Chapter 5
Deep Space 1

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This chapter describes how the Deep Space 1 (DS1) spacecraft and the Deep Space Network (DSN) ground systems received and transmitted data[1]. The signal to the spacecraft was at X-band, and the signal to the ground was at X-band or Ka-band or both together. The description is at a functional level, intended to illuminate the unique DS1 mission requirements and constraints that led to the communications-system design, and how the spacecraft was operated in flight.

DS1 was the first project at JPL that used the Small Deep Space Transponder (SDST), the spacecraft radio that has become standard hardware for many deep space missions using X-band. In the DS1 era, the DSN acquired many of its current characteristics. This chapter includes descriptions of the DSN systems used for carrier tracking, radiometric data, command transmission, and telemetry reception as DS1 used them through 2001.

[1] This chapter describes the DS1 spacecraft as it operated from 1998–2001. The mission ended December 18, 2001. Though the functions remain the same, some details of the 2001-era DSN and project ground systems that supported DS1 differ from the current versions. Chapter 1 has a current description of DSN operations.

5.1 Mission and Spacecraft Description

5.1.1 Technology Validation

DS1 was the first of the New Millennium Program (NMP) deep-space technology-validation missions. The development of DS1 was led by JPL, with Spectrum Astro, Inc. as the industry partner for spacecraft development.

DS1's payload consisted of 12 advanced technologies for deep space that flew for the first time. With the three involving telecom listed first, the technologies demonstrated by DS1 are:

1) Small Deep Space Transponder (SDST) for X-band uplink and X- and Ka-band downlink
2) Ka-band solid-state Power Amplifier (KaPA) and associated experiments in Ka-band carrier tracking, telemetry demodulation, and turnaround ranging
3) Beacon Monitor Operations Experiment (BMOX) for autonomous onboard health and status summarization and request for ground assistance
4) Miniature Integrated CAmera Spectrometer (MICAS), a panchromatic visible imager and infrared and ultraviolet imaging spectrometers
5) Solar-electric propulsion (SEP) technology, implemented as the Ion-Propulsion System (IPS)
6) Autonomous onboard navigation (AutoNav)
7) Solar-Concentrator Arrays, using Refractive Linear Element-Technology (SCARLET)
8) Integrated ion-and-electron spectrometer, known as the Plasma Experiment for Planetary Exploration (PEPE)
9) Remote Agent eXperiment (RAX) architecture for autonomous-onboard planning and execution
10) Set of Low-Power Electronics (LPE)
11) High-packaging-density smart power switch, known as a Power-Actuation and Switching Module (PASM)
12) Multi-Functional Structure (MFS) experiment combining electronics and thermal control in a structural element.

Although there were 12 advanced technologies on DS1, the rest of the spacecraft payload was composed of components that were already current, low-cost, and tested on other missions when DS1 was designed. For example, the high-gain antenna (HGA) was a flight spare from the Mars Pathfinder program, and the flight computer was based on that used by Mars Pathfinder [2].

This approach—combining new technologies with tried-and-true components—was used because the New Millennium Program focus has been to prove that certain advanced technologies work in space, not to build a spacecraft out of advanced but unproven components.

5.1.2 Mission Overview

DS1 was launched October 24, 1998 [3] and completed its extended mission on December 18, 2001 [4]. The DS1 primary-mission design and execution focused exclusively on the validation of the 12 new technologies [5]. Technology testing was completed two weeks before the encounter with Asteroid 9969 1992KD (renamed Braille shortly before the encounter) on July 29, 1999 [3]. As a bonus to its technology-validation mission, DS1 collected a wealth of science data. The MICAS instrument recorded pictures and spectra of Mars, Jupiter, and selected stars. PEPE recorded extensive solar-wind data, some in collaboration with the Cassini spacecraft.

The primary mission concluded, having met or exceeded all of the mission success criteria, on September 18, 1999.

The extended mission's goal, in contrast to technology validation, was to return science data from the encounter with comet Borrelly in September 22, 2001.[2] The primary challenge in the extended mission was working around the failure in November 1999 of the star tracker, or stellar-reference unit (SRU). By June 2000, the flight team had devised a major revision of the flight software to use the science camera (MICAS) as a substitute for feeding star data to the attitude-control system. Since then, project-mission planning also accommodated a solar conjunction (spacecraft on the opposite side of the Sun from Earth) in November 2000 and another flight-software update in March 2001 to improve

[2] The original plan for the DS1 extended mission was for a flyby of the comet Borelly [8]. During technology validation, as we learned how, and how well, the spacecraft worked, we added a flyby of comet Wilson-Harrington for early 2001. The stellar-reference unit (SRU) failure and the recovery from that failure resulted in an extended period without IPS thrusting and a consequent replanning of the mission for a Borelly flyby only.

the probability of acquiring remote-sensing data during the Borrelly encounter. The risky encounter with comet Borrelly went well on September 22, 2001 [6], and the spacecraft used all four of its instruments.

For telecom operations, the DS1 flight team initially responded to the onboard SRU failure by substituting from the ground in near-real time, downlink carrier-signal observation, telecom analysis, and uplink control. The replaced functionality achieves pointing the body-mounted HGA to within an acceptable angle of Earth. The “HGA activity” [7] described more fully later, was labor-intensive and exacting in timing requirements. The RTLT (round-trip light time) delay in the HGA activity’s downlink signal monitor and corrective-command transmission process was manageable. The RTLT was about 30 min in early 2000, 40 min at solar conjunction, 34 min during the March 2001 software update, and about 25 min during the Borrelly encounter.

Following the successful flyby of the comet Borrelly, DS1 began what was colloquially named the hyperextended mission. This final mission phase, which included some additional technology validation of the IPS and the KaPA, ended with the spacecraft’s downlink being shut off on December 18, 2001 [4,8].

5.1.3 Telecom Subsystem Overview

By project policy, and like other parts of the spacecraft, the DS1 telecom subsystem was “single string” (without block redundancy). The subsystem elements include a transponder (receiver-transmitter in which the downlink can be phase-coherent with the uplink), power amplifiers for X- and Ka-band, and selectable directive and wide-beamwidth antennas. See Figs. 4-1 and 4-2 in Section 5.3.

The primary communication link was on Channel 19 at X-band (7.168-gigahertz [GHz] uplink and 8.422-GHz downlink). The SDST included the X-band receiver, command-detection and telemetry-modulation functions, and X- and Ka-band exciters.[3] The X- and Ka-band solid-state power amplifiers (XPA and KaPA) provided 12 W of RF power at X-band, and 2.2 W at Ka-band.

The Ka-band downlink carrier, phase coherent with the X-band downlink carrier, was also on Channel 19 (32,156 megahertz [MHz]). The Ka-band

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[3] “Exciter” is a generic term for the portion of a radio transmitter that produces the carrier frequency. The SDST had two exciter functions, one for X-band and the other for Ka-band. Besides generating the output carrier frequency, each exciter also had a phase modulator and the modulation index control for each kind of downlink modulation.

carrier can be unmodulated, or modulated with telemetry or ranging data like the X-band carrier.

DS1 had four X-band antennas. The high-gain antenna had a half-power beamwidth[4] of about ±4.0 degree (deg), and ±4.5 deg on the downlink and uplink, respectively. The three low-gain antennas were pointed along different spacecraft axes and had beamwidths of about ±35 deg for both downlink and uplink. As controlled through waveguide-transfer switches, the X-band uplink and downlink were always on the same antenna.

The Ka-band downlink was transmitted from the KHA (Ka-band horn antenna), which had a half-power beamwidth of about ±3.5 deg.

5.2 Telecom Subsystem Requirements

The DS1 development-phase project policies and top-level requirements led to a number of high-level directives regarding subsystem implementation. DS1 was intended as a capability-driven—as opposed to science-driven—mission.

"Science-driven" means the requirements that define a scientific mission govern the design of the spacecraft, its mission design, and its ground system. "Capability-driven" means that the requirements placed on the spacecraft, etc., follow from (rather than determine) the definition of hardware and software systems that are available.

Deep Space 1 spacecraft- and ground-system designs were driven strongly by existing hardware, software, and system capabilities in order to meet cost, schedule, and risk constraints:

- Capability-Driven Design: High-level requirements could be renegotiated (requirements reduced) if they conflicted with understood capabilities of existing hardware
- Single-String Implementation: The project policy identified that a single-string design was to be employed unless an existing design already incorporated redundancy.

[4] The direction of maximum gain of an antenna is called the boresight. The half-power beamwidth is defined in terms of the angle from boresight at which the antenna would have the capability to transmit (or receive) half as much power as at the boresight. In this article, to avoid ambiguity, the half-power beamwidth is expressed in terms of ± deg from boresight. A half-power beamwidth of ±4 deg would be a total beamwidth of 8 deg.

For telecom, these constraints resulted in flying a single unit of each of two advanced technology subsystems: the SDST and the KaPA. The SDST was a flight-engineering model (FEM), as project development and test schedules precluded a full flight model.

Except where functional redundancies already existed (for example, telemetry available on either X- or Ka-band downlink, and X-band downlink available via either high- or low-gain antenna), project policy precluded "conventional" backups for these functions. Furthermore, it was project policy to employ single-string design, and avoid cross-strapped redundancy unless existing designs (off-the-shelf or advanced technologies) already had it, and it was cost-effective to retain it.

Unlike a traditional science-driven mission, DS1 imposed fewer absolute link-performance requirements (such as minimum downlink rate vs. time) that the telecom subsystem had to meet. Nevertheless, a number of issues imposed requirements on the telecom subsystem. Sources of these system requirements were:

- Project policies
- Mission-coverage needs
- Technology-validation goals
- End-to-end information-flow considerations
- Interoperability with the DSN
- Spacecraft-architecture constraints
- Radiometric-tracking accuracy.

The above considerations led to the definition of the flight-system (spacecraft) telecom requirements. Top-level telecom-subsystem capabilities and link design to meet the requirements were defined in the DS1 Project Requirements/TMOD Support Agreement (PR/TSA) [9]. SDST parameter values measured during prelaunch testing were in the “Telecommunication FEM SDST/DSN compatibility and performance Motorola test report” [10].

5.3 Telecom System Description

The DS1 telecom subsystem provided X-band uplink and X/Ka-band downlink capabilities to handle all RF communications between the DS1 spacecraft and the DS1 mission operations team via DSN. The telecom subsystem received and demodulated uplink commands, transmits science- and engineering-telemetry data on either an X-band or a Ka-band downlink or both, and provided coherent two-way Doppler and range-measurement capabilities using the X-band uplink, and the X- or Ka-band downlink. Figure 5-1 is a block diagram of the telecom-system functional elements.

The DS1 spacecraft had four antennas for X-band (one HGA and three LGAs) and one Ka-band antenna (the KHA). Figure 5-2 shows the antenna locations on the spacecraft. Each DS1 antennas had a direction of maximum gain, often called the boresight. The boresights of the HGA, LGAX, and KHA were parallel to the +x-axis. The boresights of LGAZ+ and LGAZ– were parallel to the +z-axis and the –z-axis, respectively. Orienting the DS1 spacecraft so that the +x-axis pointed at Earth maximized the performance of links using the HGA, LGAX, or KHA. All antennas were right-circularly polarized (RCP) except LGAZ–, which was left-circularly polarized (LCP).[5]

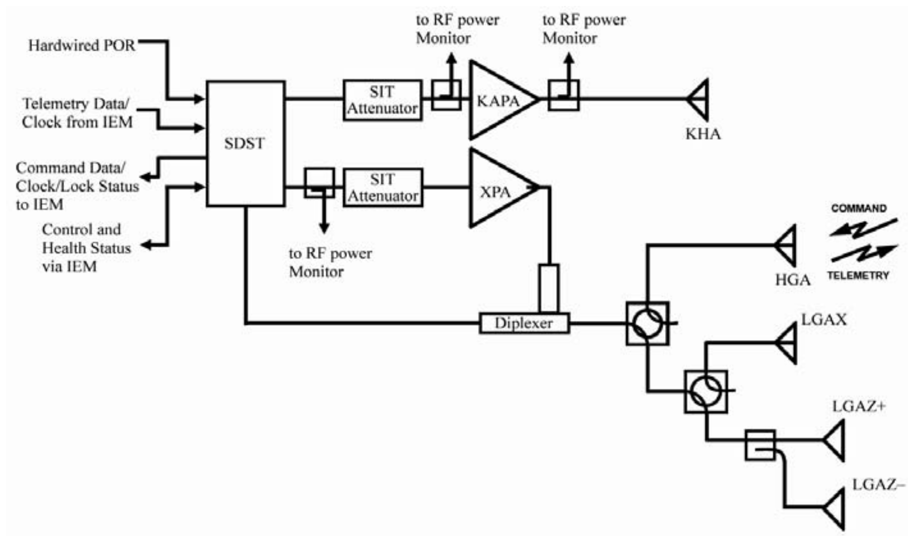

Fig. 5-1. DS-1 spacecraft telecom system functional block diagram.

[5] The LGAZ– antenna element was a duplicate of LGAZ+, mounted midway out on the service boom, with its boresight oriented along the –z-axis. LGAZ– was added to the spacecraft late in the development phase, less than one year before the planned launch date. The need for the antenna was in the first weeks after launch, when the range was small (strong signals) but Earth-spacecraft geometry would result in blockage of signal paths to LGAX or LGAZ+. Antenna-system design needed to preserve the capability of LGAZ+ as much as possible, and at the same time to disturb the existing configuration and spacecraft system interfaces as little as possible. These needs led to the choice of a passive vs. an active-coupling system, and to a 25 percent/75 percent power split between the LGAZs.

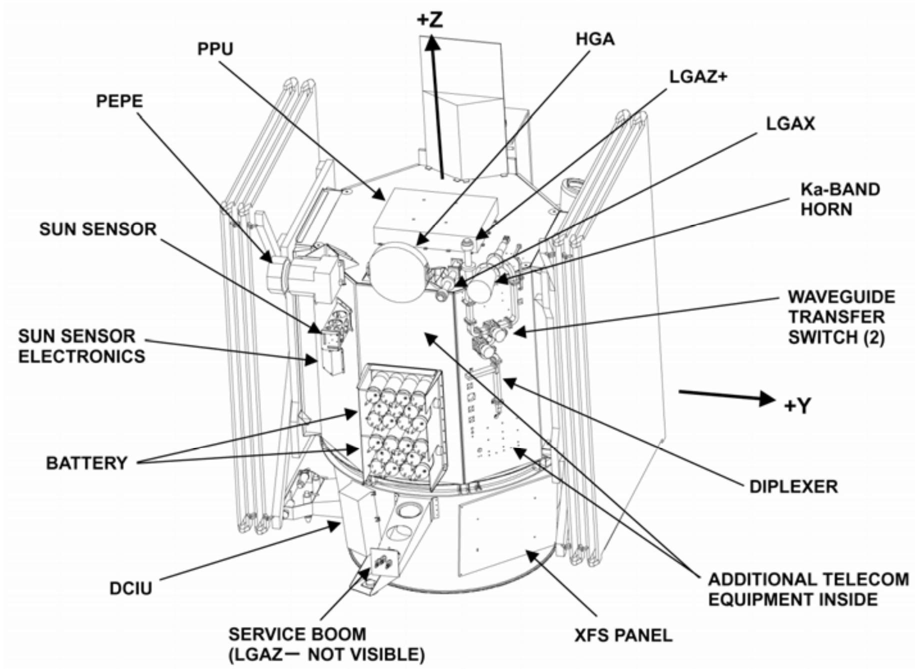

Fig. 5-2. Launch mode configuration with telecom subsystem components.

Figure 5-3 shows the downlink pattern of each LGA; Fig. 5-4 shows the X-band downlink pattern of the HGA. The X-band uplink patterns were similar, but slightly broader because of the lower-uplink frequency. Figure 5-5 shows the KHA pattern.

The SDST provided the detected-command bits for decoding and an in-lock/out-of-lock indicator to the Integrated Electronics Module (IEM) of the avionics subsystem. The IEM could send a power-on-reset (POR) signal to the SDST to activate a relay to remove spacecraft power from the SDST for 3 s, and then restore power. The SDST received a serial stream of telemetry-data bits and a clock signal from the IEM.

The amount of RF power input to the XPA from the SDST X-band exciter was established by a "select in test" (SIT) attenuator. Similarly, a SIT attenuator established the KaPA's input RF-power level. A 6-dB passive coupler connected the two z-axis LGAs, making both LGAZ+ and LGAZ– active when "the LGAZs" were selected for X-band. This means that (on the downlink) RF energy radiated out of both antennas when the LGAZs were selected, with the 6-dB coupler sending 25 percent of the energy to LGAZ–.

