Small Deep Space Transponder (SDST) DS1 Technology Validation Report

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EXTENDED ABSTRACT

The small deep space transponder (SDST) is a Level-1 technology validation objective of the New Millennium Deep Space 1 (DS1) mission. The SDST was developed as a replacement for the Cassini deep space transponder (DST) and supports the radio frequency transmit, receive, and radio metric functions, as did previous transponders. Additionally, the SDST provides significantly greater functional integration by combining the command detection unit (CDU) and telemetry modulation unit (TMU) in one assembly. The integrated design allows for smaller size, mass, and power consumption of the telecom subsystem compared to the previous generation of hardware. Furthermore, the SDST is the first Ka-band capable deep space transponder. Previous Ka-band capable missions, such as Mars Observer (MO), Mars Global Surveyor (MGS), and Cassini, have relied on either an external frequency translator or a frequency multiplier to provide the Ka-band downlink. The SDST provides full support of Ka-band downlink functions, including telemetry modulation, and radio metrics (coherent Doppler, ranging, and differential one-way ranging [DOR]).

The development of the SDST was performed by Motorola Inc., Scottsdale, AZ, under funding from a JPL multimission consortium. Developed over a 3-year span at a cost of $10.4 million (including non-recurring engineering and flight unit costs), the SDST development process is a model for the better-faster-cheaper development paradigm. Key technologies enabling the SDST design include: radio frequency integrated circuit (RFIC), advanced high frequency multichip modules (MCMs), and 70,000-gate complimentary metal oxide semiconductor (CMOS) application specific integrated circuits (ASICs), that implement the bulk of the receiver and telemetry modulation functions. Some of the design (down-conversion frequency scheme, dialectic resonator oscillators [DROs]) were derived directly from the Cassini DST, while others, such as the MCMs and ASICs, were new developments. The mixture of inherited technology and new development shortened the design cycle and lowered the development cost.

A high firmware content was implemented in the SDST's digital signal processing module, which was designed to work in X-band deep space, S-band Spaceflight Tracking and Data Network (STDN) facilities, and S-band Space Ground Link System (SGLS) transponders. The high firmware content enables many optional capabilities to be provided with only firmware changes, and allows specific tailoring for each mission. Particular attention was paid during development to ensure that the SDST provides flexible control in software. This feature was important for the multimission consortium, where different spacecraft designs may dictate slightly different control interfaces. Transponder modes, such as the telemetry and ranging modulation indices, telemetry subcarrier frequency, and convolutional coding type, are user-controllable during mission operation. Other functions, such as the carrier-tracking loop bandwidth and automatic uplink acquisition, are firmware options. Furthermore, the SDST design accommodates interface with the spacecraft avionics via either a MIL-STD-1553, MIL-STD-1773, or RS422 serial bus, using the 1553 protocol. This design allows future flight users maximum flexibility in selecting the system architecture.

This report summarizes the results of DS1's in-flight technology validation activities related to the SDST. These activities were designed to show that the intended functions of the transponder can be achieved under the operating environment in space. Specific in-flight checkout activities were designed to exercise the transponder through different operating modes. Relevant performance data were collected both onboard by the flight system and on the ground by monitoring Deep Space Network (DSN) stations. Additional validation data were obtained through routine operations of the spacecraft by thoroughly monitoring the telecom-link performance and relevant SDST performance data. All SDST functions for uplink, downlink, and radio metric measurements were successfully validated, including the optional Ka-band downlink. In some cases, such as frequency stability measurements, the in-flight checkout activity also provided measurements of SDST performance in the actual operating environment not achievable with ground-based testing. Specifically, the in-flight technology validation activities focused on the following performance criteria:

Uplink:

- Uplink carrier receiver acquisition.
- Command data rate and command threshold.
- Carrier-tracking and uplink power measurements.

Downlink:

- Verification of telemetry encoding and carrier modulation.
- Verification of the transition between two-way coherent and one-way modes.
- Validation of the phase-modulator performance model.
- Validation of the Ka-band exciter technology and its associated performance characteristics.
- Validation of beacon tone generation.

Radio metrics:

- Measurement of the frequency stability of the DS1 auxiliary oscillator under in-flight temperature conditions.
- Verification of coherent carrier-tracking performance.

- Verification of the X/Ka-band relative carrier-tracking performance.
- Verification of the X/Ka-band ranging functions.

Although not strictly an SDST validation objective, the availability of a stable Ka-band downlink signal from DS1 permitted a direct verification of the Deep Space Network's operational readiness at Ka-band. The DS1 Ka-band downlink was used to:

- Demonstrate dual-band (X/Ka) end-to-end telemetry flow from a spacecraft to the DS1 Mission Support Area (MSA).
- Demonstrate the capability to generate necessary station predicts for Ka-band tracking.
- Demonstrate station capability to perform radio metric tracking (Doppler and ranging) on the Ka-band downlink.
- Verify X/Ka-band radio metrics performance.
- Measure Ka-band system noise temperature, which compares favorably with the model.
- Demonstrate DSS-25 capability to accurately point the 34-m antenna using blind pointing.

The in-flight checkout activities and ongoing flight validation of the SDST provided confidence in the transponder design. With successful flight validation and experience gained through mission operations, the risk of using the transponder design for future missions has been substantially reduced.

Subsequent to a successful DS1 flight validation, the design of the SDST has been enhanced to remove some of the operational idiosyncrasies due to the nonlinearity of the phase modulator and the changes in the receiver best-lock frequency. The current generation of SDST, scheduled to be flown on the Mars 01 and Space Infrared Telescope Facility (SIRTF) missions, has incorporated these changes. Furthermore, unlike the DS1 SDST, which functioned only with single-string command and data handing (C&DH), the Mars 01 SDST supports dual-string cross strapping with the C&DH subsystem. These performance improvements and this added functionality, together with DS1's in-flight validation, make use of the SDST truly low-risk for future flights.

