinds of data, as well as supporting material such as sequences and SOEs, have to be accessible for stored sequences, in-flight tests, and planned or unplanned real-time activities (such as recoveries from safing). Data come in different forms (electronic and hard copy), from different platforms, and at different rates. To cope with the data variety and to maintain a permanent record, telecommunications adopted a paper-based system of loose-leaf notebooks with sections made for each tracking day.

**11. Post-Pass and Performance Trend Analysis.** DS1 repeated the good fortune of most previous flight projects in that the onboard telecommunications hardware and software were extremely stable in-flight. Their performance had been well characterized during subsystem testing and spacecraft–DSN compatibility testing. The availability of the pre-launch telecommunications development team was crucial in training the flight team telecommunications analysts in the meaning of the data and how to interpret them (what was nominal, what was not, why a channel updated or not, and so forth).

There have been no unexpected trends in performance telemetry of any of the onboard telecommunications hardware. In contrast, there have been unexpected variations in measured station monitor data. The prediction tool, the TFP, and the analysis tools, TelRet/DCP, were used to compare reported values against predicted values for each station pass.

An example of the use of these tools together is shown in Fig. 2. This figure is a plot of telemetry symbol SNR versus time for one station pass. The reported values (actuals), appearing as scattered points, were obtained through one tool, called the Telemetry Retriever (TelRet). The predicted values (predicts), appearing as a smooth curve, were generated with the TFP. A third tool, the DCP, first did time synchronization of the actuals and predicts. Then, by plotting them together, the DCP shows the analyst the link residual (the actual level minus the predict level).

Use of the post-pass and trend-analysis results enabled telecommunications to quickly verify which spacecraft antenna was in use, whether that antenna was pointed as planned, and whether the telemetry mode corresponded to a normal or a "safe mode" condition. The station might be able to lock up on a downlink carrier at the beginning of a track but have difficulty with the telemetry subcarrier or symbols. Previous telecommunications assessment of the carrier level might result in a recommendation to the ACE to have the station change a receiver loop bandwidth or to look for a different subcarrier frequency. In another instance, a weaker than expected uplink received carrier power in the telemetry data suggested that the station antenna pointing model required update.

## V. Asteroid Braille Flyby and Safing Support

### A. Telecommunications Planning for the Encounter Rehearsal

Flyby of the asteroid Braille by DS1 occurred in the late evening of July 28, 1999. Several weeks before that, the DS1 spacecraft rehearsed the portion of the sequence from several hours before closest approach to several hours after. As nearly as possible, the rehearsal sequence duplicated the commands and sub-sequences that were being developed for the real encounter. The rehearsal also validated the sequence generation and review and provided some personnel training, although the latter was not its purpose.

### B. Telecommunications Planning for the Encounter Closest-Approach Sequence

The telecommunications involvement in the encounter was similar in kind to previous sequences, although more complex. For some passes, 70-m stations supported the downlink at a higher rate than the 34-m stations would be able to support. For the passes just before, during, and just after closest approach, dual support was provided by both 70-m and 34-m stations, and also as much overlapping coverage as geometry permitted between the Goldstone and Canberra sites. In addition to periods of the normal configuration with the DS1 HGA pointed at the Earth, numerous portions of the sequence involved deliberate off point of the axes to accomplish navigational and science data taking by the onboard camera and other instruments.

Some of these pointing activities, within a few hours of closest approach, were to be governed by onboard software by the autonomous navigation (autonav) system, one of the DS1 technologies being validated. Turn magnitudes and start/stop times could only be estimated on the ground. From these estimates, telecommunications analysis generated spreadsheets of predicted signal levels and configuration change times, for use by the ACE in directing the stations to configure the receivers for the downlink and to control the uplink transmitter frequency profiles. Integral to this process was a set of signal-level predicts to be included in the spreadsheet time line.