The HGA had a larger on-boresight gain, but also a narrower pattern. When the spacecraft x-axis could be kept within 6 deg of Earthline, the HGA was selected (it had 15 dB more gain than LGAX). Otherwise, the spacecraft was commanded or sequenced to operate on either LGAX (aligned with the +x-axis) or on the system of LGAZ+ and LGAZ– (aligned with the +z- and –z-axis, respectively).

The three LGAs all had the same patterns of gain as a function of angle from boresight. Because of different circuit losses between the SDST and each antenna, LGAZ+ had an effective gain about 1.5 dB lower than LGAX, and LGAZ– about 7 dB lower than LGAX. Much of the in-flight telecom analysis involved what uplink- or downlink-data rates would be available for different conditions of spacecraft pointing and antenna selection.

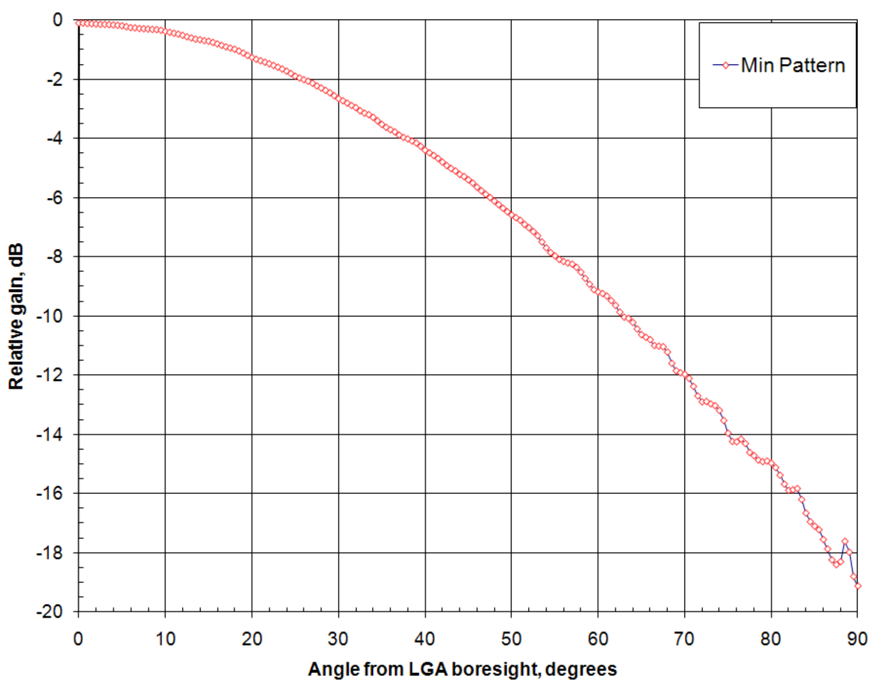

Fig. 5-3. LGA downlink pattern (relative gain as a function of angle from boresight).

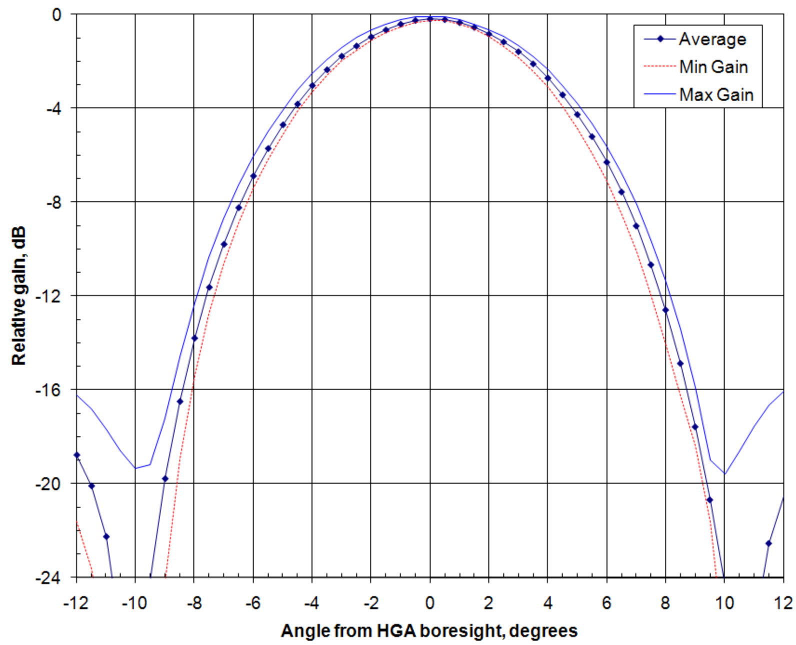

Fig. 5-4. HGA downlink pattern (relative gain as a function of angle from boresight).

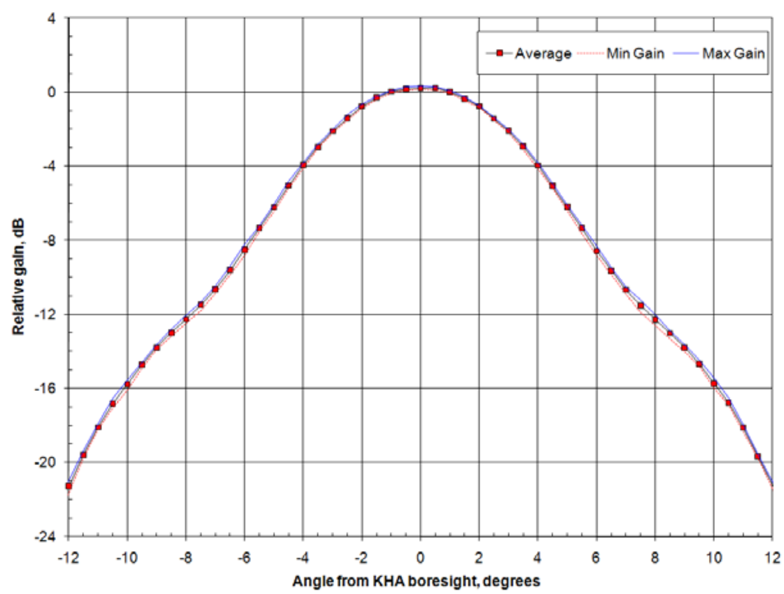

Fig. 5-5. KHA pattern (relative gain as a function of angle from boresight).

5.4 DS1 Telecom Technology

The three telecom-related technologies [5] demonstrated during the DS1 prime mission were:

1) Small Deep Space Transponder
2) Ka-band
3) Beacon Monitor Operations Experiment (BMOX).

5.4.1 Small Deep Space Transponder (SDST)

The design of the SDST (Fig. 5-6) facilitated command, telemetry, and radiometric communication between mission control and the spacecraft. The SDST combined the spacecraft receiver, command detector, telemetry modulator, turnaround-ranging channels, exciters, and control functions into one 3-kg package, about 18 × 11 × 16 cm in size. Developed by Motorola, Inc., Scottsdale, Arizona, under funding from NASA's Jet Propulsion Laboratory, the DS1 SDST provided a spacecraft terminal for X- and Ka-band telecoms with the NASA DSN, allowing X-band uplink, and X- and Ka-band downlink. It also provided coherent and noncoherent operation for radio-navigation purposes. This compact, low-mass transponder design was enabled by the use of advanced GaAs (gallium arsenide) monolithic microwave-integrated circuits.

As the heart of the telecom subsystem, SDST performed the following key functions.

5.4.1.1 Uplink-Receiving Functions

- Reception and demodulation of the X-band-uplink carrier
- Provision of an uplink AGC (automatic gain control) function for receive-power control and measurement
- Reception and demodulation the command subcarrier and data stream.

5.4.1.2 Downlink-Transmitting Functions. The SDST provided downlink capabilities that were used by DS1 and others that were not utilized. Some capabilities, noted in italics below, were not used or used only in the extended mission.

- Generation of a noncoherent downlink with either the SDST auxiliary oscillator *or an external ultrastable oscillator (USO)*. DS1 used the SDST aux osc only.

Fig. 5-6. The small deep-space transponder (SDST)

- Performing convolutional encoding[6] and subcarrier modulation of the downlink telemetry.
- Modulation of X- and Ka-band carriers with telemetry subcarriers *or with telemetry symbols directly onto the carrier*. The DS1 telemetry downlink symbol rate was low enough to allow for use of subcarrier modulation only.
- Independent control of X- and Ka-band modulation-index values.

5.4.1.3 Radio Metrics

- Generation of two-way coherent downlink carriers by phase locking with uplink signal.[7]

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[6] See Section 5.6 for a description of the telemetry-transfer frame, which was convolutionally encoded by the SDST.

[7] DS1 operated on DSN channel 19, with frequencies as defined in the PR/TSA (Project Requirements/TMOD Support Agreement) [9] and in JPL document 810-005 [11]. The defined X-band-downlink frequency (8.422 GHz) is 880/729 times the defined X-band-uplink frequency (7.168 GHz). The defined Ka-band-downlink frequency (32.156 GHz) is 3360/749 times the X-band-uplink frequency.

- Demodulation of uplink-ranging signal and remodulation of the signal on the downlink.
- *Generation of differential one-way ranging (DOR) tones for downlink*. The SDST DOR tone capability was checked out but not used for navigation during the prime mission technical validation. Late in the extended mission, to improve the navigational knowledge of the flyby past Borrelly, the project scheduled the DSN operational delta-DOR equipment and transmitted DOR tones from the SDST twice in the week prior to the Borrelly encounter.

5.4.1.4 SDST Performance Monitoring and Spacecraft Data Interfaces

- Acceptance of control signals from the Integrated Electronics Module (IEM)
- Generation of analog-engineering status within the subsystem
- Providing status and performance parameters to the IEM
- The SDST design accommodated interfaces with spacecraft avionics via a MIL-STD-1553 [12], a MIL-STD-1773 [13], or an RS422 [14] serial bus using the 1553 protocol. The DS1 SDST Command and Data Handling (C&DH) communication was via the 1553, and the data interface uses the RS422 [5].

Technology-validation, link-performance tests for SDST (and the KaPA, below) included transmitting each of the 19 DS1 telemetry rates simultaneously over X- and Ka-band to verify that the station could lock up to and decode data at each rate. The ranging channel was operated at low- and high-modulation index values, and the received-range delay compared between the two bands. Frequency-stability and carrier-noise levels (both affecting Doppler data quality) were compared between the bands. The SDST DOR modulation was turned on briefly to verify its operability.

As a result of DS1's success in proving the SDST design in flight, numerous other missions have since used the SDST, including the Mars orbiter and Mars rover missions described in this book. Typically, several missions pool their resources with "group buy" SDSTs. For instance, the Mars Science Laboratory (Chapter 7) and Juno will launch in 2011 with Group Buy III SDSTs.

5.4.2 Ka-Band Solid-State Power Amplifier (KaPA)

5.4.2.1 KaPA and Ka-Band Overview. At DS1 launch, the KaPA (Fig. 5-7) was the highest-power deep-space solid-state Ka-band amplifier yet flown. The KaPA, developed by Lockheed Martin Communication and Power Center, operated at 32 GHz and weighed 0.7 kg. As established during in-flight-

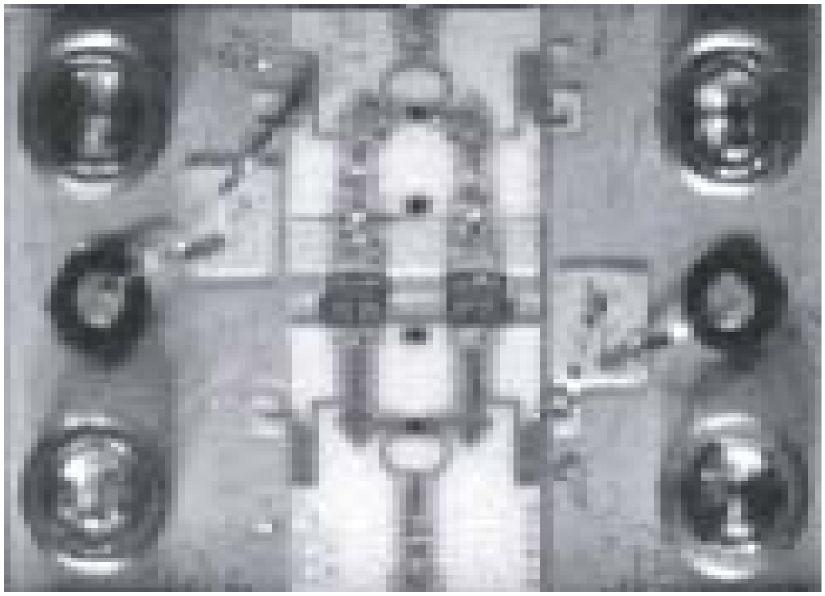

Fig. 5-7. Ka-band power amplifier (KaPA).

technology validation, the KaPA amplified the RF output from the SDST Ka-band exciter to 2.2 W with an overall efficiency of 12 percent [5].

The DS1 SDST was the first to include an internal Ka-band exciter. A later mission, MRO (Chapter 6), carried SDSTs to generate and modulate carriers that could be used to generate Ka-band downlinks external to the SDST.

Ka-band offers a potential link-performance advantage for deep-space communications. With future improvement of ground facilities and spacecraft hardware, assuming similar power efficiencies and spacecraft antenna sizes, Ka-band holds a potential four-fold increase in data rate compared to X-band. This fact alone is obviously important as in the end it means reduced project cost. Ka-band offers greater available bandwidth as NASA and other agencies move away from lower frequencies shared with personal communications systems and other emerging information-technology ventures.

On the debit side, the need for a KaPA/Ka-band technology demonstration on DS1 spoke to the relative immaturity of flight systems at this frequency, in contrast to X-band. Ka-band link performance is also more sensitive than X-band to clouds and rain, which continues to be a challenge to designing reliable deep-space Ka-band links. Arrays that take into consideration different seasonal weather patterns at each DSN longitude (for example, California and Arizona) can increase link reliability. Once necessary Ka-band ground systems are in place, a higher data rate requires fewer ground resources and less mission-operation support per spacecraft-operation week.

5.4.2.2 KaPA and Ka-Band In-Flight Technology Validation. As part of the technology validation, DS1 first successfully demonstrated the KaPA in flight less than two months after launch. On December 9 and 10, 1998, the SDST Ka-band exciter and the KaPA were first powered on in flight. During two passes, the Ka-band link functions were methodically verified. These functions (also tested with the X-band downlink) included coherent and noncoherent downlink carrier tracking, turnaround ranging, and telemetry decoding at all DS1 downlink rates.

KaPA engineering-telemetry measurements were confirmed as nominal during these tests. Internal to the KaPA were temperature sensor, gate current, and gate-voltage telemetry measurements. External to the KaPA were other temperature sensors, as well as RF power detectors to monitor both input and output RF power. From these, RF gain could be deduced. At the same time, the SDST collected internal and external diagnostic-telemetry signals that could isolate (to the SDST RF output, the intervening telecom-system components, or the KaPA) the location of any potential degradation of performance. This ability to isolate problems was part of the DS1 technology-validation plan, as SDST and KaPA came from different industrial partners.

Besides characterizing the KaPA operation and link during the primary mission, DS1 subsequently provided Ka-band modulated and unmodulated signals for DSN performance-verification, and improved ground-system design and network-component upgrades to operational use of Ka-band. The lifetime of the KaPA was proven through hundreds of hours of reliable operation through the end of the mission.

5.4.3 Beacon Monitor Operations Experiment (BMOX)

5.4.3.1 Beacon System Concept Description. Beacon-monitor technology allows a spacecraft to report its status without transmitting telemetry on the downlink. The status provides information the ground system requires to intervene by scheduling a telemetry-downlink or command-uplink session.

The Mars landing missions (such as the Mars Exploration Rover in Chapter 6 and the Mars Science Laboratory in Chapter 7) employ a form of beacon operations during their critical Entry-Descent-Landing phase. These beacons, called “semaphores” or (multiple frequency shift keying) “MFSK tones” are based on the same principles as the DS1 BMOX, though their intent is to signal successful completion of a series of activities rather than to signal a problem.

The main appeal of a beacon system is that when DSN resources are scarce and spread out among many missions, it is cheaper to build and deploy small stations at different locations with tone-detection capability only. The beacon monitor concept behind the DS1 experiment envisioned dedicated antennas 3 to 10 m in diameter [2]. Noncoherent tone does not require phase-locked receivers, and detection is possible at a lower total-received power than for telemetry at even low-bit rates. Figure 5-8 shows beacon monitoring-system elements as they were envisioned at the time of the DS1 BMOX activities.