Small Deep Space Transponder *Fact Sheet*

Key Features

- Deep Space Network Compatible
- X-band Receiver, X-band and Ka-band Exciters
- 2.5 dB Noise Figure (Nominal @25 o C)
- -156 dBm Receiver Threshold
- Temperature Compensated Receiver VCO
- Low Exciter Spurious, Phase Noise and Allan Deviation
- Radio Science Mode (USO Input Available)
- 40 ns Maximum Ranging Delay Vairation
- 3 ns Maximum Carrier Delay Variation
- Bus Interface - Mil-Std 1553/1773 Options
- External Power Converter Synchronization Capability
- Operates Under Launch Environments
- Radiation and SEU Resistant
- Internal Telemetry Modulation Encoder
- Internal Command Detector
- Mounting in Either of Two Axes

Performance Characteristics

Transponder	
X-band Uplink Frequency Range	7.145–7.235 GHz
X-band Downlink Frequency Range	8.400–8.450 GHz
X-band Tx/Rx Ratio	880/749
Ka-band Downlink Frequency Range	31.800–32.300 GHz
Ka-band Tx/Rx Ratio	3360/749
Carrier Delay Variation	< 3ns p-p
Ranging Delay Variation	< 40 ns p-p

X-band Receiver	
Noise Figure	<2.5 dB @ 25° C
Carrier Tracking Signal Range	–70 to –156 dBm
Carrier Loop BW (2-sided)	20 Hz nom. At threshold, expands to 200 Hz strong signal
Carrier Loop Damping Factor	0.5 @ 0 dB loop S/N
Tracking Range	>200 kHz about f0
Cmd Subcarrier Frequency	16 kHz
Cmd Subcarrier Mod Index	0.2–1.3 rad pk.
Ranging Filter Type	3-pole Chebychev
Ranging Filter BW	1700 kHz nominal
Temperature Stability	+/- 6.5 ppm (–40 to +50° C)

Exciters (X- and Ka-band)	
X-band Output Power	+12 dBm @ 25° C
X-band Residual Phase Noise	–20 dBc/Hz at 1 Hz offset –80 dBc/Hz at 100-100 kHz
Ka-band Output Power	+4.0 dBm @ 25° C
Frequency Stability, 0 to +50° C	5.0 ppm
Spurious and Harmonic Outputs	<–50 dBc
Phase Mod Linearity	10% to 2.0 rad pk.
Tlm Format	NRZ-L
Tlm Convolutional Encoding	15-1/2, 15-1/4, 15-1/6, 7-1/2
Tlm Subcarrier	Programmable, 2kHz to 4 MHz sq wave.
Tlm Phase Deviation	0 to 90° peak
Ranging Modulation Index	Selectable, 2.1875, 4.375, 8.75, 17.5, 35° pk.
Differential One-way Ranging Tones	19.2 MHz, Coherent with carrier
Direct Modulation Mode	Available
Bi-ϕ -L Coding	Available

	SDST	Mars Pathfinder Equivalent
Mass	3 kg	TMU: 0.435 kg DST: 4.000 kg CDU: 0.365 kg Ka-band Exciter: N/A
Power	12.9 W	TMU: 1.4 W DST+CDU: 13.1 W

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ABSTRACT

This report summarizes the in-flight technology validation results for the small deep space transponder (SDST). Specific in-flight checkout activities were designed to exercise the transponder through different operating modes; relevant performance data were collected both onboard by the flight system and on the ground by monitoring Deep Space Network (DSN) stations. Additional validation data were obtained through routine operations of the spacecraft by thoroughly monitoring the telecom-link performance and relevant SDST performance data. All SDST functions for uplink, downlink, and radio metric measurements were successfully validated under the intended operating environment, including the optional Ka-band downlink.

1.0 INTRODUCTION

The small deep space transponder (SDST) is a Level-1 technology validation objective of the New Millennium Deep Space 1 mission (DS1). The SDST was developed as a replacement for the Cassini deep space transponder (DST) and supports the radio frequency transmit, receive, and radiometric functions, as did previous transponders. Additionally, the SDST provides a significantly greater functional integration by combining the command detection unit (CDU) and telemetry modulation unit (TMU) in one assembly. The integrated design allows for smaller size, mass, and power consumption of the telecom subsystem compared to the previous generation of hardware. A comparison of mass and power consumption of the SDST with the Mars Pathfinder (MPF) telecom subsystem is shown in Table 1.

Table 1. Comparison of SDST Mass and Power Consumption with those of Mars Pathfinder (MPF) Telecom Components with Equivalent Functions

	DS1	Mars Pathfinder (equivalent function)
Mass	3 kg	TMU: 0.435 kg DST: 4.000 kg CDU: 0.365 kg
Power	12.9 W	TMU: 1.4 W DST+CDU: 13.1 W

The development of the SDST was performed by Motorola Inc., Scottsdale, AZ, under funding from a JPL multimission consortium. Developed over a three-year span at a cost of less than $10.4 million (including nonrecurring engineering (NRE) and flight unit costs), the SDST development process is a model for the better-faster-cheaper development paradigm.

Key technologies enabling the SDST design include the radio frequency integrated circuit (RFIC), advanced high-frequency multichip modules (MCMs), and 70,000-gate complimentary metal-oxide semiconductor (CMOS) application specific integrated circuits (ASICs), that implement the bulk of the receiver and telemetry modulation functions. Some of the designs (downconversion frequency scheme, dielectric resonator oscillators (DROs)) were derived directly from the Cassini DST, while others, such as the MCMs and ASICs, were new developments. This mixture of inherited technologies and new developments shortened the design cycle and lowered development costs. A summary of key SDST technologies and their design heritage is shown in Table 2.