Because the DS1 spacecraft is much more autonomous than previous ones flown by JPL flight teams, its attitude was not always known until quite late. This required an ability to create telecommunications predicts on a very fast turnaround basis as well as detailed spreadsheet sequences of events (SOEs) for up to four DSN stations simultaneously. Using the input GUI, it was possible to set up, run, validate, and print predicts for ACE use in 1 to 5 minutes, depending on the level of detail. Validation was accomplished by review of the configuration log. The log replicates the significant GUI inputs and is automatically placed at the top of the predict tabulation.

Telecommunications developed predicts for contingencies, such as the possibility of a particular autonav turn not being executed or the spacecraft entering safing. Given the availability of two trained telecommunications analysts, plus support by the telecommunications hardware developers, and using the spreadsheet time line, telecommunications recommended staffing for the more critical activities, especially those involving turns and use of the low-gain antennas. Telecommunications staffing was required for portions of two shifts per day for several days and at specific times around the clock the day of the flyby.

### C. Detection of Abnormal Carrier Power and Recovery from Safing

Early on encounter day, about 12 hours before closest approach, the telecommunications analyst and the ACE were the only members of the flight team in the MSA. Monitoring the downlink at the end of an autonomous navigation (autonav) sequence, the telecommunications analyst found the carrier signal level being reported by the tracking station at Canberra changed by several dB from that expected. However, the new level was within 1 dB of what telecommunications expected if the spacecraft had stopped the autonav activity and had gone to safe mode. For telecommunications, safe mode means the spacecraft +x-axis is pointed to the Sun for maximum power from the solar arrays, with the x-axis low-gain antenna selected for maximum signal return to Earth at this attitude. Within a few minutes, telecommunications recommended to the ACE that the station search for the safe mode telemetry rate (20 symbols per second), using a narrower carrier-loop bandwidth. The station found the subcarrier, then the symbol rate, which confirmed entry into safing. Within 15 minutes (at 5:30 a.m.), telecommunications and the ACE had notified the mission director, system engineer, and fault protection engineer of the safing event.

Over the next several hours, some of the flight team generated a recovery sequence for approval. In parallel, other members tested the onboard sequence that had been executing in the test bed and found a very probable cause for the occurrence. The test bed and analysis results gave the project confidence to approve the recovery sequence and to continue with the remainder of the onboard encounter sequence. As part of the recovery process, the telecommunications analyst in the MSA assessed the downlink carrier level as a function of time and was able to confidently state when the spacecraft was pointed at the Sun, and subsequently to the Earth, all without any telemetry data yet in lock. The end-to-end detection, analysis, testing, and recovery sequencing took 6 hours, beating the best-case expectation by an hour. The encounter sequence resumed about 6 hours before closest approach. This was 10 minutes before it would have been too late to resume, which would have caused consequent loss of the encounter science data. The safing recovery proved the value of an experienced though small flight team, the extensive encounter rehearsal, the routine use of the test bed, the solid modeling of telecommunications link performance, and the “just in time” availability of accurate prediction capability.

## VI. Lessons Learned

Let us preface these lessons learned by saying that the DS1 mission has been a tremendous success. All 12 new technologies were extensively validated, demonstrating that they can be used on future deep-space missions. Yet, in looking back at the feverish pace of testing, development, and flight operations of the last 2 years, we asked ourselves, "What have we learned?" and "What could be done better?" The answers are statements expressing our opinion based on our experience, and they do not constitute a JPL policy or commitment.

In this context, many of the specifics below suggest better process design. Some of these telecommunications lessons learned are being applied to make DS1 telecommunications analysis for the extended mission more efficient. We also hope these experiences and suggestions will result in TMOD being able to provide less expensive telecommunications analysis service to projects in the future.

### A. Planning the Types and Extent of Analysis

We found DS1 telecommunications analysis often takes longer to do than planned and budgeted. Our experience over several missions is that the amount of time telecommunications analysis requires is roughly proportional to the amount of time the spacecraft is being tracked. When the product of an analysis is not well defined, the analyst or customer thinks of related questions to be answered or the customer levies new requirements. Sometimes the analyst needs to create data initially believed already available. Computer processes may not run smoothly, and valuable analyst time goes into discovering that input data had not been recorded or that a server is down. It is an art to remember to allow enough time to complete a task, accounting for delays of these types.