The onboard monitoring subsystem for a typical, beacon-equipped spacecraft [15,16] would consist of flight software and part of the telecom subsystem, and be responsible for:

- Analyzing the engineering data to determine spacecraft health
- Reducing health status to one of a few (perhaps the four implemented in DS1) monitoring states, also known as beacon states or tone states
- Mapping current monitoring state into an appropriate monitoring signal
- Transmitting the monitoring signal to the ground.

During DS1, system-ground components were envisioned as a set of separate ground stations (not currently implemented) and a coordination computer. A beacon system would also include support by project-operations teams and DSN-station scheduling, prediction, and operation systems.

On board, the concept envisioned translating the overall spacecraft health and status into one of four general states. Using the spacecraft's radio, the software would direct the radio to create one of four subcarrier frequencies (without any telemetry modulation on the subcarrier) that would then be modulated onto the downlink carrier. The tone frequency indicated the spacecraft state. A so-called "green" tone indicated that the spacecraft was operating within acceptable conditions. An "orange" tone indicated that an anomaly was resolved by the spacecraft but conditions were acceptable. A "yellow" tone indicated a desire to send data to the ground or to request help with a problem that might escalate to jeopardize the mission. Finally, a "red" tone indicated that the spacecraft had a critical anomaly it could not resolve and required urgent assistance from the ground.

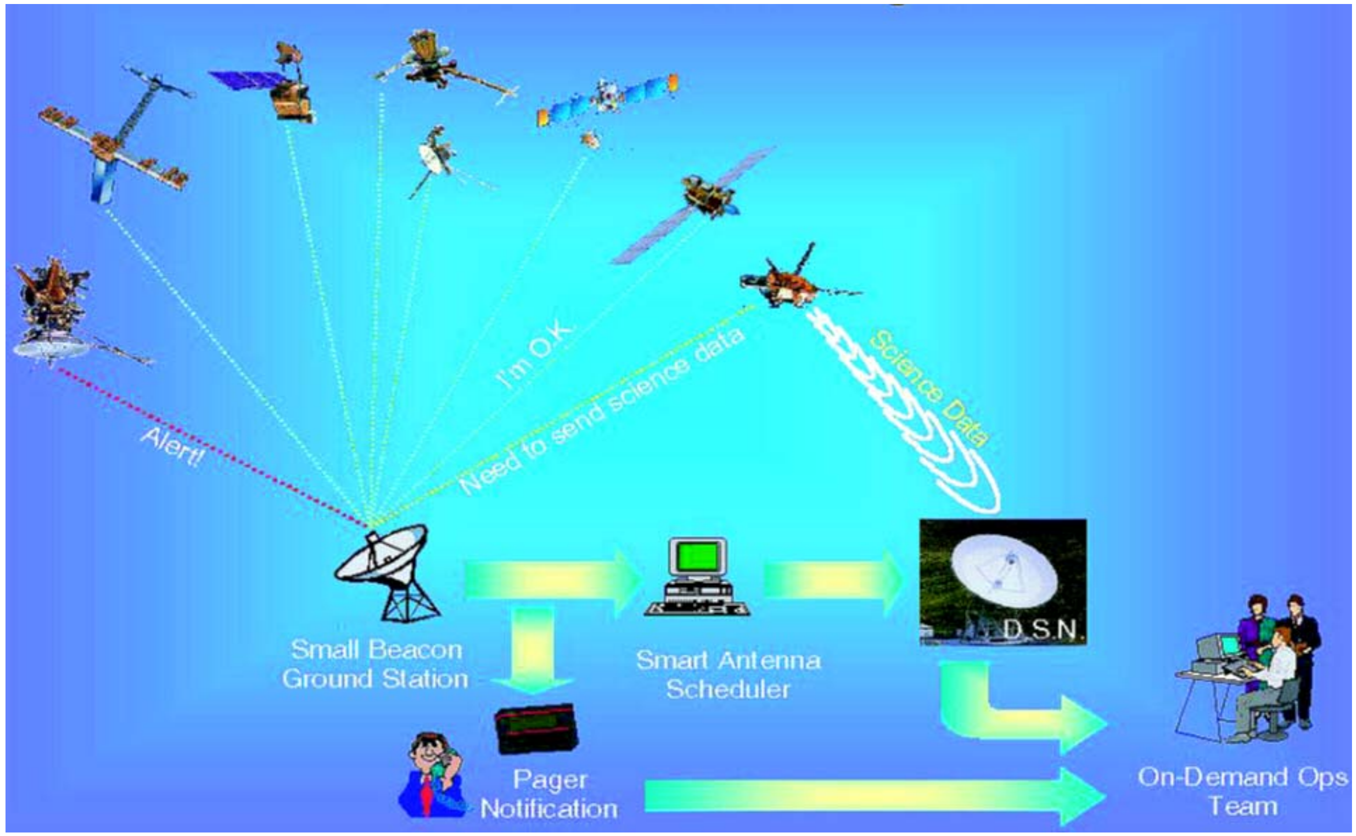

Fig. 5-8. Beacon monitoring system elements building on DS1 BMOX demonstration concepts.

A beacon-monitoring station would detect the monitoring signal using the schedule and predictions from the coordination computer, and then send the result back to the computer. The computer would interpret the beacon message based on rules established by the project. It would maintain a monitoring schedule for all spacecraft, and it would make pass requests for a 34-m or 70-m antenna and notify the project when needed. It would also initiate urgent responses when triggered by an urgent message. The DSN prediction systems would provide carrier-frequency and antenna-pointing predictions to the computer, which would send these to the monitor station. The DSN would be responsible for scheduling 34-m or 70-m antenna passes in response to the computer requests, as triggered by the detected messages. This future beacon-monitoring system is complemented with the DSN's larger antennas to track spacecraft and send telemetry data to the projects in accordance with the DSN schedule.

When operating in monitoring mode, each spacecraft would maintain a continuous ability to receive commands from the ground. It would transmit its monitoring signal continuously or on a scheduled basis if constrained by spacecraft power or other factors. In the scheduled case, a pre-agreed communication window could be established for monitoring purposes.

During a spacecraft emergency, the DSN would work directly with the project-operations teams as usual, bypassing the coordination computer. When intensive interaction is needed between the spacecraft and the ground, the monitoring mode could be terminated by a ground command, or by the onboard computer. If onboard fault-protection software detected a condition requiring rapid ground intervention, the spacecraft would revert to safe mode and transmit low-rate telemetry to the ground.

5.4.3.2 The DS1 Beacon Monitor Operations Experiment (BMOX). The DS1 BMOX new technology consisted of flight software to control existing SDST subcarrier-frequency modes to provide two functions:

1) Problem- or condition-detection and tone transmission—instead of routinely sending spacecraft-health data, the spacecraft evaluated its own state and transmitted one of four beacon tones to reveal how urgent it would be to send high-rate health data

2) Data summarization—when telemetry tracking was required, the data summarization function created and transmitted "intelligent" summaries of onboard conditions to the ground instead of bulk-telemetry data.

The tone-generation function was validated first. Stored-command sequences controlled the SDST directly, producing, over a period of several hours, an unmodulated carrier, and a suppressed carrier that was successively modulated by subcarrier frequencies of 20, 25, 30, and 35 kHz. The subcarrier frequencies served as the tones. In a fully functional beacon system, the particular tone would indicate a "nominal," "interesting," "important," or "urgent" condition.

The spacecraft-technology validation's tone-transmission also checked the station-predict function, the BMOX station-control software, and the station's ability to detect weak X- and Ka-band tone-modulated carriers. Subsequently, the BMOX flight software did not depend on just a stored sequence; it controlled which SDST subcarrier would be produced. The experiment also depended on use of the existing DSN 34-m stations that have full tracking, command, and telemetry capabilities.

In early 2000, weekly tone-transmission tests over scheduled 34-m stations were sequenced to complete the station BMOX-operations automation. The end-to end-process completed with e-mailed reports indicating the time and frequency of the tone received.

Tone-transmission capability was first used operationally in mid-2000, not for BMOX but as part of the overall spacecraft-pointing algorithm[8] and IPS-thrusting operation. At this time, the tones conveyed one piece of information: the pointing algorithm's star-lock history. Transmission of star-lock time information served a real operational purpose and did not involve the BMOX software for detection. The BMOX data-summarization function matured later in both the prime and the extended mission.

5.4.4 Telecom System Mass and Input Power

For comparison with similar functions in other spacecraft, Table 5-1 shows values of mass and spacecraft power for major elements of the DS1 telecom hardware discussed in Sections 5.3 and 5.4. The mass values and some power values come from the technology validation reports [5] and pre-launch project reports (JPL internal documents). Where available, the power values were taken from in-flight engineering telemetry. The telemetry confirmed there was

[8] The attitude control system (ACS) pointing algorithm developed after the SRU failure depended on the software maintaining lock to a reference star. A "tone detection" sequence that was activated during selected tracking passes would cause a 35-kHz frequency to modulate the downlink carrier if star-lock status had remained normal since the last check. It would modulate the downlink with a 20-kHz frequency if star-lock had been lost for more than a preset time—1.5 hours.

negligible drift in power usage by the receiver, exciters, or power amplifiers from launch through the end of mission.

Table 5-1. DS1 telecom system mass and power summary.

System Unit	Input Power (W[a])	Mass (kg)	Dimensions (cm)
Receiver	11.8		
X-band exciter, 2-way	1.8		
X-band exciter, 1-way	2.3		
Ka-band exciter	3.9		
SDST		3.1	17.9 × 11.2 × 16.4
XPA	52.5	1.6	
KAPA	16.9	0.7	14.2 × 15.2
HGA		1.2	
KHA		0.8	
LGAX		0.4	
LGAZ+		0.4	
LGAZ–	0.4		

[a] Based on in-flight telemetry data

5.5 Telecom Ground System Description

While not duplicating the current general information in Chapter 1, this section includes brief descriptions of the DSN systems as they existed in 1998–2001 to provide carrier tracking, radiometric data (Doppler and ranging) collection, command uplinking, and telemetry reception and decoding for DS1.

Specific DSN numerical parameters for DS1 were defined in the PR/TSA [10] and the DS1 Project Network Operations Plan [16].

5.5.1 Uplink and Downlink Carrier Operation

During the DS1 era (1998 through 2001) the 34-m stations had X-band uplink capability. In 2001, the transmitter power was 4 kW. The 70-m stations were X-band downlink only at DS1 launch in October 1998; by the end of mission in December 2001, all three had X-band uplink capability also.

For DS1, the station transmitter was set to RCP except during passes that the spacecraft LGAZ– (which was LCP) was scheduled to be in view of Earth.

Of the operational 70-m and 34-m-BWG stations, only DSS-25 had Ka-band-downlink capability throughout the DS1 mission.

5.5.2 Radiometric Data (Doppler and Ranging)

As with other deep space missions, the DS1 uplink-and-downlink carriers provided a means of measuring the station-to-spacecraft velocity as a Doppler shift. In addition, ranging modulation applied to the uplink was turned around by the SDST to modulate the downlink to provide a means of measuring the station-to-spacecraft distance. Together, Doppler-and-ranging data provided radio navigation inputs to the project. Both radio navigation and optical navigation were mainstays for DS1 orbit determination. Radio navigation also played a part in the technology validation of “auto-nav.” In the final 30 days of the spacecraft’s approach to the asteroid Braille, auto-nav collected optical navigation images and conducted trajectory correction maneuvers at increasing frequencies to control the targeting of the final encounter.

The metric data assembly (MDA) at the tracking station processed DS1 Doppler data. The sequential ranging assembly (SRA) and the MDA together processed ranging data. The Fig. 5-9 block diagram shows the MDA in context with other major station elements and the spacecraft. The Fig. 5-10 block diagram adds the SRA and also shows the routing of radiometric data at JPL to the DS1 project navigation. Both diagrams are from the Network Operations Plan [17].

5.5.2.1 Doppler Data. The Doppler-sample rate for DS1 was normally 10 samples/s. Doppler-integration times were sometimes made longer to counter weak downlink levels.

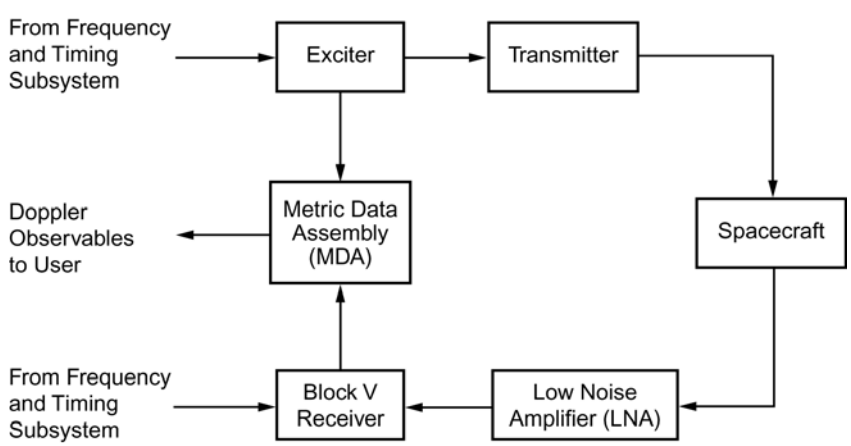

Fig. 5-9. DSN Doppler system.

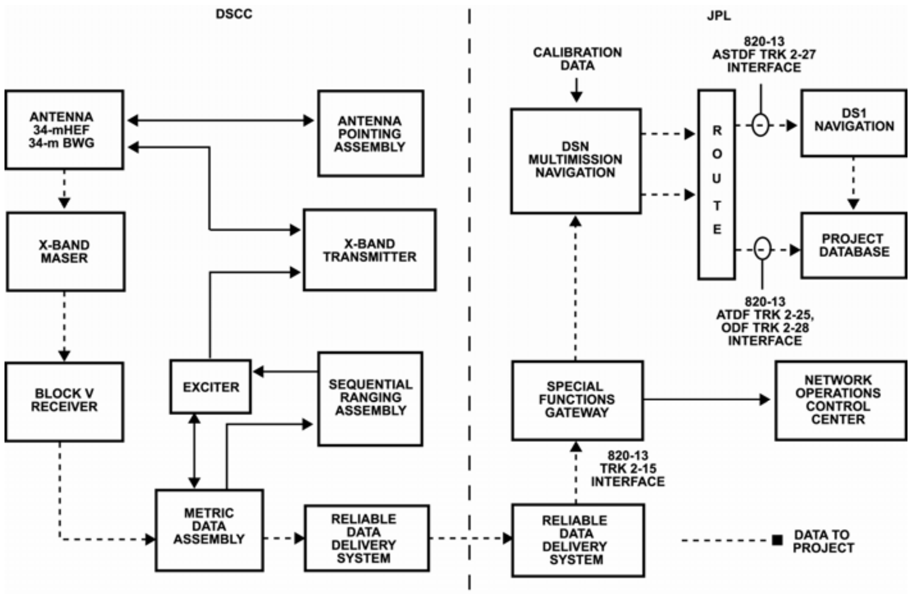

Fig. 5-10. DSN end-to-end radiometric data-flow diagram.

5.5.2.2 Ranging Data. Figure 5-11 shows the end-to-end turnaround ranging data flow in the DS1 era. The block diagram is from Ref. 17. The ranging uplink was transmitted from the station antenna to the spacecraft, and the ranging downlink from the spacecraft was received via the same-station antenna for two-way ranging or at another station for three-way ranging.

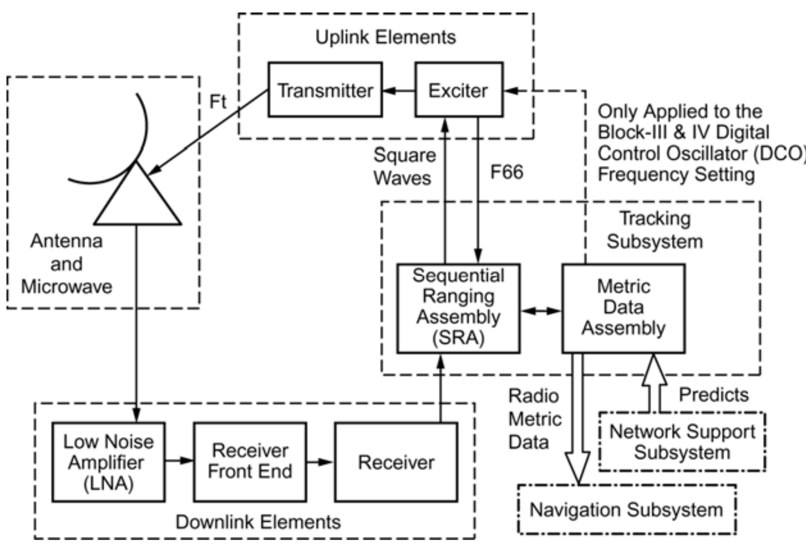

Fig. 5-11. DSN ranging system.