A high firmware content was implemented in the SDST's digital signal processing module, which was designed to work in X-band deep space, S-band NASA Spaceflight Tracking and Data Network (STDN) facilities, and S-band USAF Space Ground Link System (SGLS) transponders. The high firmware content enables many optional capabilities to be provided with only firmware changes, and allows specific tailoring for each mission. Particular attention was paid during development to ensure that the SDST provides flexible control in software. This feature was important for the multimission consortium, where different spacecraft designs may dictate slightly different control interfaces. Transponder modes, such as the telemetry and ranging modulation indices, telemetry subcarrier frequency, and convolutional coding type, are user-controllable during mission operation. Other functions, such as the carrier-tracking loop bandwidth and automatic uplink acquisition, are firmware options. Furthermore, the SDST design accommodates interface with the spacecraft avionics via either a MIL-STD-1553, MIL-STD-1773, or RS422 serial bus, using the 1553 protocol. This design allows future flight users maximum flexibility in selecting the system architecture.

Table 2. SDST Technologies and their Design Heritage

Key Technologies	SDST Heritage
Frequency scheme	Cassini
Dielectric resonator oscillators (DROs)	Cassini (smaller)
DRO lock technique	New (sampling phase detectors (SPDs))
Ceramic first intermediate frequency filter	Cassini
Preselector	Cassini
Voltage-controlled oscillator (VCO) and Auxiliary Oscillator (AuxOsc)	Cassini
Ka-band multiplier	JPL heritage
Low-noise RFIC	Motorola heritage
Power supply design	Cassini
RFIC phase modulator	New (JPL small business innovative research (SBIR))
RF board manufacturing technique	Duroid boards bonded (not fused)
Low-temp cofired ceramic MCMs	Motorola heritage
Command and control interface	1553, 422, 1773
Uplink/downlink interface	Cassini
Mechanical packaging	Cassini

The capabilities of the SDST include:

- X-band receiver/downconverter capable of carrier tracking at or below –156 dBm.
- Command detector unit function.
- Telemetry modulation function.
- X- and Ka-band exciters.
- Beacon mode operation.
- Coherent and noncoherent operation choice.
- X- and Ka-band ranging.
- Differential one-way ranging (DOR) for both X-band and Ka-band.
- Command and Data Handling (C&DH) communication via 1553.
- Data interface via RS422.
- External ports for temperature sensors.
- External port for an analog signal.

All SDST functional capabilities were verified on the DS1 mission, including the optional Ka-band downlink. This report summarizes the results of DS1's technology validation activities related to the SDST. With successful flight validation and experience gained through mission operations, the risk of using the transponder design for future missions has been substantially reduced. Indeed, the SDST is currently in full production for the Mars 2001 and Space Infrared Telescope Facility (SIRTF) missions.

2.0 KEY SDST FUNCTIONS

The SDST is the first deep space transponder using digital receiver technology. The use of digital technology allows for tighter integration of functions and more flexibility in their control. Additionally, the SDST is the first Ka-band-capable deep space transponder. Previous Ka-band-capable missions, such as Mars Observer (MO), Mars Global Surveyor (MGS) and Cassini, rely on either an external frequency translator or frequency multiplier to provide the Ka-band downlink. The SDST provides full support of Ka-band downlink functions, including telemetry modulation and radio metrics (coherent Doppler, ranging, and DOR).

The design of SDST supports the following functions:

1. Uplink-related functions:
   - Receive and demodulate the X-band uplink carrier.
   - Monitor for self or false lock.
   - Provide an uplink automatic gain control (AGC) for receiver power measurement.
   - Receive and demodulate the command subcarrier and data stream.

2. Downlink-related functions:
   - Provide the capability of an noncoherent downlink with auxiliary oscillator or ultrastable oscillator (USO).
   - Perform convolutional encoding and subcarrier modulation of downlink telemetry.
   - Perform X- and Ka-band carrier modulation of downlink with variable modulation indices.
   - Provide independent control of X- and Ka-band downlinks.
   - Provide differential one-way ranging (DOR) modulation on downlink.
   - Generate a beacon tone.

3. Radio metrics:
   - Provide stable one-way downlink for use when the transponder is not in lock with the uplink.
   - Support two-way coherent operations by phase locking downlink with the uplink signal carrier.
   - Demodulate uplink ranging modulation and remodulate ranging signals on the downlink.

4. Collect analog engineering status within the subsystem

A summary of SDST functions and relevant requirements can be found in the SDST detailed functional specifications [1].

3.0 SDST VALIDATION OBJECTIVES

The SDST design has been subjected to a series of verification and validation tests before and after launch. Before launch, the SDST was subjected to a series of functional verification tests. These tests were intended to verify functional specifications and performance requirements. Additionally, continuous checkout and monitoring of transponder performance throughout the integration and test (I&T) process ensured that the performance and functional specifications of the transponder were met.

In contrast to the verification tests, the technology validation activities were designed to ensure that the intended functions of the transponder could be achieved by the design. This was achieved through a series of Deep Space Network (DSN) compatibility tests on the ground, several planned in-flight checkout (IC) activities, and monitoring of transponder/downlink performance throughout normal mission operations. The DSN compatibility tests were conducted using the Compatibility Test Trailer (CTT) at Motorola and at the Kennedy Space Center (KSC). Additional compatibility tests were conducted at JPL using the DSN Development and Test Facility. These tests validated the Level-3 system requirements to ensure flight-ground compatibility and key functions of the telecommunications subsystem. The results of the testing are summarized in a DSN compatibility test report [2].