### B. Flight Team and Project Co-Location

Having the flight team members co-located proved to be beneficial overall since points brought out in face-to-face discussion sometimes would not have surfaced through e-mail, memoranda, or telephone calls. The turnaround time in the iterative sequence generation/review process was greatly shortened. However, in terms of analyst efficiency, there is a down side to co-location. Co-location makes is easier for one person to interrupt another with, "Got just a minute?" Every analyst needed to learn how to prioritize tasks and minimize interruptions from competing tasks while working the highest priority ones.

### C. Telecommunications Analysis Budgeted Staffing Level

It is difficult to estimate the level of effort required to support a deep-space mission operating with many "firsts": a dozen new technologies, a shorter development cycle, a smaller flight team, and an evolving TMOD service architecture. DS1 budgeted and contracted with TMOD to receive the services of one senior-level telecommunications analyst. This analyst joined the project about 1 year before the planned launch. The DS1 project also intended to augment this analyst with members of telecommunications systems and hardware design during the high-activity initial technology validation period of 40 days. Because unexpected problems during technology validation stretched out that period and also required more real-time command and short turnaround sequences, the actual telecommunications staffing level averaged about two people. This possibly could have been reduced to 1.5 if the software tools used by telecommunications had been fully in place and mature.

It became obvious that being able to draw on a pool of three or four people was the only way to cover the "round-the-clock" staffing requirements for the first 2 weeks after launch. Also, having two or three individuals trained in DS1 flight operations and telecommunications software was essential to continue telecommunications support through vacation periods, illness, and critical demands on analyst time from other projects being supported.

### D. Telecommunications Analysis Staffing Mix

The DS1 spacecraft safing events and restoration to operation have proved the need for a knowledgeable, experienced, and well trained analyst, but not to be "just a data watcher." During one shift, the analyst may need to interpret health and safety data, do a performance trade study, review command sequences, and give highly reliable and timely link performance predictions. In addition to taking care of the spacecraft, this analyst adds value in understanding the needs of the DSN and how a station operates. On the other hand, it also became evident that some DS1 telecommunications analysis operations, especially those involved in running the software, became routine but still required about 1 hour of analyst time per station pass. This kind of activity could be performed by less experienced people, though interpretation of the products would continue to require the senior analysts. Looking forward more, these repetitive software tasks could be made more automated, given the time and budget to do so. An efficient and economical telecommunications analysis service, especially one providing support to more than a single project, requires several individuals trained in the use of the tools, each with a sufficient degree of experience to handle the tasks that the project has specified.

### E. Need for Sequence Standardization

Improved efficiency and greater reliability result from use of tested blocks of commands that perform higher level functions—but only for repeated use. Telecommunications no longer has to review 90 percent of the telecommunications commands that appear individually in a DS1 sequence because these commands are the expansion of activity types and utilities. Activity types are templates for sequences in which command parameter values may vary each time the activity occurs. A utility is a fixed set of commands that repeats exactly each time the utility occurs.

In hindsight, it may not have been worth developing activity types for the telecommunications technology validation tests. In complexity, each test required from 10 to 50 commands. The activity types, however, are intended to be reusable, but each test was only performed once. Because almost all commands were for telecommunications subsystem control, a customized sequence, with careful telecommunications review, might have required fewer work hours overall.

In the asteroid encounter sequence, telecommunications commands appeared in many nested levels of subsequences. These sequences were generated independently by several engineers, and their files were not all in one place. Consequently, the telecommunications analyst spent much time hunting down the latest sequences and hand merging them, because the merged product, automatically generated by the sequence team, was not correct yet. The merged products for the less complex and subsystem-interactive sequences that followed Braille encounter generally have been correct with every iteration. The cost to the telecommunications analyst of not having a correct encounter merged product was a series of numbingly painstaking and late manual sequence reviews. Recognizing that encounter sequences are always complex and unique, the team plans to centralize the sequence development some and to constrain the types of subsequences into which telecommunications (and other individual subsystem) commands can be placed. The extended mission encounter provides another chance to accomplish this.