For the DS1 mission, the highest frequency ("clock") provided fine resolution in range. The remaining components are known as ambiguity-resolving components. The number of ambiguity-resolving components that should be used in the ranging sequence for any particular range measurement was determined by the required ambiguity-resolving capability for that measurement. To accommodate the lower-link margins in the extended mission, DS1 used a 300-s integration time for the clock component and 20-s integration time for the lower-frequency components. Standard DS1 ranging used components 4 through 20 [17] for ambiguity resolution.

5.5.2.3 Ground Processing of Doppler and Ranging Data. At JPL, the Radiometric Data Conditioning Group, part of the Multimission Navigation function, processes and delivers the Doppler and ranging data to project navigation. DS1 navigation sometimes did further processing of the delivered Doppler and ranging files in the trajectory-determination process by, for example, weighting[9] the values of data from specific passes relative to other passes. The DS1 project relied on radio navigation data to plan the interplanetary trajectory and the use of the ion thruster system. The radio-navigation data sets were also used to generate P-files for delivery back to the DSN, for use in creating the frequency and pointing predicts for subsequent tracking passes. Frequency predicts were input to the BVR to assist in locking the receiver to expected periods of one-way, two-way, or three-way data. Pointing predicts were used to drive the station antenna in elevation and azimuth angle during the pass. Pointing predicts were supplemented by several tables that were specific to the station type, the antenna coordinates on the Earth, and the general declination of the spacecraft. These supplementary tables include corrections for atmospheric refraction as a function of elevation angle and azimuth as well as for deformation of the antenna structures (and thus, changes in the beam direction) as a function of elevation angle.

[9] Weighting is an art in navigation-orbit determination, in which the available datasets (or even individual-ranging points) are assigned relative value (importance) relative to other datasets. Weighting may involve such factors as the amount of scatter between successive points, the agreement between the range and Doppler points within a pass, and how well the points from one pass "fit" into the solution model, as determined from previous passes. Orbit determination for DS1 was a challenging process because of the extensive periods of low-level thrusting. The effects of thrusting have to be separated from other small forces, such as solar pressure.

5.5.3 Command Processing and Radiation

The following description is of the systems used to command DS1. Figure 5-12 shows the systems at JPL and the station that were involved in the commanding process [17] for DS1.

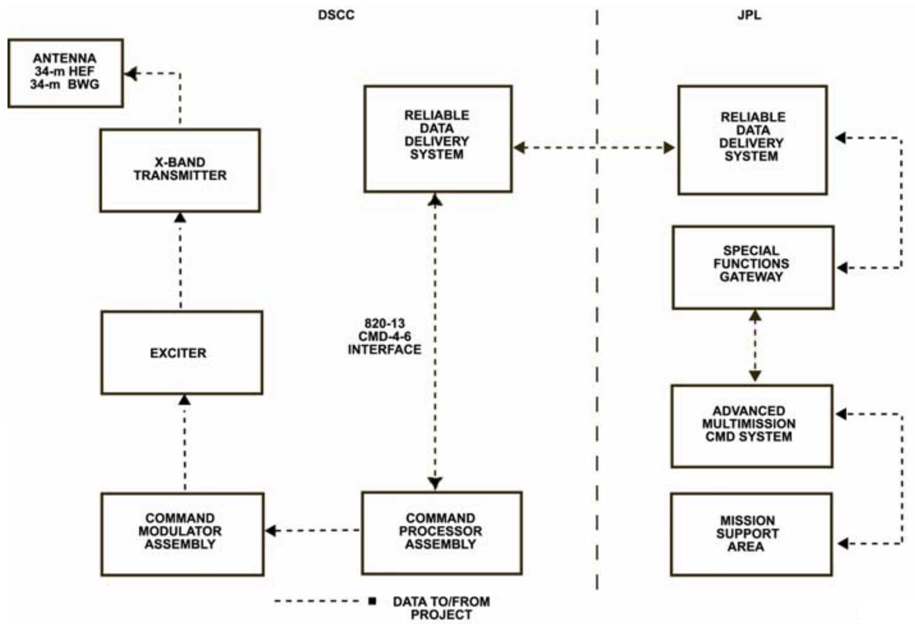

Fig. 5-12. DSN end-to-end command data-flow diagram.

At the station, the command-processor assembly (CPA) and the command-modulator assembly (CMA) clocked out the command bit stream, modulated the command subcarrier, and provided the subcarrier to the exciter for RF-uplink carrier modulation. Bit rates, the command subcarrier frequency, and the command-modulation index (suppression of the uplink carrier) were controlled through standards and limits (S&L) tables.

At JPL, the DS1 ACE (call sign for project real-time mission controller) operated the multimission command system from a workstation in the DS1 mission-support area (MSA). Experience with DS1 critical-command timing, such as in the "HGA Activities" described in Section 5.7, showed that an ACE was able to activate command transmission within 2 s of the nominal time.

To begin or end a command session, the ACE requested the station to turn the command modulation on or off, respectively. The ACE selected a command rate the uplink would support, for example 125 bps. The selected rate was associated with one of four values of uplink-carrier suppression by command modulation (or modulation index). The carrier suppression was established by use of one of four calibrated "buffers" in the station's CMA. The CMA produced the command subcarrier at a nominal frequency of 16000.2 Hz to match the subcarrier tracking loop best-lock frequency in the DS1 SDST. The CMA also modulated the command-bit waveform onto the subcarrier.

The Reliable Data Delivery System transferred the command files to the station in the staging process, as well as the ACE directives for radiation of the staged commands. At the station, the command processor assembly performed the digital processing to create the command-bit stream from the command files as well as the activation signal.

5.5.4 Telemetry Demodulation, Decoding, Synchronization, and Display

Figure 5-13 is a block diagram of the station and JPL equipment that was involved in DS1 telemetry-demodulation and decoding [17].

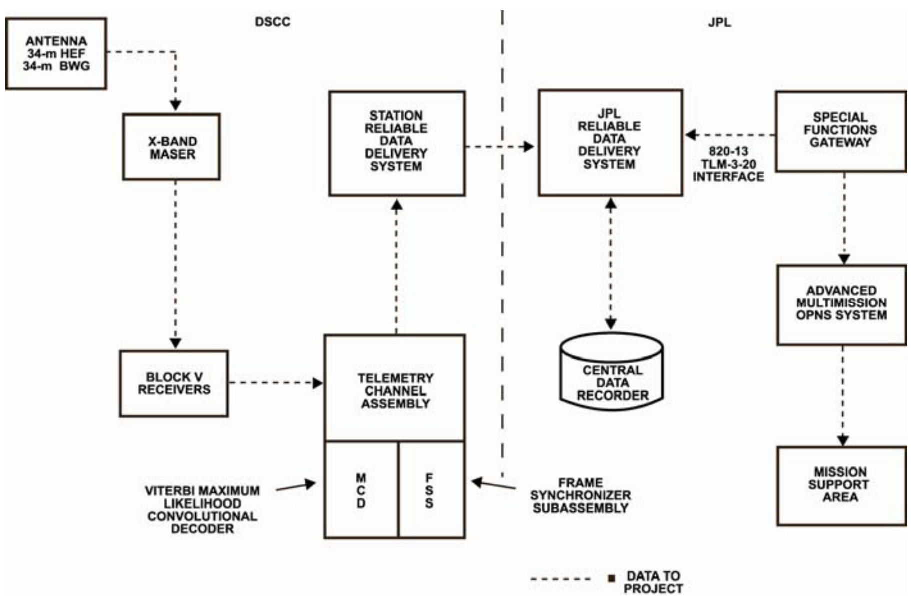

Fig. 5-13. DSN end-to-end telemetry-data-flow diagram (from 871-010-030 [11]).

The Advanced Multimission Operations System (AMMOS) processed telemetry in both near-real time (delays up to one minute) and in non-real time (as complete a record as possible, but with a delivery time guaranteed within 2 hours of the end of track. The non-real time version included retransmission of data lost between the station and JPL and replays from the central data recorder (CDR) as necessary.

Telemetry processing at JPL includes “channelizing” the data from the packets received, ordering the telemetry data that may have been transmitted in real time or from spacecraft storage, and time-tagging the data either by Earth-received time (ERT) or spacecraft-event time (SCET).

Station configuration and performance (“monitor”) data were output by the Link Monitor and Control (LMC) at the station. Monitor data was channelized similarly to telemetry data and can be displayed or queried for telecom analysis.

Figure 5-14 shows in more detail the station equipment for DS1 telemetry demodulation and decoding. This equipment is still in use for some missions, though turbo codes are now standard for the newer missions.

Each redundant BVR has phase-locked loops for receiving (locking to) the carrier, the telemetry subcarrier, and the telemetry-symbol stream. DS1 generated a 375-kHz subcarrier for telemetry bit rates of 2100 bps or greater, and a 25-kHz subcarrier for bit rates lower than 2100 bps. DS1 X-band carrier-modulation index values range from 40 deg for the lowest data rate (10 bps) to 72 deg for the highest (19,908 kbps).

For DS1 the BVR delivered telemetry symbols to the maximum-likelihood convolutional decoder (MCD). The (15,1/6) convolutional code normally used by DS1 required the use of the MCD3. An MCD/FSS (Frame Synchronizer System) pair made up a telemetry-channel assembly (TCA). The telemetry-group controller (TGC) controlled the operation of TCA1 (containing the MCD3) and TCA2 (containing an MCD2)[10].

For DS1 the MCD output decoded telemetry bits to the frame-synchronizer (FS) subsystem. After the MCD declared lock, the FSS required recognition of a minimum of two successive frame-sync words to output (“flow”) telemetry to the project. Validation required recognition of a third-sync word. The number of sync-word-allowable bit miscompares for recognition and validation could be set in the software.

[10] The MCD2 and MCD3 are distinct types of maximum-likelihood convolutional decoders. The MCD3, developed later, can handle both the r = 1/2 code and the r = 1/6 code. Though still in use by some deep space missions, the r = 1/6 code has been replaced by the turbo code, and MCD3s are becoming scarce through attrition.

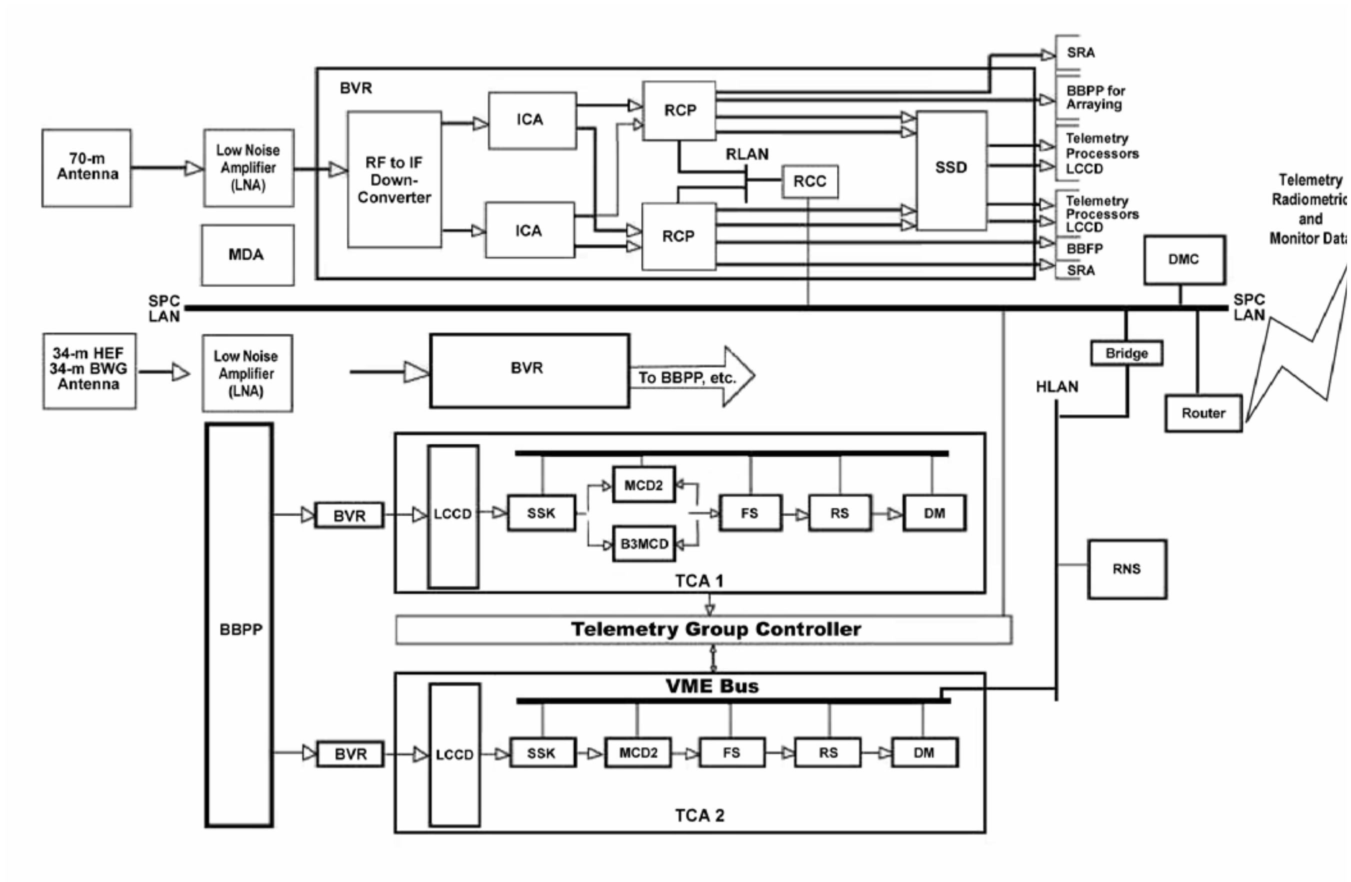

Fig. 5-14. DSN demodulation and production of telemetry data (from 871-010-030).

In the DS1 MSA, the near-real-time data was "broadcast" to workstations, which could display them in the form of DMD (data monitor and display) pages. DS1 pages could be in list form, plots, or specially formatted "fixed" pages. Also, at their workstations, the DS1 analysts could query either the telemetry or the station monitor data. The query output was displayed as tabulations or plots on the screen, routed to a printer, or saved as a file for further processing.

5.6 Telecom Link Performance

As is the case for all modern deep space missions, the DS1 communication-link margins were calculated using statistical techniques to establish expected values from the mean and variance, and a further indication of variability from the tolerances and shape (uniform, Gaussian, etc.) [18]. When in-flight link performance was seen to differ significantly from the modeled predictions, link models (such as the LGAX antenna pattern, and the interaction of telemetry-and-ranging modulation in the SDST downlink) were updated from theoretical or pre-launch test data by additional or iterative assessment of available data.

The three DS1 link functions were command, telemetry, and ranging. Each had a minimum signal-to-noise ratio (called the threshold) at which the quality of the link meets a project-defined criterion.

Link performance is book-kept using a design-control table. In-flight DS1 operations were based on a criterion of positive-link margin under the following conditions: (a) command: mean minus three standard deviations (3σ), (b) telemetry: mean minus 2σ, and (c) ranging: mean minus 2σ. The command link did not have error-correcting coding, so data-stream bits were the same as channel symbols. The telemetry link had concatenated Reed-Solomon and convolutional coding. The parameter σ (spelled out as sigma) in the DCT refers to the standard deviation of the command E_b/N_0 (bit energy to noise-spectral-density ratio), the telemetry E_s/N_0 (symbol energy to noise-spectral-density ratio), or the downlink ranging P_r/N_0 (ranging power to noise-spectral-density ratio).[11] The quantity N_0 is the noise-spectral density; E_b is the energy per bit, E_s is the energy per symbol, and P_r is the ranging power.

[11] The ranging DCT defines mean and variance for P_r/N_o, as a bottom-line telecom-analysis quantity that can be compared against a like-named channel in the station-monitor data. Beyond this, navigation also defines a ranging "sigma" (computed as a function of P_r/N_0, but which is not included in DS1 DCTs) that is a prediction of the ranging-measurement scatter.