After launch, the technology validation activities were designed to show that the intended functions of the transponder could be achieved by the design under a relevant operating environment. To that end, several in-flight checkout (IC) activities were planned specifically to verify and validate that the SDST reliably performed its required uplink, downlink, and radio metric functions with the tracking stations. In some cases, such as frequency stability measurements, the in-flight checkout activity also provided measurements of SDST performance in the actual operating environment, measurements not obtainable through ground-based testing.

The objectives of flight validation tests for each of the uplink, downlink, and radio metric functions are summarized below.

3.1 Uplink Functions

The receiver receives and demodulates X-band uplink. The SDST implements a hybrid analog-digital receiver. The uplink signal is first passed through the downconverter stages. The receiver also performs the wide-band AGC function. The downconverted intermediate-frequency signal is then digitized at a rate of 4/3 F1 (approximately 12.6 megahertz). The rest of the receiver functions are implemented in the digital ASIC, which includes the narrow-band AGC, the carrier demodulation, and the command data demodulation functions. The digital receiver also derives the phase error between the receiver voltage-controlled oscillator (VCO) and the incoming radio frequency (RF) carrier. This error signal is then filtered and used to drive the VCO to close the carrier phase-tracking loop.

Once the carrier signal is demodulated, the command subcarrier synchronization and demodulation is performed by the command detector unit (CDU) within the digital ASIC. The SDST CDU uses a digital implementation similar to the Cassini/Mars Observer CDU. The CDU outputs the command data, clock, and a lock-detect indicator to allow for subsequent decoding of the command uplink by the spacecraft avionics.

In-flight validation objectives related to the uplink functions include validation of the following functions:

- Uplink carrier receiver acquisition.
- Command data rate and command threshold.
- Carrier-tracking and uplink power measurements.

3.2 Downlink Functions

The SDST contains two independently controllable exciters: one for X-band downlink and one for Ka-band downlink. These two downlinks are provided with independent subcarrier generator and convolutional encoder and can be configured to transmit independent downlinks. For the DS1 SDST, the X-band and Ka-band share common telemetry and clock inputs (since there is only a single-string avionics) and the two streams are configured for the same encoding rate.

In-flight validation objectives for the downlink functions include:

- Verification of telemetry encoding and carrier modulation.
- Verification of the transition between two-way coherent and one-way modes.
- Validation of the phase modulator performance model.
- Validation of the Ka-band exciter technology and its associated performance characteristics.
- Validation of beacon tone generation.

The phase modulator performance model is particular to the DS1 SDST, which exhibited nonlinear phase modulation characteristics under test. The nonlinearity results in a large intermodulation loss when both ranging and telemetry modulations are applied. A nonlinear loss model was constructed prior to launch using ground-test data; in-flight validation of the phase modulator performance model verified the validity of the performance model.

3.3 Radio Metrics
The SDST supports radio metric functions by providing two-way coherent transponding of the uplink carrier and by providing the turn-around ranging capability. These functions are similar to previous deep space transponders except, of course, that the SDST supports radio metric measurements in both the X-band and the Ka-band.

In-flight validation objectives for the radio metric functions include:

- Measurement of the frequency stability of the DS1 auxiliary oscillator under in-flight temperature conditions.
- Verification of coherent carrier-tracking performance.
- Verification of the X/Ka-band relative carrier-tracking performance.
- Verification of the X/Ka-band ranging functions.

3.4 Analog Engineering Telemetry Collection
In addition to reporting the internal status of the SDST, the external analog telemetry interface built into the SDST is also used to collect external analog engineering status from the telecom subsystem. Four (4) analog voltages and four (4) external temperature sensor interfaces are provided by the SDST. For the DS1 radio frequency subsystem (RFS), these input channels are mapped to the following SDST analog measurement channel assignments:

Ext channel	Measurements
1	Ka-band power amplifier (KAPA) input power monitor
2	KAPA output power monitor
3	X-band power amplifier (XPA) input power monitor
4	Detector amplifier module (DAM) secondary voltage

Ext temp sensor	Location
1	DAM temperature
2	SDST sidewall temperature
3	KAPA input detector temp
4	KAPA output detector temp

Collection of these engineering telemetry values, especially those related to the Ka-band power amplifier, were intended to support the KAPA technology validation activity, which will be described in a separate report.

3.5 Ka-band Readiness Demonstration
Although not strictly an SDST validation objective, the availability of a stable Ka-band downlink signal from DS1 permitted a direct verification of the Deep Space Network's operational readiness at the Ka-band. The DS1 Ka-band downlink was used to:

- Demonstrate dual-band (X/Ka), end-to-end telemetry flow from a spacecraft to the DS1 Mission Support Area (MSA) (DS1-g).
- Demonstrate the capability to generate necessary station predicts for Ka-band tracking.
- Demonstrate the station capability to perform radio metric tracking (Doppler and ranging) on the Ka-band downlink.
- Verify X/Ka-band radio metrics performance.
- Demonstrate the Deep Space Network Station 25 (DSS-25) capability to accurately point the 34-m antenna using blind pointing.
- Measure the Ka-band system noise temperature, which compares favorably with the model.

Additionally, the DS1 Ka-band downlink was used to support characterization of 70-m antenna pointing accuracy at the Ka-band.

4.0 SDST Validation Process

For in-flight checkout of the transponder, a series of validation objectives were identified. Each SDST validation objective, summarized individually in Table 3, requires the active participation of the ground tracking station. Depending on the purpose of the activity, the station provided an X-band uplink carrier and received either an X-band downlink or simultaneous X-band and Ka-band signals from the spacecraft.

In most SDST flight-validation activities, the power level of the carrier or the signal-to-noise ratio (SNR) of the command, telemetry, or ranging data was collected and compared with the values predicted on the basis of the DS1 communications link models. Some of the data are available from SDST (for example, uplink-related measurements) while others are available through DSN station monitoring.