### F. Trade-Offs Between “Make Play” and “Make Better” (Sequence Optimization)

The necessary complexity and interaction of spacecraft activities made some sequences difficult to integrate and review. The complex sequences had many iterations, and some valuable analyst time was used up re-reviewing unchanged telecommunications commands in intermediate sequences. Any sequence almost always required at least four iterations, and the more complex ones twice that. The sequence integration engineers became good at localizing the effects of the changes, relieving telecommunications of a full review each time. Limiting the number of iterations to the minimum to “make play” and automating the sequence review process is needed to operate an extended mission with a reduced staff. The DS1 process to generate, review, test, and approve a sequence worked, but at a high cost in workload. The telecommunications review process was largely manual, with some simple software checks involving character string searches and comparisons. When the sequence process and its products becomes more standardized from project to project, telecommunications analysis should develop more automated tools for sequence review.

### G. Need for an "As Flown" Sequence

DS1 chose not to pay for the creation of an "as flown" listing of commands. The experience of other projects has shown that maintaining an accurate and complete list of commands actually executed is very labor intensive. Commands need to be merged from the approved sequences, the approved ad hoc real-time commands transmitted by the ACE, and the commands resulting from unplanned events, such as safing and the resulting execution of onboard fault protection scripts and subsequent ground-transmitted recovery sequences and commands. More complexity results from the real-time commands being able to activate, deactivate, and delete sequences of commands stored onboard.

It has been labor intensive for telecommunications to respond to questions about what the telecommunications mode was at arbitrary times in the past. The questions are simple—for example, how many times has the X-band exciter been cycled off/on since launch? While such mode data can be queried over short periods of time, for long intervals, it takes intelligent manual browsing of the planned sequences, the telecommunications "book," and the ACE log to answer the question. DS1 is investigating, for the extended mission, the amount of adaptation required to make use of "state tracking" software developed for another project.

### H. Drawback of Simultaneous Telecommunications Model/Tool Development and Use

The work that telecommunications analysts do has become more software intensive in part because spacecraft and station operations have become more dependent on software. On the spacecraft, this shows up in the form of a greater variety of commands and with more onboard functions controlled by the flight software. The SDST receives and outputs digital data on the spacecraft data. At the station, the small operating staff is dependent on automated functions that previously were manually controlled. Software helped DS1 telecommunications analysis make inputs to sequencing and review the completed sequence products. The SPW would allow DS1 telecommunications analysis to provide service packages directly to a more automated station control system being developed by TMOD.

DS1 was the first project to use the SPW and the first project to use the UTP to generate a DRCF. The TFP had been used previously on one other project, Cassini, but during the DS1 mission, very substantial changes in the TFP architecture and "common" (station) telecommunications models were being implemented. Also, priorities in the software development organization meant the comparison tools (TelRet/DCP) were not adapted for DS1 until several months after launch. The result is that DS1 telecommunications analysis had a very raw set of tools in place at launch. The telecommunications analysts had to learn the tools, use the tools, make updates of the TFP models, and verify upgrades of the tools all simultaneously. Many hours were consumed by these concurrent engineering activities that should more properly be considered development rather than operations.

### I. Drawback of Simultaneous Operations Procedure Development and Use

DS1 attempted to use lessons learned by other recent flight teams, in particular Mars Pathfinder and Cassini, in doing the process engineering that led to specific procedures being required. However, there were enough differences that the formally approved procedures were very late relative to the functions being performed. One suggestion is that there be a much better definition of roles—of who does what and on what team. Within telecommunications, we have a good idea of what is needed to predict and verify link performance, even though the depth of analysis required was at times a matter of discussion. It was less clear what products or review or support other disciplines need from telecommunications. More iterations and more rework are the result of imprecise questions, often under great time pressure. At the beginning of the extended mission, the sequence process issues are being raised anew as every discipline is being downsized.