Tables 5-2, 5-3, and 5-4 are design-control tables (DCTs) containing predictions of DS1 telecom performance, generated by a software tool, the Telecom Forecaster Predictor (TFP). TFP, still in use for deep space telecom prediction in 2010, is a multimission tool for link-performance prediction built upon Matlab [19]. DS1 TFP used standard models for station parameters (the same for each project's TFP) adapted to include DS1 spacecraft models.

The three DCTs are all for a specific arbitrary instant in time, 2000-173/16:00 UTC (9 a.m. Pacific daylight time, June 23, 2000). At that instant in time, the DS1 spacecraft was scheduled to operate with the 70-m DSS-14 antenna at Goldstone. The spacecraft was configured for X-band uplink and downlink on the HGA. The command rate was 2000 bps, at an uplink-modulation index of 1.2 rad. The ranging modulation also suppressed the uplink, at a value of 3 dB. The downlink rate was 3150 bps, at a modulation index of 65.8 deg. The ranging also phase-modulated the downlink, at an index of 0.3 rad. The HGA was presumed to have its boresight misaligned from Earth by 2.5 deg.

TFP shows the time variation of link performance either as tabulations (columns of numbers to be read into a spreadsheet for formatting and printing) or as plot images for viewing or printing.

Performance of ranging and telemetry during the entire DSS-14 pass on June 21, 2000 is summarized in the two pairs of plots (Fig. 5-15 and Fig. 5-16) that come just before the three DCTs. The plots were created from the same computer run that produced the three DCTs. All plots contain values predicted once every 20 min, starting at the DCT time of 16:00 UTC and continuing to 04:00 UTC the next day. Quantities plotted for illustration are the mean values of the parameters.

The first plot-pair shows the downlink-ranging mean P_r/N_0 and its threshold of –10 dB at the top and the uplink command mean E_b/N_0 and its threshold of +9.6 dB at the bottom. The second plot-pair shows the station-elevation angle at the top and the downlink-telemetry mean E_s/N_0 with its threshold of –7.5 dB at the bottom. Figures 5-15 and 5-16 list, respectively, the downlink P_r/N_0 and uplink E_b/N_o; and station-elevation angle, and downlink-telemetry symbol SNR.

The top plot indicates how the ranging performance (predicted as downlink-ranging power to noise-spectral-density ratio) varies during a DSS-14 pass on June 21, 2000. Below a threshold of –10 dB, ranging quality would be unacceptable for navigation; below –5 dB, the quality would be marginal.

Table 5-2. DS1 uplink (command and ranging) DCT.

Parameter	Value			
Basic Link Conditions				
Predict	2000-173T16:00:00 UTC			
Up- /Downlink	Two-way			
RF band	X:X			
Telecom link	DSS-14-HighGain. ConfigA-DSS-14			
Command Uplink Parameter Inputs				
Cmd data rate	2000 bps			
Cmd mod index	1.20 rad			
Cmd rngmod index	44.9 deg			
Operations mode	Nominal			
Mission phase	Launch phase			
DSN site	Gold-Gold			
DSN elevation	In view			
Percent probability of better weather	25			
Attitude pointing	Earth pointed			
External Data				
Range	(km)	3.0816e+08		
Range	(AU)	2.0599e+00		
One-way light time (OWLT)	(hh:mm:ss)	00:17:07		
Station elevation(s)	(deg)	14.41		
DOFF: HGA, KHA	(deg)	2.50	2.50	
DOFF: LGA1, LGA2, LGA3	(deg)	2.50	92.50	87.50
Clk: HGA, KHA	(deg)	159.49	0.00	
Clk: LGA1, LGA2, LGA3	(deg)	159.49	0.00	0.00
Added s/c antenna pointing offset	(deg)	2.5		
DSN site considered	DSS-14/DSS-14			
At time	0.00 hours after the start time			

Table 5-2. DS1 uplink (command and ranging) DCT (continued).

Link Parameter	Unit	Design Value	Fav Tol	Adv Tol	Mean Value	Var
Transmitter Parameters						
1. Total Xmitter power	dBm	73.01	0.00	–1.00	72.68	0.0556
2. Xmitter WG loss	dB	–0.41	0.05	–0.05	–0.41	0.0004
3. DSN antenna gain	dBi	72.45	0.20	–0.20	72.45	0.0133
4. Antenna pointing loss	dB	–0.10	0.10	–0.10	–0.10	0.0017
5. EIRP (1 + 2 + 3 + 4)	dB	144.62	–0.80	–0.80	144.62	0.0710
Path Parameters						
6. Space loss	dB	–279.33	0.00	0.00	–279.33	0.0000
7. Atmospheric atten	dB	–0.14	0.00	0.00	–0.14	0.0000
Receiver Parameters						
8. Polarization loss	dB	–0.03	0.10	–0.10	–0.03	–0.0033
9. S/C ant pointing control loss	dB	–0.30	0.20	–0.20	–0.30	0.0133
10. Deg-off- boresight (DOFF) loss	dB	–0.44	0.43	–0.48	–0.47	0.0691
11. S/C antenna gain (at boresight)	dBi	20.10	0.50	–0.50	20.10	0.0417
12. Lumped circuit loss	dB	–1.79	0.30	–0.30	–1.79	0.0300
Total Power Summary						
13. Tot rcvd pwr (5 + 6 + 7 + 8+ 9 + 10 + 11 +12)	dBm	–117.34	–1.43	1.43	–117.34	0.2284
14. Noise spectral density	dBm/Hz	–172.22	–0.70	0.66	–172.23	0.0779
15. System noise temp.	K	434.75	–65.08	71.69	436.95	779.9427
16. Received P_t/N_0 (13–14)	dB-Hz	54.89	1.66	–1.66	54.89	0.3063
17. Required P_t/N_0	dB-Hz	50.60	0.00	0.00	50.60	0.0000
18. P_t/N_0 margin (16–17)	dB	4.29	1.66	–1.66	4.29	0.3063
19. P_t/N_0 margin sigma	dB	0.00	0.00	0.00	0.55	0.0000
20. P_t/N_0 margin-3 sigma (18–3*19)	dB	0.00	0.00	0.00	2.63	0.0000
Carrier Performance						
21. Recovered P_t/N_0 (16 + [AGC+BW])	dB-Hz	54.89	1.66	–1.66	54.89	0.3063
22. Command carrier suppression	dB	–3.46	0.20	–0.20	–3.46	0.0067

Table 5-2. DS1 uplink (command and ranging) DCT (continued).

Link Parameter	Unit	Design Value	Fav Tol	Adv Tol	Mean Value	Var
23. Ranging carrier suppression	dB	–3.00	0.10	–0.10	–3.00	0.0017
24. Carrier power (AGC)	dBm	–123.80	–1.46	1.46	–123.80	0.2367
25. Received P_c/N_0 (21 + 22 + 23)	dB-Hz	48.43	1.68	–1.68	48.43	0.3146
26. Carrier loop noise BW	dB-Hz	20.16	–0.20	0.15	20.13	0.0102
27. Carrier loop SNR (CNR) (25–26)	dB	28.30	1.71	–1.71	28.30	0.3248
28. Recommended CNR	dB	12.00	0.00	0.00	12.00	0.0000
29. Carrier loop SNR margin (27–28)	dB	16.30	1.71	–1.71	16.30	0.3248
Channel Performance						
30. Command data suppression	dB	–3.04	0.17	–0.18	–3.04	0.0051
31. Ranging data suppression	dB	–3.00	0.10	–0.10	–3.00	0.0017
32. Received P_d/N_0 (21 + 30 + 31)	dB-Hz	48.85	1.68	–1.68	48.85	0.3130
33. 3-sigma P_d/N_0 (32-3*sqrt [32var])	dB-Hz	47.17	0.00	0.00	47.17	0.0000
34. Data rate (dB-Hz)	dB-Hz	33.01	0.00	0.00	33.01	0.0000
35. Available E_b/N_0 (32–34)	dB	15.84	1.68	–1.68	15.84	0.3130
36. Implementation loss	dB	1.50	–0.50	0.50	1.50	0.0833
37. Radio loss	dB	0.00	–0.30	0.30	0.00	0.0300
38. Output E_b/N_0 (35–36–37)	dB	14.34	1.96	–1.96	14.34	0.4264
39. Required E_b/N_0	dB	9.60	0.00	0.00	9.60	0.0000
40. E_b/N_0 margin (38–39)	dB	4.74	1.96	–1.96	4.74	0.4264
41. E_b/N_0 marg sigma	dB	0.00	0.00	0.00	0.65	0.0000
42. E_b/N_0 margin-3 sigma (40–3*41)	dB	0.00	0.00	0.00	2.78	0.0000
43. BER (from 38) 8.5494e–14	None					

Table 5-3. DS1 downlink (telemetry and ranging) DCT.

Parameter	Value			
Basic Link Conditions				
Predict	2000-173T16:00:00 UTC			
Up-/Downlink	Two–way			
RF band	X:X			
Diplex mode	N/A			
LNA* selection	LNA-1			
Telecom link	DSS-14-HighGain.ConfigA-DSS-14			
Telemetry Downlink Parameter Inputs				
Encoding	Reed-Solomon (255,223) concatenated with convolutional encoding (C.E.) (15,1/6)			
Carrier tracking	Residual			
Oscillator	Voltage-controlled oscillator (VCO)			
Subcarrier mode	Squarewave			
Phase-locked loop (PLL) bandwidth	1.00Hz			
Tlm usage	Engineering (ENG) - real time			
Tlm data rate/mod index	3150bps/ 65.80deg (38 DN)			
Operations mode	Nominal			
Mission phase	Launch phase			
DSN site	Gold-Gold			
DSN elevation	In View			
Percent probability of better weather	25			
Attitude pointing	Earth pointed			
External Data				
Range	(km)	3.0816e+08		
Range	(AU)	2.0599e+00		
One-way light time (OWLT)	(hh:mm:ss)	00:17:07		
Station elevation(s)	(deg)	14.41		
DOFF: HGA, KHA	(deg)	2.50	2.50	
DOFF: LGA1, LGA2, LGA3	(deg)	2.50	92.50	87.50
Clk: HGA, KHA	(deg)	159.49	0.00	
Clk: LGA1, LGA2, LGA3	(deg)	159.49	0.00	0.00
Added s/c ant pnt offset	(deg)	2.5		
DSN site considered	DSS-14/DSS-14			
At time	0.00 hours after the start time			

Table 5-3. DS1 downlink (telemetry and ranging) DCT (continued).

Link Parameter	Unit	Design Value	Fav Tol	Adv Tol	Mean Value	Var
Transmitter Parameters						
1. S/C transmitter power	dBm	40.97	0.50	–0.50	40.97	0.0417
2. S/C xmit circuit loss	dB	–1.91	0.30	–0.30	–1.91	0.0300
3. S/C antenna gain	dBi	24.60	0.60	–0.60	24.60	0.0600
4. Deg-off-boresight (DOFF) loss	dB	–0.98	0.21	–0.19	–0.97	0.0134
5. S/C pointing control loss	dB	–0.30	0.20	–0.20	–0.30	0.0133
6. EIRP (1 + 2 + 3 + 4 + 5)	dBm	62.39	1.19	–1.19	62.39	0.1584
Path Parameters						
7. Space loss	dB	–280.73	0.00	0.00	–280.73	0.0000
8. Atmospheric attenuation	dB	–0.14	0.00	0.00	–0.14	0.0000
Receiver Parameters						
9. DSN antenna gain	dBi	74.00	0.20	–0.20	74.00	0.0133
10. DSN antenna pnt loss	dB	–0.10	0.10	–0.10	–0.10	0.0033
11. Polarization loss	dB	–0.02	0.10	–0.10	–0.02	0.0033
Total Power Summary						
12. Tot rcvd pwr (6 + 7 + 8 + 9 + 10 + 11)	dBm	–144.61	–1.27	1.27	–144.61	0.1784
13. SNT (system-noise temperature) at zenith	K	18.39	–2.00	2.00	18.39	0.6667
14. SNT due to elevation	K	5.02	0.00	0.00	5.02	0.0000
15. SNT due to atmosphere	K	8.60	0.00	0.00	8.60	0.0000
16. SNT due to the Sun	K	0.00	0.00	0.00	0.00	0.0000
17. SNT due to other hot bodies	K	0.00	0.00	0.00	0.00	0.0000
18. System noise temperature (13 + 14 +15 + 16 +17)	K	32.01	–2.00	2.00	32.01	0.4444
19. Noise spectral density	dBm/Hz	–183.55	–0.28	0.26	–183.56	0.0082
20. Received P_t/N_0 (12–19)	dB-Hz	38.95	1.30	–1.30	38.95	0.1866
21. Required P_t/N_0	dB-Hz	38.30	0.00	0.00	38.30	0.0000
22. P_t/N_0 margin (20–21)	dB	0.65	1.30	–1.30	0.65	0.1866

Table 5-3. DS1 downlink (telemetry and ranging) DCT (continued).

Link Parameter	Unit	Design Value	Fav Tol	Adv Tol	Mean Value	Var
23. P_t/N_0 marg sigma	dB	0.00	0.00	0.00	0.43	0.0000
24. P_t/N_0 margin-2sigma (22–2*23)	dB	0.00	0.00	0.00	–0.22	0.0000
Carrier Performance						
25. Recovered P_t/N_0 (20 + [AGC+BPF])	dB-Hz	38.95	1.30	–1.30	38.95	0.1866
26. Theoretical tlm carrier sup	dB	–7.75	0.56	–0.61	–7.76	0.0570
27. Non-lin SDST tlm carr sup	dB	0.20	0.20	–0.20	0.20	0.0067
28. Total tlm carr sup (26 + 27)	dB	–7.56	–0.76	0.76	–7.56	0.0637
29. Theoretical rng carrier sup	dB	–0.26	0.04	–0.05	–0.26	0.0003
30. Non-lin SDST rng carr sup	dB	–0.54	0.20	–0.20	–0.54	0.0067
31. Total rng carr sup (29 + 30)	dB-Hz	–0.80	–0.25	0.25	–0.80	0.0070
32. DOR carrier suppression	dB	0.00	0.00	0.00	0.00	0.0000
33. Carrier power (AGC) (12 + 28 + 31 +32)	dBm	–152.97	–1.50	1.50	–152.97	0.2491
34. Received P_c/N_0 (25 +28 +31 +32)	dB-Hz	30.58	1.52	–1.52	30.58	0.2573
35. Carrier loop noise BW	dB-Hz	0.00	0.00	0.00	0.00	0.0000
36. Carrier loop SNR (CNR)	(34–35)	dB	30.58	1.52	–1.52	30.58
37. Recommended CNR	dB	10.00	0.00	0.00	10.00	0.0000
38. Carrier loop SNR margin (36–37)	dB	20.58	1.52	–1.52	20.58	0.2573
Telemetry Performance						
39. Theoretical tlm data sup	dB	–0.80	0.11	–0.12	–0.80	0.0023
40. Non-lin SDST tlm data sup	dB	0.00	0.20	–0.20	0.00	0.0067
41. Total tlm data sup (39 + 40)	dB	–0.80	–0.28	0.28	–0.80	0.0090
42. Theoretical rng data sup	dB	–0.26	0.04	–0.05	–0.26	0.0003

Table 5-3. DS1 downlink (telemetry and ranging) DCT (continued).

Link Parameter	Unit	Design Value	Fav Tol	Adv Tol	Mean Value	Var
43. Non-lin SDST rng data sup	dB	–1.10	0.20	–0.20	–1.10	0.0067
44. Total rng data sup (42 + 43)	dB-Hz	–1.36	–0.25	0.25	–1.36	0.0070
45. DOR data suppression	dB	0.00	0.00	0.00	0.00	0.0000
46. Received P_d/N_0 (25 + 41 + 44 + 45)	dB-Hz	36.79	1.35	–1.35	36.79	0.2025
47. Two sigma P_d/N_0 (46–2*sqrt(46var))	dB-Hz	35.89	0.00	0.00	35.89	0.0000
48. Data rate	dB-Hz	34.98	0.00	0.00	34.98	0.0000
49. Available E_b/N_0 (46–48)	dB	1.80	1.35	–1.35	1.80	0.2025
50. Subcarrier démodé loss	dB	0.01	0.00	0.00	0.01	0.0000
51. Symbol sync loss	dB	0.01	0.00	0.00	0.01	0.0000
52. Radio loss	dB	0.01	–0.00	0.00	0.01	0.0000
53. Output E_b/N_0 (49–50–51–52)	dB	1.78	1.35	–1.35	1.78	0.2025
54. Output SSNR (E_s/N_0)	dB	–6.00	–1.35	1.35	–6.00	0.2025
55. Required E_b/N_o	dB	0.30	0.00	0.00	0.30	0.0000
56. E_b/N_0 margin (53–55)	dB	1.48	1.35	–1.35	1.48	0.2025
57. E_b/N_0 margin sigma	dB	0.00	0.00	0.00	0.45	0.0000
58. E_b/N_0 margin–2sigma (56–2*57)	dB	0.00	0.00	0.00	0.58	0.0000
59. BER of conv decoder (from 53)	none	1.1063e-05				

The bottom plot shows the 2000-bps command performance (predicted as uplink-command bit energy to noise-spectral-density ratio) for the same pass. Threshold is +9.6 dB for a bit-error rate of 10^{-5}.