Since DS1 supports both Ka-band and X-band downlinks, a significant portion of the validation activities need to be performed at both the Ka-band and the X-band. However, the Ka-band horn antenna on DS1 is directive and must be pointed to Earth in order to conduct Ka-band related validation activities. The pointing constraints of the spacecraft, therefore, limit the times at which Ka-band activities can take place. During the initial checkout phase, the Miniature Imaging Camera and Spectrometer (MICAS) pointing constraints resulted in delaying the Ka-band related activities until 25 days after launch (L+25D). In contrast, X-band validation activities can be conducted using the X-band low-gain antenna (LGA) and are not constrained by spacecraft attitude. A second operational constraint on Ka-band activities is that the Goldstone tracking complex has the only DSN station (DSS-25) capable of receiving Ka-band transmissions. Therefore, technology validation tests involving Ka-band downlinks were conducted over Goldstone sites only.

Table 3. SDST Validation Objectives

Objectives	Pre-launch	In-flight Checkout	Tests
Receiver best lock frequency	Measure	Validate	Routine ops
Signal acquisition range and rate	Measure	Validate	Routine ops
Self/false lock characterization	Measure	Validate	Routine ops
Uplink command reception	Measure	Validate	Routine ops
Uplink power measurements	Characterize	Validate	Routine ops
Telemetry encoding and modulation	Test	Validate	Routine ops, Xtlm
Noncoherent mode operation	Test	Validate	Routine ops
Phase modulator performance	Characterize	Validate	Routine ops, Xrange
Noncoherent carrier frequency stability	Test	Measure	Xstable
Coherent Doppler tracking performance	Test	Validate	Routine ops
Ranging functional verification	Test	Validate	Xrange Krange
Beacon mode (a separate experiment)	Test	Validate	Xtone
Analog engineering telemetry sampling	Test	Validate	Routine ops

4.1 Receiver Best Lock Frequency

A predictable best lock frequency (BLF) is important for deep space mission operations. An accurate receiver BLF predict would allow the ground station to provide an uplink acquisition sweep over a sufficiently narrow range to rapidly acquire the SDST. During ground testing, it was discovered that the transponder's best lock frequency is a sensitive function of temperature. Over the in-flight allowable range, the receiver BLF can vary by as much as ±25 kHz from its predicted frequency profile. This fact was verified with in-flight measurement (see Figure 1). Subsequent development of the SDST for Mars 2001 missions has significantly reduced the amount of BLF drift compared to that of the DS1 SDST.

4.2 Signal Acquisition Range and Rate

Even though ground/flight testing of the transponder showed significant BLF variation, ground testing of the SDST also showed that the transponder can be acquired at a much higher rate than could previous transponders. Shown in Figure 2 is a plot of the acquisition rate as a function of uplink power level measured during the final DSN compatibility test at KSC prior to launch.

Based on the test data, it was recommended that a frequency sweep range of ±30 kHz be used. A sweep rate of 900 Hz/s was recommended at power levels above −130 dBm and a sweep rate of 300 Hz/s was recommended at power levels less than −130 dBm. The combined sweep rate/range resulted in a sweep-acquisition time of less than 400 seconds in the worst case, and 130 seconds at higher power levels.

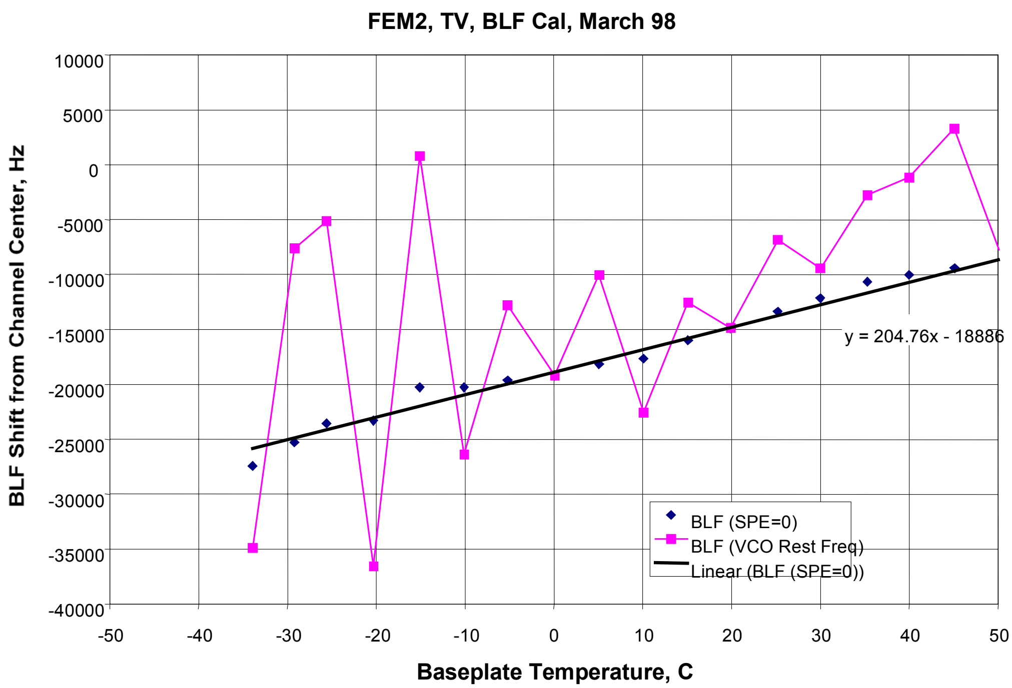
The SDST acquisition performance was validated on every track where coherent downlink is required. Over the mission lifetime of a year, there has been no uplink acquisition failure due to the transponder.