### J. Heavy Reliance on a Capability that Never Arrived

DS1 agreed to the use of service packages (SPs) as opposed to some other means of making telecommunications configuration inputs to the sequence process. This is because TMOD was restructuring the entire station configuration control process from the one known as the Network Support Subsystem (NSS) to one called Network Planning and Preparation (NPP). NSS used a time-ordered DSN keyword file (DKF) as the project statement of spacecraft telecommunications configuration and the resulting station requirements for a pass. NPP was to use the service package as a hierarchically organized listing of spacecraft information and requested services for a pass. Originally, a functional NPP was planned to be operational before DS1 launch. Implementation difficulties delayed the NPP to 3 months after launch, and TMOD and the project agreed to an interim DKF backup to the DSN, while also requiring service packages on the project side. Continuing difficulties with NPP resulted in the DKF being used throughout the entire primary mission, and eventual NPP cancellation means DKF will be used for the extended mission as well.

Maintaining the dual DKF–SP process through most of the prime mission increased the workload on telecommunications analysis well above the originally budgeted amount. On past missions, DKFs were automatically generated from the project SOE and did not require individual review. On DS1, there was no requirement for a project SOE, so the DKF was improvised from other software shortly before launch. This DKF did need review and hand editing, and this burden was placed on telecommunications analysts. By the beginning of the extended mission, DKF generation had become reliable enough that hand edits became the exception.

Preparation of service package inputs and checking outputs for UTP and NPP implementation absorbed telecommunications analysis time and resources but did not contribute to the success of the DS1 mission. The SP process on DS1 was intended as a precursor for other projects and an eventual cost saver. Without NPP and with a planned requirement for DKFs, the extended mission offers the possibility to streamline the process for this project alone and to make DS1 telecommunications analysis more efficient.

### K. Problems with Changing Assumptions in Sequence Design

Something similar to the flight rules but at a higher level is needed to provide guidelines for telecommunications configurations from sequence to sequence. The several individuals who were sequence integration engineers and mission planners were subject to varying pressures from competing uses of the telecommunications links. For example, when link margin was low, some sequences were designed with downlink carrier only (no telemetry modulation), others with 10 b/s telemetry. The two configurations require different station configuration codes (which specify what equipment is assigned to a pass) and different pre-calibration times. Configuration codes and activity times are formalized in an input to SPW called the station allocation file (SAF). Changes mean the project needs to have the DSN scheduling service redeliver the SAF and to have telecommunications analysis regenerate the service package. The analyst reviewing sequences had to learn the constraints by asking different individuals, rather than learning one set of rules. More sequence standardization and documentation of the guidelines in the extended mission should reduce the amount of miscommunication among members of the flight team and the resulting rework.

### L. Improved Software Ease of Use

In the rush to deliver workable and correct software tools for DS1, there was little time to make the software more user friendly. As a result, it is easy to misuse it—for example, by specifying an incorrect input parameter. Necessary steps to operate software not used frequently may be forgotten. We learned by using the DS1 telecommunications software that an analyst has the least "tool trouble" with a small tool set in which every tool is used often. Operational software should not require many steps, complex command file editing, going back and forth between typed-in commands and GUIs, etc. We found that memory aids (cheat sheets) help reduce the effect of such factors.

Software use should be easy and intuitive for individuals who are under time pressure to produce a correct output and move on to another task. The SP Writer and TFP are easy to use in these regards. The UTP/DRCF and TelRet/DCP are exacting and/or time consuming to use. The telecommunications analysis service of the future must refine and standardize the tool set for ease of use in efficiently providing the required service to the project.

Additional goals would include the ability to run on various platforms, have backups, and not be so dependent on services (network-accessed file storage, license managers, etc.) that may be unavailable at critical times.