The uplink-ranging carrier suppression was 3 dB, and the command-carrier suppression was –3.5 dB, both standard DS1 values in mid-2000 for 70-m station operation with the spacecraft HGA. The downlink ranging-modulation index was 17.5 deg (low), and the telemetry-modulation index was 65.8 deg. These are also standard DS1 values.

Table 5-4. DS1 ranging performance (uplink and downlink) DCT.

Parameter	Value			
Basic Link Conditions				
Predict	2000-173T16:00:00 UTC			
Up-/Downlink	Two-way			
RF band	X:X			
Diplex mode	N/A			
LNA selection	LNA-1			
Telecom link	DSS-14-HighGain.ConfigA-DSS-14			
Operations mode	Nominal			
Mission phase	Launch phase			
DSN site	Gold-Gold			
DSN elevation	In view			
Weather/CD	25			
Attitude pointing	EarthPointed			
Command Uplink Parameter Inputs				
Cmd data rate	2000 bps			
Cmd mod index	1.20 rad			
Cmd rngmod index	44.9 deg			
Telemetry Downlink Parameter Inputs				
Encoding	Reed Solomon (255,223) concatenated with C.E. (15,1/6)			
Carrier tracking	Residual			
Oscillator	VCO			
Subcarrier mode	Squarewave			
PLL bandwidth	1.00 Hz			
Tlm usage	Engineering (ENG) - real time			
Tlm data rate/mod index	3150 bps/ 65.80 deg (38 DN)			
Tlm rng/DOR mod index	Rng 0.3 rad / DOR 0.0 rad			
External Data				
Range	(km)	3.0816e+08		
Range	(AU)	2.0599e+00		
One-way light time (OWLT)	(hh:mm:ss)	00:17:07		
Station elevation(s)	(deg)	14.41		
DOFF: HGA, KHA	(deg)	2.50	2.50	
DOFF: LGA1, LGA2, LGA3	(deg)	2.50	92.50	87.50
Clk: HGA, KHA	(deg)	159.49	0.00	
Clk: LGA1, LGA2, LGA3	(deg)	159.49	0.00	0.00
Added S/C ant pnt offset	(deg)	2.5		
DSN site considered:	DSS-14/DSS-14			
At time:	0.00 hours after the start time			

Table 5-4. DS1 ranging performance (uplink and downlink) DCT (continued).

Link Parameter	Unit	Design Value	Fav Tol	Adv Tol	Mean Value	Var
Uplink Turnaround Ranging Channel						
1. UL recovered P_t/N_0	dB-Hz	54.89	1.66	–1.66	54.89	0.3063
2. UL cmd ranging suppression	dB	–3.46	0.20	–0.20	–3.46	0.0067
3. UL ranging suppression	dB	–3.03	0.10	–0.10	–3.03	0.0033
4. UL Pr/Pt (2 + 3)	dB	–6.49	–0.30	0.30	–6.49	0.0100
5. UL filtering loss	dB	–0.91	0.20	–0.20	–0.91	0.0067
6. UL output P_r/N_0 (1 + 4 + 5)	dB-Hz	47.49	1.70	–1.70	47.49	0.3229
7. Ranging channel noise BW	dB-Hz	63.22	–0.43	0.20	63.14	0.0176
8. UL ranging SNR (6–7)	dB	–15.65	–1.75	1.75	–15.65	0.3406
Downlink Ranging Channel						
9. DL recovered P_t/N_0	dB-Hz	38.95	1.30	–1.30	38.95	0.1866
10. Theoretical telemetry suppression	dB	–7.75	0.56	–0.61	–7.76	0.0570
11. Non-linear SDST tlm suppression	dB	–0.57	0.20	–0.20	–0.57	0.0067
12. DL total tlm suppression	dB	–8.34	–0.76	0.76	–8.34	0.0637
13. Theoretical rng modulation loss	dB	–28.30	2.38	–2.46	–28.33	0.9756
14. Non-linear SDST rng mod loss	dB	0.00	0.20	–0.20	0.00	0.0067
15. DL total rng mod loss	dB	–28.33	–2.97	2.97	–28.33	0.9823
16. DL P_r/P_t (12 + 15)	dB	–36.66	–3.07	3.07	–36.66	1.0460
17. DL received P_r/N_0 (9 + 16)	dB-Hz	2.28	3.33	–3.33	2.28	1.2326
18. DL noisy ref loss	dB	0.00	0.00	0.00	0.00	0.0000
19. DL output P_r/N_0 (17 + 18)	dB-Hz	2.28	3.33	–3.33	2.28	1.2326
20. DL out P_r/N_0 sigma	dB-Hz	0.00	0.00	0.00	1.11	0.0000
21. DL out P_r/N_0 mean-2 sigma	dB-Hz	0.06	0.00	0.00	0.06	0.0000
22. DL required P_r/N_0	dB-Hz	–10.00	0.00	0.00	–10.00	0.0000
23. Ranging margin, mean (19–22)	dB-Hz	12.28	3.33	–3.33	12.28	1.2326
24. Ranging margin, mean-2 sigma (21–22)	dB-Hz	10.06	0.00	–0.00	10.06	0.0000

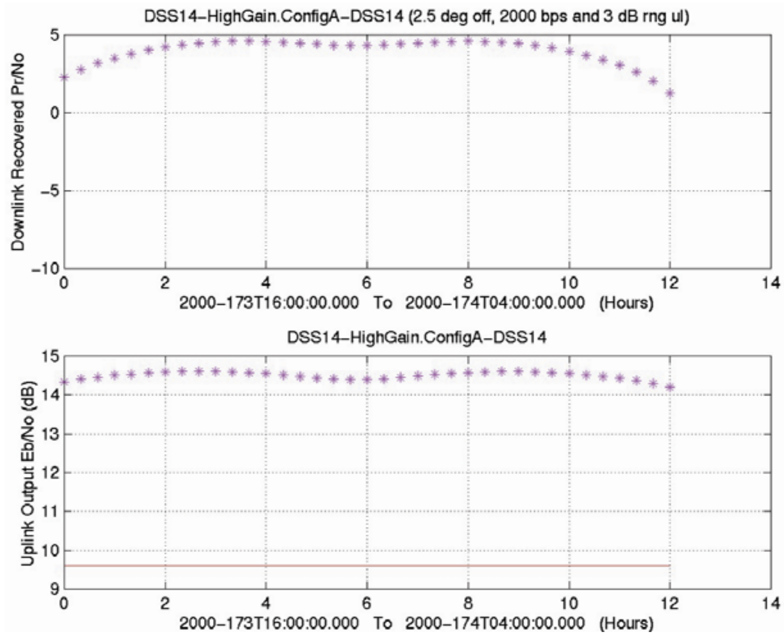

Fig. 5-15. Downlink P_r/N_0 and uplink E_b/N_0.

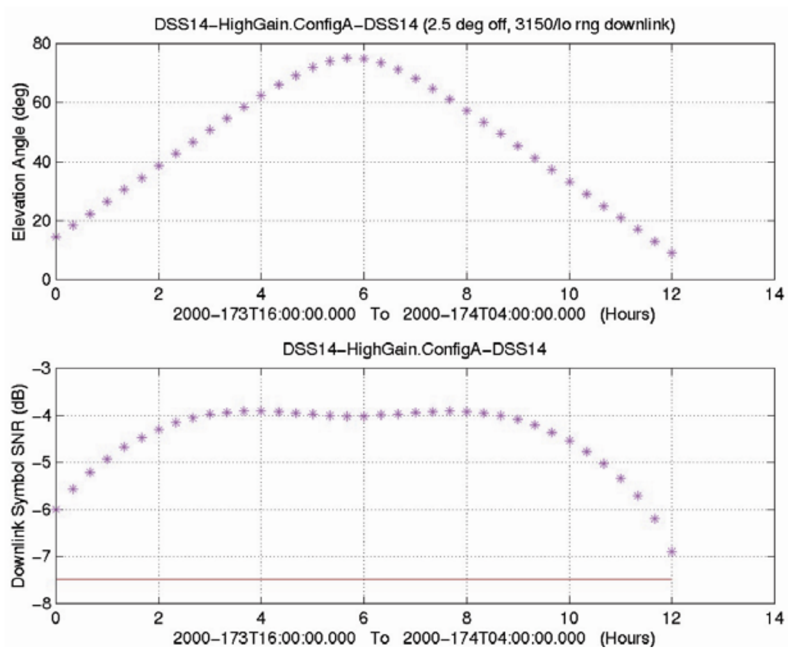

Fig. 5-16. Station elevation angle and downlink telemetry symbol SNR.

The top plot shows the variation of the DSS-14 elevation angle during the pass on June 21, 2000. Because the signal passed through more of Earth's atmosphere at lower elevation angles, the attenuation was larger and the system-noise temperature (SNT) was higher. Attenuation affected both uplink and downlink, while SNT affected downlink.

The bottom plot shows the predicted symbol signal-to-noise ratio (SSNR) of the 3150-bps telemetry. The downlink carrier also had ranging modulation at the "low" index. The telemetry-decoding threshold for the (15,1/6) concatenated code is –7.5 dB SSNR. DS1 experience showed that successful decoding by the MCD3 is improbable when the BVR produces an SSNR lower than –7.5 dB.

5.7 Operational Scenarios

The following scenarios describe the major telecom-subsystem operating modes in the context of supporting specific phases of the mission or major mission activities and modes.

5.7.1 Launch

The major prelaunch DS1 telecom decision was whether to launch with SDST in the coherent or the noncoherent mode. Noncoherent mode (coherency disabled) was chosen. The most important consideration leading to this choice was that noncoherent mode would provide an unambiguous downlink frequency for BVR acquisition regardless of whether an uplink was in lock. On the other hand, coherent mode with uplink in lock would have provided immediate two-way Doppler data to determine any corrections from errors in the launch trajectory.

The spacecraft launched with the LGAZ antennas selected, with LGAZ– at the smaller angle to Earth. One day after launch, LGAZ– was to be pointed within about 20 deg of Earth line. The uplink and downlink rates were to provide commandability and telemetry data via the selected LGA over a wide range of pointing errors. At launch, the command rate was 125 bps uncoded. The downlink rate was 2100 bps on a 25-kHz subcarrier, a 40-deg modulation index and (7,1/2) convolutional coding. During the initial acquisition pass, the SDST was commanded to go to the coherent mode ("TWNC [two-way non coherent] off" for the old timers), and to turn the X-band ranging channel on. Approximately one day after launch, the uplink rate was commanded to be 2000 bps, and a small sequence stored onboard before launch was activated to change the downlink rate to 19908 bps, the telemetry subcarrier frequency to 375 kHz, and the telemetry-modulation index to 65.8 deg. That configuration stayed the same for the first two weeks of the mission.

5.7.2 Safing

Safe mode normally occurs when the onboard fault-protection software detects a problem that requires unplanned ground intervention. (As on current spacecraft, a DS1 safe-mode configuration could also be commanded intentionally, such as when the flight software was "rebooted" after any software update.)

The original implementation of safe mode for DS1, depending on what fault occurs, would point the +x-axis either at the Sun or at Earth. After the late-1999 SRU failure, DS1 safe mode always pointed the +x-axis at the Sun and rotated the spacecraft about that axis at a rate of one revolution per hour. The system fault-protection software runs a "telecom script" (an unchanging series of commands, with defined intervals of time between the commands) to configure the SDST, XPA, and the antenna to provide the maximum degree of commandability and chance of a station receiving above-threshold telemetry. Until March 2001, much of the safe-mode telecom configuration (noncoherent mode, 7.8125-bps command rate, 40-bps telemetry rate, 25-kHz telemetry subcarrier frequency, (7,1/2) convolutional coding, ranging off, Ka-band downlink off) was similar to that of the launch mode.

Throughout the mission, the telecom script was updated as to which antenna it would select and what downlink-telemetry rate it would control. These updates matched downlink-performance changes caused by the changing Earth-DS1 distance and Sun-spacecraft-Earth angle. Telecom-script updates were through command-file uploads from the ground. As of March 2001 and through the end of the mission, the script selected LGAX, a telemetry rate of 79 bps, and the (15,1/6) coding.

5.7.3 Anchor Pass (at HGA Earth Point, High Rate)

The term "anchor" referred to the spacecraft stopping its mission activities to point the HGA at Earth and communicate. Anchor passes were scheduled approximately weekly to download telemetry data accumulated since the last anchor pass, to upload new command sequences, and to provide ranging and Doppler data. Prior to the start of the pass, the spacecraft may have been oriented toward a "thrust star" with the IPS thrusting. Since the +x-axis would be off-Earth, only minimal communication would be possible. After the SRU failure, the process of pointing to Earth for an anchor pass was based on the use of an onboard algorithm to control the spacecraft-pointing attitude without using the SRU. Before start of track, the spacecraft sequence stopped the thrusting, turned to an "Earth star" reference so the +x-axis was near Earth, selected the HGA, restarted the IPS thrust,[12] and the X-band downlink (by turning the x-band exciter on). Depending on the amount of telemetry data to be downlinked, the ranging channel was sequenced on for either the entire pass (for less telemetry data) or part of the pass (for more data). One or two hours before the end of an anchor pass, these processes were reversed: the spacecraft returned to thrust attitude, the IPS was restarted, and (just before the scheduled end of track) the downlink was turned off.[13]

The flight team had developed several variations for starting an anchor pass, based on the degree of pointing certainty at the start of the pass. The most common variant was when the initial Earth-reference star was more than 5 deg from Earth, or there might have been a question about being locked to a star at all. If so, the flight team could elect to start the pass at a low telemetry rate (79 or 600 bps, depending on the uncertainty) with HGA selected but with a "lifeboat" sequence to reselect LGAX after three hours. The telecom analyst would compare telemetry E_s/N_0 with the value predicted for the expected off-Earth angle, then recommend a higher telemetry rate to be commanded in real time. If signal level was adequate, the flight team sent a command to "cancel" (deactivate) the lifeboat, and so remain on the HGA.

During sequence planning, the telecom analyst defined for each anchor pass the uplink and downlink rates, together with associated modulation-index values and subcarrier frequencies, and ranging-channel use. The analyst determined the supportable rates, using TFP. During the primary mission, these predicts were generated as a "data-rate capability file" intended to interface directly with sequencing software. Because confident long-range planning was less feasible when successively chosen Earth-stars were involved, the telecom analyst made

[12] Thrusting on Earth-point was not usually beneficial to the trajectory but conserved the very limited attitude-control propellant, hydrazine. The IPS was gimbaled in two axes so it could perform attitude control in the x- and y-axes. Thus, while Earth-point thrusting was at a lower level, hydrazine was only expended for attitude control about the third axis (z).

[13] Until April 2001, IPS operation was nearly continuous and at a high-thrust level to reach Borrelly. This thrusting is called "deterministic," with the thrust level determined by the available spacecraft power and thrust direction as a function of time determined by reaching Borrelly at the planned time and miss distance. Subsequently, the mission moved into a period of lower-level "impulse thrusting" for continued hydrazine conservation, using successive orientations at intervals of one or two weeks toward a "north" and a "south" thrust-star, each near an ecliptic pole. Over a period of time, the impulses cancelled one another out. Like Earth-point thrusting, impulse thrusting was not at maximum thrust level and so allowed the X-band downlink to remain on between passes.

predictions for each pass with the off-point angle input directly. In either case, data rates for each allocated 34- or 70-m pass entered the sequencing process via "service-package files."