4.3 Self and False Lock

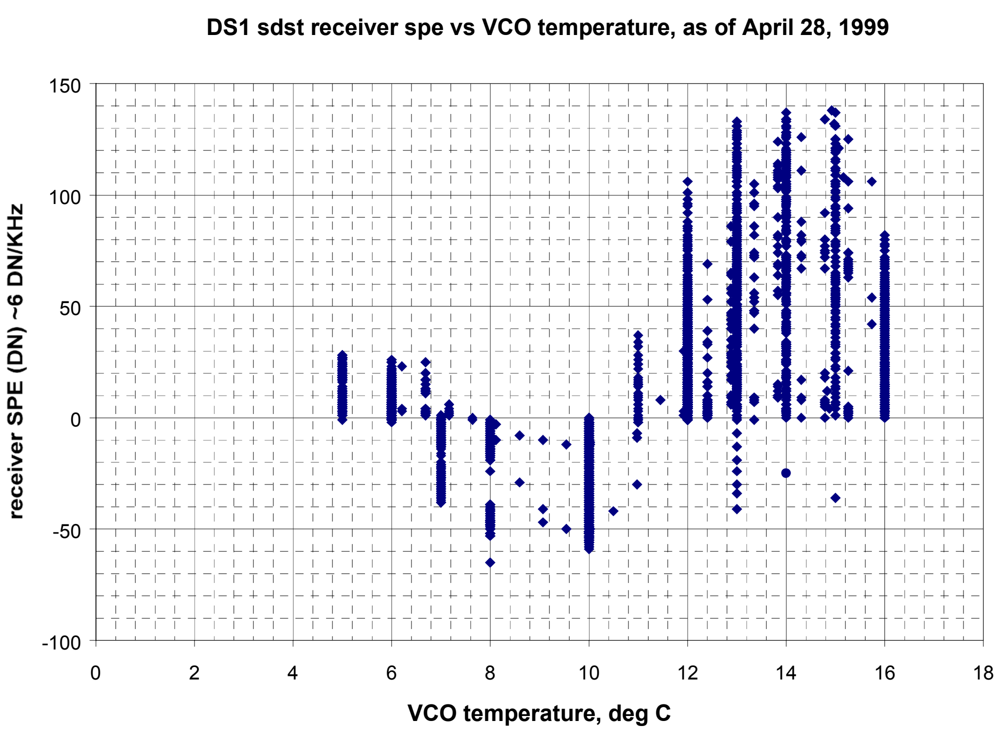
It is important that the receiver exhibit no self or false lock events. The absence of such events is critical for successful mission operations because false/self lock can prevent the receiver (SDST) from receiving a valid command uplink, rendering the spacecraft uncommandable.

The SDST provides frequent updates of its internal state. This status information is available to the spacecraft through the 1553-bus transactions for health monitoring purposes. Additionally, the SDST provides an event counter that registers every change in state of the SDST. Should an unexpected change of state occur, the event counter will advance incrementally. An unexpected lock-up and subsequent drop-lock of the carrier, for example, will advance the receiver event counter by 3 increments.

The SDST event counter was closely monitored throughout the IC period. During that period, an attempt was made to correlate incremental changes in the event counter with identifiable state changes. No self/false lock events or unexpected state changes were detected for the SDST during either ground testing or in-flight operations.



(a)



(b)

Figure 1. (A) Receiver Best Lock Frequency (BLF) Variation as a Function of Voltage-controlled Oscillator (VCO) and Baseplate Temperature During Ground Testing (A), and (b) Measured In Flight

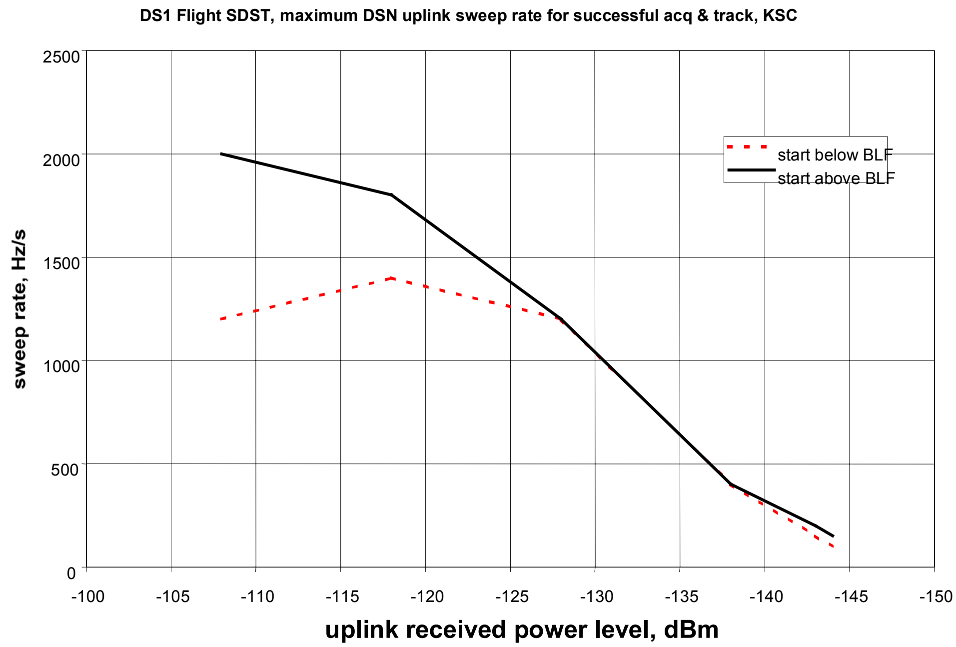


Figure 2. Measured SDST Sweep Rate at KSC Testing

4.4 Uplink Command Reception

The SDST was required to be commandable at each of the following data rates: 2000, 1000, 500, 250, 125, 62.5, 31.25, 15.625, and 7.8125 b/s. Uplink command reception at these rates was to be demonstrated by X-band uplink (XUPL) testing, as well as by routine commanding during operations. Due to project time constraints, XUPL was not completed. Instead, routine commanding was performed at all data rates except 31.25 b/s. The data rate during routine mission operations was selected based on the supportable uplink rate during a particular day (based on the spacecraft orientation, the antenna selected, the Earth-spacecraft range, and the ground transmitter power). Since DS1 mission operations require the spacecraft to employ different antennas at different spacecraft orientations, most of the required SDST data rates were verified in flight (see Table 4).