### M. The Value of Self-Documenting Software Outputs

The SP Writer produces a log of the GUI settings as a comment at the top of the file. A link model has been written to produce a similar log at the top of TFP tabular predicts. These outputs have proved immensely useful for telecommunications analyst product review, by reducing the time it takes to establish which software version produced a specific product and to verify the telecommunications link configuration.

### N. Efficiency of Telecommunications Software Processes All on One Computer Platform

DS1, like most current projects, has some software operating behind a TMOD firewall and other software outside the firewall. The link performance comparison process requires successive runs of several programs on different machines. These include

(1) Making a TFP run on a Unix workstation outside the firewall to create the prediction

(2) Reformatting the predict file using Excel on a PC

(3) Querying the spacecraft and monitor data using TelRet inside the firewall (which meant that the analyst had to physically go to a specific building), and moving the query file through the firewall

(4) Merging the predict and query file in a DCP run on a workstation outside the firewall

The present setup is very inefficient. Requiring an analyst to move files across the firewall and in some cases to physically sit in front of computers in different locations added a lot more time to the process. In the future, a better integrated and more automated set of software tools could lighten the workload of an analyst, perhaps making it possible to support several missions concurrently.

### O. Software System Reliability

Much of the telecommunications software (TFP, DCP, and SP Writer) resides in a group account on the JPL institutional Andrew File System (AFS). While AFS is quite reliable, it is not perfectly robust, so telecommunications software has not been 100 percent available. In critical times, having the software on a separate machine, not dependent on AFS, has reduced the problem to a matter of manageable inconvenience (to operate in a different building and to regenerate any immediately needed output that had been stored on AFS).

A functionally similar problem is that the telecommunications programs all require a Matlab license. Most Matlab licenses are disbursed from a central JPL license server; backup requires a machine with its own copy of Matlab.

### P. Integration of Software Tools

With a spacecraft like DS1, more capable than others of autonomous attitude decisions, telecommunications analysis will come to rely more on quick turnaround ("just-in-time") prediction and performance comparison. In this, the TFP was a huge step forward from previous batch-mode operational tools. However, more needs to be done to integrate all the tools, especially for performance comparison, long-term prediction, and trend analysis.

### Q. Need for Integration of DRCF Output into Sequencing Process

A future automation objective is to link the DRCF to the sequence-generation software to eliminate the step of manually looking up in the book and entering the bit rate that goes with a particular configuration at a particular time.

### R. Need to Provide Station Monitor Data Access Back to Launch

Presently, monitor data are stored for only 1 month. We recommend storing the monitor data, or at least a filtered version of them, for the life of the project to improve access to data and synthesis of new information over long spans of time. Monitor data could be filtered in regard to the number of channels of interest to telecommunications (under 20) and to the number of sample points (for example, 1 average per minute, when the data are well behaved).

## VII. Conclusion

DS1 has been judged a successful mission in that 100 percent of the technology validation requirements have been achieved. The primary mission, which focused on technology validation and formally concluded a few weeks after the asteroid Braille encounter, was flown with a flight team of slightly more than 40 individuals, which averaged 2 telecommunications analysts. NASA has approved an extended mission, with the emphasis on science-data gathering at an encounter of the comet Borrelly in early 2001. Beginning in fiscal year 2000, plans are for this extended mission to be flown with a flight team of about 20 people, including telecommunications analysis at the 0.5 level. The half-time telecommunications analyst, using the process and tools as evolved through the prime mission and described in this article, will be able to meet the project's needs.

The telecommunications development and in-flight telecommunications analysis for DS1 have been intense. The development schedule was tight, and several new technologies were not fully developed and successfully assembled until shortly before launch. Right after launch, for nearly 2 months, intensive technology validation was supported by a small team. Excellent analysts, excellent tools, and the dedication of an entire team made the mission a success. However, we believe better planning of project and TMOD requirements and a better definition of the roles of flight team members, as well as more complete integration of computer tools, will allow us to provide an excellent service with a lower cost.

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