5.7.4 Midweek Pass (at Thrust Attitude for IPS Operation)

Midweek passes alternated with anchor passes, which were usually scheduled for early in the week. During a midweek pass, the spacecraft was three-axis oriented for IPS thrusting through use of the Sun sensor, gyros, and science-camera data (assuming current operations without the failed SRU). During the prime mission, the LGAX or one of the LGAZ antennas dictated required-pointing direction, depending upon which antenna best supported communications on a particular day. For the rest of the extended mission, LGAX was best because thrust attitudes resulted in the +x-axis being 0 to 50 deg from Earth. If the angle was less than 7.5 deg, the HGA provided better performance than LGAX. In this case, no turn to an Earth-star was necessary, and HGA communications were possible for midweek as well as anchor passes. For larger angles, midweek passes via LGAX provided at least the beacon tone to indicate stability of pointing algorithm star-lock and two-way Doppler data to determine if thrusting was still continuing as planned.

As for anchor passes, the telecom analyst predicted midweek pass uplink and downlink performance as a function of time, and 34-m BWG, 34-m HEF, or 70-m station allocation. The spacecraft "backbone" sequence for the current period (about 2 to 3 weeks at a time) controlled the uplink-and-downlink rate to supportable values. The lowest command rate (7.8125 bps) was sequenced for 34-m BWG stations with their 4-kW, X-band transmitters. A rate of 125 bps was sequenced for either 34-m HEF stations or 70-m stations, both with 20-kW transmitters. For maximum IPS thrust capability, the X-band downlink was turned on shortly before the scheduled start of track and turned off a few minutes before the end of track. Observing the signal level change at turnoff validated that the sequence was operating. During midweek passes, the spacecraft was in the coherent mode, to provide two-way Doppler regarding the thrust.

Between tracks, the spacecraft was generally also left in a "distant-pass" configuration so that if an unscheduled pass should become necessary, DS1 was commandable. By the end of the mission, the distant-pass configuration was LGAX, 7.8125-bps command rate, and 40-bps telemetry rate.

5.7.5 High-Gain-Antenna Activity (January–June 2000, March 2001)

This section goes into some detail because it describes how the DS1 flight team creatively overcame the failure of a major onboard element of the attitude control system that was also single-string. After the failure, the team regained control well enough for short periods of HGA operation. This initial technique required exacting and labor-intensive real-time "ground in the loop" commanded pointing control. Over a little more than one year, flight software was updated to perform some of these functions on board using a science camera, then finally customized turn-size and rate commands were developed to provide pointing with sufficient accuracy for HGA communications, optical navigation, and comet science at Borrelly.

The DS1 spacecraft was launched with a Sun-sensor assembly (SSA), inertial measurement units (IMUs), and the previously mentioned SRU; together they provided three-axis control of spacecraft pointing.[14] During the prime mission and until November 11, 1999, when the HGA was required, it would be pointed at Earth within a normal dead-band tolerance of 1 deg.[15]. On that day, downlink performance was not consistent with the HGA at Earth-point. The spacecraft was found to be in safe mode (LGAX selected and x-axis pointed to the Sun) after a tracking station could not acquire the expected downlink. Subsequent telemetry analysis showed the SRU was inoperative. Afterwards, the spacecraft remained in safe mode for some months, and low-rate uplink and downlink communications were done via LGAX only.

To return valuable science data already stored onboard at the time of the failure, as well as moderately-voluminous engineering data concerning the failure itself, the project flight team invented a ground-in-the-loop method to point the spacecraft close enough to Earth to use the HGA. The name refers to the operation of feedback-control loops with delay, in which human analysts analyze spacecraft and station data in real time, then send corrective commands immediately in real time, all the while constrained by the tens of minutes of

[14] The SSA was not used for three-axis control or knowledge in normal operation. Only the SRU and IMUs were used in normal operation.

[15] The term "dead band" comes from feedback-control theory. It refers here to an angle (1 deg) relative to the deviation of the actual pointing relative to each desired axis (x, y, z). When the difference between actual and planned pointing about an axis reaches the dead-band limit (say +1 deg), the control system fires a thruster in the negative direction. No corrective action occurs so long as the pointing error remains within the dead band.

delay inherent in the light-time between Earth and the spacecraft. Fundamental to ground-in-the-loop control is the idea of moving the spacecraft from its +x-axis to the Sun attitude to a +x-axis near Earth. This was accomplished with a combination of inertial-control and attitude-control system inputs from the gyros and the SSA only. The first part of the process was to determine the position (stop the antenna); the second part was to maintain the position (keep the antenna pointed).

This special mode is described in some detail because it involved considerable use of the telecom-analyst's skills in monitoring and assessing the significance of variations in downlink-signal levels. The most basic measurement was of carrier performance as represented by the P_c/N_0 (carrier power-to-noise spectral-density ratio). The analyst assessed in real time what commands to send and when to send them. The commands were used to change basic spacecraft motion and pointing. The initial motion was called "coning," which was rotating the spacecraft around the line joining the Sun to the spacecraft, with the +x-axis at a fixed-offset angle from the Sun (equal to the Sun-spacecraft-Earth angle). The rotation (coning) rate was once per 45 min.[16] When coning was commanded to stop, the final motion was with the +x-axis pointed "near" Earth, under inertial control. Pointing control also commanded an indexing of the +x-axis by a selected number of degrees (from 2 to 8), to compensate for gyro drift during the hours of the pass.

5.7.5.1 Stopping the Antenna near Earth by Using the Planning Worksheet. Use of an Excel-planning spreadsheet requiring only simple and rapidly made inputs and providing simple and unambiguous-to-use outputs was essential to achieve the initial HGA pointing, starting from the +x-axis to the Sun condition. See Table 5-5 for a replica of the planning sheet developed by the DS1 project telecom analyst and used by the ACE to direct the times of specific station actions for the June 12, 2000 "stop coning" activity.

Before the pass began, the telecom analyst customized the spreadsheet with the allocated start-and end-track times, the "start coning" and "final conditions" sequence start times, and the one-way light time. Table 5-5 shows one of three parts of the worksheet, with the times in the two "action" cells updating as soon as the analyst had filled in the "observe" time. The two action cells defined (a)

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[16] The coning rate was one rotation per 45 min in contrast to the safe-mode rotation rate of one revolution per 60 min. As part of the SRU recovery flight-operations redesign, the coning rate was made as rapid as possible while still providing sufficient time to get a "stop-coning" command to the spacecraft. The safe-mode rate was established before launch, and there was never any mission reason to change it.

the time the station would turn on its transmitter and begin an uplink-acquisition sweep, and (b) the time the DS1 controller (ACE) would radiate the "stop-coning" activate command.

Table 5-5. Replica of "HGA Activity Planning Spreadsheet" for June 12, 2000 activity.

Action Plan (based on seeing first 2 peaks)

act_date 06/12/00

owlt_sec 1012
owlt= 0:16:52
rtlt= 0:33:44
time/rev= 0:45:00 (from 1st to 2nd observed peak)
typeover seeded items — Do **NOT** enable uplink station Conscan
type in observations — planned times/intervals

NO	coherency?
NO	ka-band dl?
NO	fsr recording?
NO	ul conscan?

station transmit	SCET	NOCC receive	QUERY receive	what	dB or time value		
		9:00:00	**0:00:00**	**observation: 1st HGA peak used in stopping HGA**			
		8:59:45		observation with delay removed			
		9:45:00		2nd HGA peak was expected	nominal =	0:45:00	
	observe-->	**9:45:00**	**9:45:00**	**observation: 2nd HGA peak used in stopping HGA**	**interval =**	**0:45:00**	(2nd - 1st peak)
		10:30:00	10:30:00	3rd HGA peak expected			
9:56:04		10:29:48	10:29:48	expected 3rd peak with delay removed			
9:48:00				Start Excel sheet update (2nd peak seen plus 1 min)	**worktime=**	**0:05:19**	
9:49:19 <--alert				Give ACE station drive_on time			
9:49:19				ACE verifies CMD buffer selected for 31.25 bps	nominal =	00:11:19	
9:54:19 <--action!			**9:54:19**	34m station's transmitter drive ON	**interval=**	**0:09:19**	(DrvOn - peak)
				start sweep (3 segments +/-10 kHz, 300 Hz/sec = 00:01:40 for sweep)			
9:55:59				Expected end of sweep (based on **ACQ** and nominal **ETX30XCN** duration of 00:01:40)			
9:56:04				Station turns command modulation ON at end of sweep			
9:56:11				ACE verifies command modulation ON	nominal =	0:13:24	
9:56:24 <--action!			**9:56:24**	"Stop coning" activate cmd bit1 (drive ON + 00:02:05)	**interval =**	**0:11:24**	(Bit1 - peak)
9:56:27				Actual radiation begin, including command system latency			
9:56:51	10:13:43			End radiation of activate command (for 31.25 bps only, excluding vc5 tail sequence)			
9:56:52	10:13:44			Sequence execution begins			
9:56:52	10:13:44			Sequence execution completes			
9:57:44	10:14:36	10:31:28		WAG: HGA stops.	0:01:40 after **real**	3rd peak	
		10:32:10	**10:32:10**	Stopped HGA expected	**00:02:10 nominal**	0:00:42	(stop - peak)
		10:37:30	**10:37:30**	HGA turn back expected	**00:05:20 nominal**	0:05:20	(back - stop)

The onboard "start-coning" sequence put the spacecraft into an attitude-control system mode that ensured the HGA would sweep its boresight past Earth periodically. The telecom system was switched from LGAX to HGA, telemetry modulation was removed from the downlink carrier, and the command rate was set to 31.25 bps. The +x-axis moved from the Sun, a distance equal to the Sun-spacecraft-Earth angle, and the spacecraft was sequenced to begin rotating about the Sun-spacecraft line at one rotation per 45 min.

Using the spreadsheet to determine the actual rotation rate, the telecom analyst observed and timed the occurrence of two sweeps of the HGA boresight past Earth, and then gave the ACE the "action" times. These two times determined when the uplink and then the command must be sent to reach the spacecraft, as the HGA was pointed near Earth the third time. Excluding station problems, 95 percent of the time this process stopped the antenna near Earth on the first attempt.

The March 2001 HGA activity was planned to stop the antenna, based on the analyst's seeing only one peak, on the assumption that the rotation was always close to once per 45 minutes and the OWLT shorter than about 20 minutes (giving 5 minutes of analysis, reaction time, and command transmission). This "single-peak" activity, which was checked against a similar one performed in June 2000, was also successful.

5.7.5.2 Keeping the Antenna Pointed Near Earth by Monitoring Signal Levels. The quantities monitored during this phase included the downlink P_c/N_0, telemetry E_s/N_0 (symbol energy to noise-spectral-density ratio), or uplink P_c (carrier power).

After the ACE had radiated the "stop-coning" command, the telecom analyst recorded the P_c/N_0 observed for each of the first two peaks from each of the two receivers. This single command activated a small stored sequence of commands that stopped the coning rotation, produced a turn-back in the opposite direction to return the HGA to near-perfect Earth-point, and reset the command and telemetry rates for further activity. The analyst compared the P_c/N_0 value against the mean value predicted by TFP that assumed the HGA boresight was Earth-pointed with all telecom-link components operating at their expected values. The purpose of this assessment was to estimate the maximum downlink rate the link could support, taking into account link performance as well as the HGA-pointing control demonstrated during previous HGA activities.

Next, the station P_c/N_0 data showed the third peak, the subsequent halt in antenna motion, and the turn back to Earth. The telecom analyst directed the ACE to command the activation of a stored "telemetry-rate" sequence to establish the supportable rate, with its subcarrier frequency and modulation index. Thereafter, through the remaining hours of the pass, the analyst continued to monitor downlink P_c/N_0, E_s/N_0, and uplink P_c to determine if the antenna had drifted too far from Earth to support the rate. If so, the analyst would direct that a "corrective-turn" activate command be transmitted. The criterion for activating a "corrective-turn" sequence was if the E_s/N_0 first fell to –6 dB (with the threshold being –7.5 dB) fairly rapidly or sank to –6 dB twice but less rapidly.

Use of this labor-intensive and real-time process enabled the project to receive high-rate telemetry data from 14 passes. Through May 2000, we went from just sending a command to stop the rotation when we saw the signal from the HGA, evolving into a sequence that would stop the rotation and then turn back when

OWLT became so large that the stop command would not arrive in time.[17] Finally, another 14 HGA activities in June 2000 enabled the project to reload several megabytes of flight software at a high rate. The new software brought to an end the routine use of the HGA activity described here because it used the science camera instead of the failed SRU to generate star data for onboard pointing control. The software update included changes to ensure near-Earth pointing for pointing relative to a thrust star for periods of ion engine thrusting. With full three-axis pointing capability restored for thrusting, DS1 resumed its science mission for a flyby of the comet Borrelly in September 2001 [7].

An activity in March 2001, using the new flight software for the Borrelly encounter [8], progressed in a manner similar to many HGA activities in 2000. For the first few hours after Earth-point was achieved, the HGA remained near Earth. However, the downlink performance became worse over a period of hours, with the likely cause being a slow drift in roll toward the HGA first null. To counter this, the DS1 attitude control analyst developed a new delta-turn "bump" sequence to mimic a fraction of a turn of the original-coning rotation. This bump restored HGA pointing, and was made standard for HGA activities required after any subsequent safe-mode events, or flight-software updates. The flight team maintained a little "kit" of sunline turn commands to bump us forward or back by a few degrees. With this basic approach, the remaining uncertainty was in the gyro bias estimates. Incorrect estimates resulted in the spacecraft having a small remnant drift rate when the spacecraft attitude control system indicated that it was stopped.

Some art was required in choosing bump size and number of bumps without prior knowledge of which side of the HGA pattern the Earth had drifted to on a particular activity day. As we gained more experience with this technique, we got the idea of deliberately trying to "park" just to one side of the peak of the antenna pattern, with the idea that the gyro bias would cause us to drift along the antenna pattern where we would see the signal strength either increasing or decreasing. That change would tell us the sign of the required correction bump. Further, by observing a few revs at 1 rev/hour, by measuring the actual time between antenna signal peaks, we could also choose which side of the peak to "park" on.[18] The remaining mission was flown using this mode.

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[17] Personal communications, Steve Collins and Tony Vanelli, JPL, July 8, 2014.

[18] Personal communications, Steve Collins and Tony Vanelli, JPL, July 8, 2014.

5.7.6 Solar Conjunction

Solar conjunction occurs when the spacecraft and the Sun are in the same angular region as viewed from the deep-space station [20]. The angular separation is the Sun-Earth-probe (SEP) angle. Effects on deep-space communications become more severe as the SEP angle becomes smaller.[19] For DS1, X-band up- and downlink, we considered an angle of 5 deg as the minimum at which to expect no degradation, and 3 deg as the minimum at which reliable communications could be planned. From October 20 to December 3, 2000, the angle was less than 5 deg, and from October 29 to November 25 it was less than 3 deg. The minimum angle was less than 0.5 deg during a scheduled pass on November 14, 2000. The 11-year solar cycle was near its maximum.

Both to minimize configuration changes and to use the HGA as much as possible, project navigation found a single-reference star with small x-axis-to-Earth angle throughout the conjunction period.[20] The HGA off-point from Earth varied from about 2.5 deg at period start to a minimum of 0.3 deg November 13, to about 2.8 deg at period end. The first scheduled post-conjunction pass that the project was able to receive telemetry was on November 20, with the Sun-Earth-spacecraft angle at 1.1 deg.

The DS1 project planned the solar conjunction as a single sequence with minimal configuration changes, to be loaded onboard for execution for the

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[19] A superior solar conjunction (like DS1's) occurs when the Sun is between the spacecraft and the Earth. Planning for superior conjunction effects on deep-space links at JPL currently takes into account only the carrier-frequency band and the Sun-Earth-spacecraft angle. Solar activity varies in cycles, with the 11-year solar cycle near a maximum in 2000–2001. The effects on a link, caused by charged particles from the Sun producing amplitude and phase scintillation, may also be highly variable over periods of a few minutes to a few hours. Coronal-mass ejections (CME) of charged particles that cross the ray path between Earth and the spacecraft have degraded Galileo low-margin S-band links even when the SEP angle is large (> 90 deg). Apparent solar effects affected DS1 X-band up- and downlink signals during a pass on April 3, 2001 (at SEP ~31 deg), less than one day after a very large (class X20) solar flare occurred.

[20] Part of the rationale in selecting the reference star used during conjunction was to yield good pointing relative to Earth for the November 20 pass. The star was also suitable for IPS thrusting which continued throughout conjunction. The 0.3-deg minimum Sun-Earth-spacecraft angle that occurred on November 13 compares with a solar radius of about 0.25 deg and meant the signal path from spacecraft to Earth was very nearly blocked by the Sun.

entire duration. The up- and downlink data rates were conservative, and the command-loss expiration was pushed to beyond the time the angle would again be greater than 3 deg. The command rate was made 7.8125 bps through the conjunction period.