In-flight verification of command threshold was not performed because of lingering project concern about deliberately sending below-threshold command data to the flight software. The possibility of a resulting spacecraft safing could not be ruled out and the mission timeline had no margin to recover from safing. Although no command tests have been done, these command thresholds have been verified indirectly: during flight operations, the predicted command rate was always successful. Shown in Table 5 are the predicted thresholds that are used routinely to determine what command rate can be used on a particular DSN pass. The successful uplink activities provide indirect confirmation that the receiver noise floor had not been degraded.

Table 4. SDST Command Rates Verified In Flight to Date

Command Bit Rate, b/s	Verified in Flight Operations?	Operational Signal Level, Pt, dB (1 mW)
2000	Yes	–114
1000	Yes	–124
500	Yes	–120
250	Yes	–131
125	Yes	–128
62.5	Yes	–132
31.25	Not yet	N/A
15.625	Yes	N/A
7.8125	Yes, used when recovering from fault protection	–140

4.5 Uplink Power Measurements

Uplink carrier threshold was indirectly verified using the uplink residuals measurements: the SDST measures the uplink signal-to-noise ratio and telemeters the measured data (carrier lock accumulator). This data is then compared to the predicted uplink carrier power and predicted system noise temperature of the receiver. The results provide an indirect confirmation of the receiver sensitivity and carrier threshold.

Table 5. Command Threshold Table as Predicted

Command Bit Rate, b/s	Mod Index, Radians	Uplink Carrier Suppression, dB	Threshold Pt/No (Ranging OFF), dB-Hz	Threshold Pt/No (3 dB Uplink Ranging Suppression), dB-Hz
2000	1.2	–3.5	47.55	50.6
1000	1.2	–3.5	44.3	47.3
500	1.2	–3.5	41.2	44.2
250	1.2	–3.5	38.5	41.5
125	1	–2.3	36	39
62.5	1	–2.3	32.7	35.7
31.25	1	–2.3	30	33
15.625	0.9	–1.9	27.5	30.5
7.8125	0.8	–1.4	26.2	29.2

Link residuals may be due to a modeling error (antenna gain or system noise temperature), operating conditions (spacecraft deadbanding), or changes in system performance. Shown in Table 6 are the uplink residual data compiled for passes when the high-gain antenna (HGA) was in use and when the spacecraft was Earth-pointed (in order to eliminate uncertainties due to spacecraft attitude). It is seen that the uplink residual is in reasonable agreement with the prediction. The larger standard deviation (two sigma is 1.2 dB) shows that the project should plan its link capability based on a link margin of at least 2 dB (3 sigma).

The uplink residuals served to provide only indirect verification of the SDST uplink threshold. Ongoing activities to monitor the uplink residuals will be required to monitor for long-term trend.

4.6 Telemetry Encoding and Modulation

The SDST is designed to support multiple telemetry encoding modes using an externally supplied data stream and clock signal up to 4.4 megasymbols per seconds. The external clock signal supplied needs to be coherent with the data stream and at a rate equal to the symbol coding rate selected (e.g., at multiples of the data rate). Additionally, the SDST supports both subcarrier modulation and direct carrier modulation (see SDST specifications [1]).

Full validation of telemetry encoding and modulation mode was not performed due to configuration limits of the spacecraft and DS1 downlink strategy. The available clock rate from avionics (the Reed Solomon downlink (RSDL) ASIC) supports only clock rates that are 1×, 2×, and 6× the data rate. Additionally, DS1's flight avionics system (hardware plus software) supports a maximum telemetry data rate of only 19908 b/s. The downlink strategy for DS1 requires that (7,1/2) and (15,1/6) codes be supported for subcarrier modulation mode only (no direct carrier modulation). The (7,1/2) code was used during initial acquisition (2100 b/s) and when the spacecraft was in one of the several standby modes. Most of the mission was conducted using the (15,1/6) code.

Table 6. Uplink Residuals as Measured In Flight

Time	DSS	Uplink Residual (Actual-Predict)	Spacecraft Antenna
1999-009 02:25-07:59	25	+0.8	HGA
1999-009 17:00-010 02:09	65	+0.8	HGA
1999-012 17:40-013 00:09	65	+0.7	HGA
1999-013 16:55-23:36	65	+0.7	HGA
1999-014 16:55-015 03:44	65	–0.2	HGA
1999-016 3:25-07:39	15	+0.7	HGA
1999-016 16:40-017 00:29	65	+0.3	HGA
1999-017 00:25-05:44	15	+0.7	HGA
1999-017 16:40-018 00:44	65	+0.3	HGA
1999-018 00:25-09:29	15	+0.3	HGA
1999-019 02:55-07:44	25	–1.1	HGA
1999-021 03:10-07:34	25	–0.6	HGA
1999-022 01:10-09:59	15	+0.7	HGA
1999-022 10:55-15:44	34	–0.3	HGA
1999-022 19:40-023 00:24	54	+1.7	HGA
1999-023 16:25-23:44	65	0.	HGA
1999-024 02:55-11:44	25	+0.03	HGA
1999-024 19:40-025 00:09	54	+0.13	HGA
1999-025 03:25-11:14	25	+0.15	HGA
Average		0.3 dB	
Standard deviation		0.6 dB	

4.6.1 Telemetry Data Rate Verification (X- and Ka-band, Coherent Mode)—Telemetry encoding and modulation was verified for SDST using the 19 planned data rates for both X-band and Ka-band downlinks at the planned encoding modes (Table 7). The activity (Xtlm) was conducted when the SDST was operating in the two-way coherent mode. The SDST provided a convolutionally encoded telemetry data stream at the symbol rate (either (7,1/2) or (15,1/6)) and modulated the symbol stream onto the required subcarrier (either a 25-kHz or 375-kHz square wave). Finally, the SDST modulated this subcarrier plus data onto the RF carrier (either X-band or Ka-band) at the desired modulation index.