Downlink strategy, as a function of Sun-Earth-spacecraft angle, was to:

- Sequence a downlink rate that was reduced by one or two data rates from normal between an angle of 3 and 5 deg. For example, instead of 4424 bps, sequence 3150 bps or 2100 bps. Instead of 790 bps sequence 600 bps or 420 bps. This increased the margin by about 1.2 to 3.1 dB
- Sequence 40 bps for passes with an angle less than 3 deg
- Modulate downlink carrier with only a subcarrier tone for passes with an angle less than 1 deg.

Link configurations were based on experience from recent solar conjunctions of Mars Global Surveyor and Cassini, as well as on the expert recommendations of the JPL Telecommunications Systems and Research Section. The sequence included operating both the X- and Ka-band downlinks. It also included periods with the downlink in the two-way coherent mode (SDST-coherency enabled and uplink in lock) and other periods with no planned uplink. The objective was to maximize the probability that at least one frequency band would be receivable during the scheduled weekly tracking passes. The strategy was successful both in monitoring spacecraft health and providing open- and closed-loop data for telecom analysis, and planning other project conjunctions [20].

5.7.7 Ka-Band Downlink

Using the Ka-band downlink during the first months after launch was for technology validation of the KaPA. Ka-band was also used operationally during portions of the solar conjunction in November 2000. The Ka-band downlink was receivable via the KHA only when the +x-axis pointed at Earth and a station with Ka-band capability had been allocated. Sequencing of the Ka-band exciter of the SDST and the KaPA was through previously stored commands.

During the 1998–99 technology validation period, the Ka-band downlink carried telemetry and ranging data. Ranging channel on/off and modulation index (low/high) were individually controllable for X- and Ka-band, as was the telemetry subcarrier frequency and modulation index. However, only a single downlink rate was available at a time for use on both bands. Because the KHA and HGA gains were similar, but the KaPA had one-fifth of XPA's RF output, the Ka-band supportable telemetry rate was similarly reduced relative to X-band. Because DS1 was downlink-rate limited, the project generally chose the higher rate supportable on X-band. Subsequently through the end of the mission, except for special tests, the Ka-band downlink was left unmodulated.

5.8 Lessons Learned

5.8.1 Telecom-Related Lessons Learned

In December 1999, the telecommunications group at JPL presented lessons learned to DS1. This section is an update of that material [21], covering the development and testing of the SDST and KaPA, as well as the flight operations. Going on two decades since DS1 was active, many of recommendations have proved themselves in the testing and flight operations of other Deep Space missions. For future projects, the staffing-related experience has been incorporated into a task and level-of-effort model that is used during a project's mission operations design.

The section begins with some things we did mostly right and ends with other things that caused us difficulty.

5.8.1.1 Telecom Pre-Launch Testing. Telecom hardware testing by the manufacturer, telecom-development lab (TDL) subsystem testing, DSN-compatibility testing, and spacecraft-level prelaunch system testing was thorough enough on DS1 that the flight team found an untested SDST characteristic that was needed for in-flight planning or analysis. The DS1 telecom test plan should be used as a model for our in-development projects. Future test plans do not need to include repeats of development tests already done for unchanged components; however, the planning needs to be equally thorough in considering the telecom functions (command, telemetry, carrier tracking, including the presence of Doppler shifts, ranging) and mission plans.

5.8.1.2 Development-to-Operations "Handover." This was properly scheduled and well executed. The flight-team telecom analyst came onboard a year before the planned launch, and the development telecom-system people remained to lend a hand through the planned "40-day" technology-validation period that lasted six months. The intense period of telecom in-flight characterization (planning and execution) probably lasted half that long, with the formal SDST, KaPA, and BMOX technology-validation activities on the spacecraft occupying all or portions of about 15 passes. The telecom analyst was well seasoned by launch, including a sufficient familiarity with the DS1 spacecraft and specifically its subsystem. Even so, the telecom-development engineers played important roles in the formal-technology validation. Plans for our in-development projects need to include a development-to-operations handover of at least one year.

5.8.1.3 Flight Team Telecom-Support Level. The flight-team plan for telecom staffing was 1.0 full-time equivalent (FTE) in the prime mission, reducing to 0.5 during the extended mission. The reality was the need for 1.5 to 2.0 FTEs; through in-flight characterization, remaining at 1.0 through the SRU-anomaly resolution, and 0.75 by May 2001. Some causes: our software tools were not mature; there was more than expected hands-on flying of this dynamic spacecraft; and there was a continuing need to produce two forms of telecom-configuration definitions (a DSN keywords file and service packages). The DS1 experience taught us that we need a full-time, seasoned telecom analyst for each spacecraft, with moderately active telecom planning and execution, with tracking a half or more of the total time. This level can begin to be cut back once several projects have a common set of automation tools for telecom planning and analysis.

5.8.1.4 Effective Staffing Mix. On DS1, the senior-lead telecom analyst trained and mentored two junior analysts successively through the prime mission. We verified that routine or repetitive tasks such as performance-comparison runs do not require a senior analyst. A second, on-call senior analyst can step in for vacations, illness, etc. DS1 hoped to do the link-analysis task using a pool of qualified engineers. However, this “plug and play” approach did not work for DS1 because there were never enough members in the pool, and there were not enough projects subscribing to the concept. The implication here is that these problems have to be overcome to make a pure “service” approach work, and—even then—a senior analyst with continuity on each project is vital to mission success for a telecom-active mission. In the future, availability of more effective or integrated telecom software would allow for automation of the routine tasks, requiring only a review of the results by a less senior analyst.

5.8.1.5 Flight Team Co-location, near the MSA. Operating from a separate building by telephone and e-mail would not have worked during the highly interactive primary mission. Co-location reduced sequence-integration/review turnaround-time during iterations. The data was accessible only behind the firewall in the MSA. Interruptions were a resultant co-location cost in individual-analyst efficiency. These results underscore the lesson that the planning portions of the link-analysis task are project-dedicated flight-team functions, not a generic task.

5.8.1.6 Effective, Easy-to-Use Data Displays. DS1 made a formal agreement with the DSN to provide access in the MSA to operate (via graphical user interface) the workstations of the DSN’s Network Operations Control-Center Real-Time (NOCC RT) System. This allowed a telecom analyst or the ACE to resolve configuration and bandwidth problems. DS1 demonstrated the need for rapid access to station configuration and performance data for telecom support of any deep space mission. To meet this need, the AMMOS system has subsequently developed DMD tabular and plot displays that access data from station monitor data (called "mon0158"). Telecom analysts on a variety of deep space missions use these displays when operating in the mission support area.

5.8.1.7 Querying Data. The AMMOS query system has limitations, particularly for even a few telemetry channels over long durations. Consequently, to complete the technology validation required 2-1/2 weeks of senior-analyst time for queries of KaPA performance and configuration back to the time of the in-flight characterization (December 1998). The set of tools, DMD/EZquery/Oplot is capable, but it works easily only for fairly recent data (of a few weeks' duration). (This problem has been eased in recent missions by use of alternative AMMOS query tools and improved yet again by use of the post-AMMOS data processors.)

5.8.1.8 Telecom-Sequencing Standardization. In DS1, configuration of the onboard telecom subsystem for the beginning of a station pass and after the end of a station pass was made standard by using sets of commands created by spacecraft blocks. Likewise, the configuration of the station to set up for and conduct a tracking pass was through the use of a DSN keywords file (DKF). Early in operations, DS1 analysts spent much time re-reviewing sequence products and even editing DKFs manually. Dual lessons here are to (a) publish sequence-generation guidelines early and stick to them, and (b) modularize for reuse the sequence elements at several levels higher than individual commands.

5.8.1.9 Need for an as-Flown Sequence. On DS1, we needed both a good one-page-per-day spaceflight operations schedule (SFOS) for planning and a good as-flown sequence of events (SOE) for problem analysis and technology validation. On subsequent projects, with standardized sequencing processes, there were fewer changes between plans and execution. We learned that the "as flown" products could be replaced by the excellent query and analysis tools.

5.8.1.10 Simultaneous Update. Selection of TFP (over the spreadsheet-based predictor that is still used for pre-launch telecom link design) was the correct choice for the solid tool needed for the operational environment, but it was new software. In the several months before and after launch, there were several deliveries of TFP as well as the need for individual "add path" telecom models.[21] As much as several hours of analyst time are needed to verify the

[21] See Ref. 19 for a description of TFP, including the "add path" capability. The name refers to maintaining the officially-delivered TFP spacecraft and station models in

correctness of each add-path update and several days to verify a formal TFP delivery before use in project-mission planning. The nonlinearity in the flight-engineering model SDST X-band modulator [21] required 1-1/2 months for users to determine how to model and implement in TFP. In a dozen projects since DS1, most of these TFP-development "growing pains" became less severe for in-development projects that adapted the same tool. The DS1 lesson is that the project-development plan needs to provide for a sufficient adaptation, debug, and shakedown effort for a new link-analysis tool ensemble.

5.8.1.11 Service Packages and DSN Keyword Files. As part of a ground-system "new technology," DS1 worked with the DSN to define the SP for both the telecom-configuration input to project-sequence planning and the project input to the new Network Planning and Preparation (NPP) system. An SP was a computer-generated listing of the services required of the DSN by a project. Services might include the station transmitting an uplink; commanding, transmitting, and receiving Doppler and ranging data; and receiving and decoding telemetry on the downlink. The Service concept was intended to replace an older station-configuration-management input called the DSN Keyword File (DKF).

A DKF is a time-ordered series of standardized information items or directive items. Each of these items has a defined stem (the "keyword") and may have parameters. A typical spacecraft information keyword is "S/C TLM X-MOD" with parameters that define the bit rate, subcarrier use and frequency, coding, and modulation index. A typical directive keyword is "D/L ACQ" with parameters specifying the frequency band, channel number, and tracking mode. These two examples refer to spacecraft status defining the X-band modulation conditions, and a directive to the station to acquire the downlink, respectively. Table 5-6 provides examples of these two keywords from a DKF for the Dawn spacecraft in 2014.

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specific computer directories, then establishing updated models, as needed, in separate directories. TFP allows the user to specify that a TFP run use the updated model by adding its directory path (for short, an "add path" to the run instructions. For example, when many station performance parameters and models changed as the interface document 810-5 was updated to its current Rev. E in January 2001, the DS1 telecom analyst used an add path until an updated TFP could be delivered to the project.

For a list of 810-5 revisions from the first on-line version in 1996 to the present, see http://deepspace.jpl.nasa.gov/dsndocs/810-005/history.cfm?force_external=0

Table 5-6. Example Dawn DKF keywords and definitions.

! 203 65 00299 209 163912 NMC D65	S/C TLM X-MOD, 40T6, 25.000, 53.0DG,
! 203 65 00300 209 163912 NMC D65	D/L ACQ, 2-WAY, X/CH. 29
From left to right, the fields in these typical keywords carry the values	
Spacecraft ID = 203 (Dawn)	
Tracking station ID = 65 (34m station at Madrid)	
Row number in the DKF = 00299 (and 00300)	
Day of year and UTC = 209 16:39:12	
Tracking station ID = D65 (a redundancy)	
Telemetry bit rate = 40 bps	
Coding = Turbo 1/6 (T6)	
Telemetry subcarrier frequency = 25 kHz	
Telemetry modulation index = 53 deg.	
Acquisition mode = 2-way	
Acquisition band = X	
DSN channel number = 29	

The NPP, intended as an automated means for station-configuration management, never became operational. As DS1 launch neared, significant concern about the NPP development resulted in a TMOD/project agreement for the project to use the older DKF station-configuration-management input. The project used SPs for telecom input to the sequencing process, as planned. Telecom time was lost before launch to develop and test the SP as an NPP input. With hindsight, a telecom interface for project sequence input only, could have been less complex than the SP. The late changeover to the DKF interface resulted in the need for several updates to the DKF-generation software through flight, and still a need for some hand-editing and a review of DKF outputs.

Numerous lessons that came from the DS1-SP experience were applied to later projects to make their data-rate-capability generation, configuration trade-off, and telecom-planning input processes and tools simple to use and easy to modify. On the DSN side, configuration codes (which existed for DS1) are an integral part of scheduling passes. The configuration codes define the services (such as transmitter, command, and telemetry) for each pass. At the other end of the sequence-generation process, DKF generation has become automated through project-sequencing tools and input to the DSN through a successor to the NPP.

5.8.2 Project-Level Lessons Learned

In December 2000, the former and current DS1 project managers and the spacecraft-development system manager presented the “lessons learned” to JPL

[1]. The presentation included a mission summary, a discussion of the mission-success criteria, and the spacecraft-system-development schedule to place things into context.

Following one page titled, “Why did DS1 accomplish so much?” and another two titled, “What worked well?” there are 12 pages headed, “What didn’t work well and why?”

Here, from that presentation, is a summary of the DS1 project-level lessons learned. Without the inclusion of the events that motivated each lesson, these can be taken more as a checklist for deep-space project operations in the future.

5.8.2.1 Project Management

- A project needs at least a year for Phase A/B, culminating in a review to ensure the mission concept is sound, the requirements are agreed to, and there are sufficient resources to do the job.
- During the early project phases, define phasing of funding, need dates for the launch vehicle, requirements and success criteria, etc., and do not proceed with further commitments until the entire project is better understood and agreement is in place with NASA Headquarters.

5.8.2.2 Organization-and-Team Dynamics

- The team is the most important factor in mission success.
- An unambiguous organization, adequate resources and the right environment are essential to allow the team to succeed. It is critical to have adequate resources to allow the team to do their job in a humane way.

5.8.2.3 Reviews

- Peer Reviews add the most value.
- Set up a peer-review plan early and get line-management support. Make sure the industry partner buys into the peer-review process.

5.8.2.4 Advanced Technologies

- Develop a technology plan during formulation that addresses risk-mitigation and technology readiness. Include meaningful technology-readiness gates to assess development progress, include clear-action plans if the gates are not met.
- Be cautious about having one technology rely on another for testing.
- If technologies are coupled, treat the independent technology as critical.

5.8.2.5 Communications and Data Transfer. Require data transfer to occur at the technical level, without intermediaries.

5.8.2.6 Assembly, Test, and Launch Operations. Include adequate margin in development schedules, particularly for technology development. Develop an Assembly, Test and Launch Operations plan that is resilient to late deliveries.

5.8.2.7 Operations

- Resources (personnel and schedule) need to be made available in order to allow spacecraft-and payload-team participation early in operations planning.
- Allocate time to allow development personnel to complete integration and test activities and to prepare for mission operations.

5.8.2.8 Contingency Procedures. Develop contingency procedures and update them during development and operations as new information makes them obsolete.

5.8.2.9 Operations-Test-Bed Environment

- If an activity is important and uncertain enough to test in a test bed, then require all subsystems with major involvement in it to review the test results.
- The test-bed configuration should be as flight-like as possible, and differences must be completely understood by the operations team.

5.8.2.10 Single-String Teams

- Build in human redundancy.
- Allocate funds for training and mentoring. Identify this as a major risk if the budget will not allow additional staffing.

5.8.2.11 External Communications. Define and maintain clear lines of communication to management and to the news media. Communicate the probable outcome of critical events and their impact clearly to JPL, Headquarters, and the media.

5.8.2.12 Science in a Technology-Validation Mission. Speak clearly as a project, with one voice, to ensure that external expectations match priorities. Project, JPL, and Headquarters must be in agreement on mission-success criteria.

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ADDITIONAL RESOURCES

1. M. I. Herman, S. Valas, W. Hatch, C.-C. Chen, S. H. Zingales, R. P. Scaramastra, L. R. Amaro, M. D. Rayman, "DS1 Telecommunication Development," SSC98-IV, *Utah Small Satellite Conference*, September 1, 1998.

2. *Basics of Space Flight*, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California. This is a training module designed primarily to help JPL operations staff identify the range of concepts associated with deep-space missions and grasp the relationships these concepts exhibit for space flight. It also enjoys growing popularity among high school and college students, as well as faculty and those everywhere who are interested in interplanetary space flight. Its major sections are

Environment, Flight Projects, and Operations:
http://www2.jpl.nasa.gov/basics/toc.php (accessed February 21, 2013)

3. Solar activity and space weather information:

- http://www.spaceweather.com/ (accessed February 21, 2013)
- http://www.nrl.navy.mil/accomplishments/solar-lunar-studies/lasco/ (accessed February 21, 2013)
- http://www.sec.noaa.gov/SWN/ (accessed February 21, 2013)