All the data rates and both convolutional codes have been validated at X band, not only during Xtlm, but during routine operations at many data rates. At each planned operating rate, the ground station successfully locked onto and decoded the telemetry data stream (at both the X-band and Ka-band) and transmitted the decoded telemetry stream to the DS1 MSA.

Table 7. Telemetry Data Rates Verified In Flight

Data Rate	X Mod Index (DN), Ranging ON	Ka (DN), Ranging ON	Convolutional Code
19908	38	54	(15,1/6)
13272	38	53	(15,1/6)
9480	38	Not used	(15,1/6)
6636	38	Not used	(15,1/6)
4424	38	Not used	(15,1/6)
3150	38	Not used	(15,1/6)
2100	38	40	(15,1/6)
1422	38	45	(15,1/6)
1050	38	44	(15,1/6)
790	38	43	(15,1/6)
600	38	42	(15,1/6)
420	38	41	(15,1/6)
300	37	39	(15,1/6)
200	36	38	(15,1/6)
150	36	37	(15,1/6)
79	33	33	(15,1/6)
40	30	27	(7,1/2)
10	23	16	(7,1/2)

4.6.2 X-band Telemetry Link Performance (Link Residuals)—In addition to verifying that the SDST can effectively modulate the downlink, the X-band downlink performance has also been verified by tracking the link residuals over multiple passes. Shown in Table 8 are the X-band downlink performance values versus the expected downlink signal values (carrier power and symbol SNR) measured using the block-V receiver (BVR). Spacecraft deadbanding (an attitude control error that varies between ±1 degree) can result in a significant degradation of the downlink (as much as several tenths of dB). This deadband effect has been removed from the data by using the peak signal level for each pass. However, bad weather—system noise temperature variation—has not been taken into account.

The average symbol SNR (SSNR) residual is comparable to the carrier power residual (+0.5 dB). Furthermore, when adjusted for system noise temperature (SNT), the residual is only 0.1 dB. This indicates that the link model (total power, modulation index, as well as downlink signal quality) is sufficiently accurate. The measured residual spread (0.4 dB, one sigma) with SNT and spacecraft deadband effects removed provides a measurement of the uncertainty in link performance. These data are useful for future missions and can be used to estimate the effective link margins required.

4.7 Noncoherent Mode Operation

The DS1 SDST typically operates in the coherency-enabled mode with downlink driven by a VCO. When no uplink signal is detected (no receiver lock) or when the SDST is configured for coherency-inhibited mode (two-way noncoherent mode), the downlink is driven by an auxiliary oscillator (AuxOsc). Validation of noncoherent mode operation must:

a. Validate that the SDST can successfully generate a noncoherent downlink signal driven by the AuxOsc. The SDST was commanded to the noncoherent mode during initial acquisition and standby modes and during certain technical validation activities (like Xstable and beacon mode testing).

b. Validate that the SDST can generate a noncoherent downlink with telemetry modulation. This is the standard operating mode at the beginning of any station pass that does not overlap a previous pass. The station is usually able to acquire one-way downlink telemetry before it locks to the two-way downlink a round trip light time later. Data rates verified during IC activities are shown in Table 9.

c. Validate that the transponder can be successfully commanded out of a coherency-inhibited (two-way non-coherent (TWNC)) mode. Although DS1's standard operating mode is coherency-enabled, the transponder was intentionally set to operate in TWNC mode during launch and when the spacecraft enters standby mode. This is so that there will be a detectable downlink signal even if there is a problem with the uplink. Since launch, the spacecraft has entered standby mode at least six times, and every time the spacecraft was successfully commanded to return to the normal (coherency-enabled) mode.

Table 8. Measured Downlink Telemetry Residuals In Flight

Day of Year and Time	DSS	SSNR	SSNR	SSNR Delta	Pc	Pc	Pc Delta	SNT	SNT	SNT	Adjusted for System Noise Temp (SNT)		
		Actual	Predicted	Actual-Pred	Actual	Pred	Actual-Pred	Actual	Pred	dB Delta	SSNR Delta	Pc Delta	Spacecraft Antenna
1999-009 02:15–07:59	25	7.85	7.15	0.7	–131.2	–131.7	0.5	30	32.5	0.3	0.4	0.2	HGA
1999-009 17:00–010 02:09	65				–131.8	–132.2	0.4	25	32	1.1	–1.1	–0.7	HGA
1999-012 17:30–013 00:14	65	7.2	6.4	0.8	–132.8	–132.75	–0.1	24	30.5	1.0	–0.2	–1.1	HGA
1999-013 16:45–23:41	65	6.75	6.2	0.6	–132.4	–133	0.6	26.5	33.5	1.0	–0.5	–0.4	HGA
1999-014 03:15–07:49	25	6.5	6	0.5	–132.5	–132.85	0.3	30.4	32.8	0.3	0.2	0.0	HGA
1999-015 03:15–08:02	25	6.3	5.8	0.5	–132.6	–133.05	0.5	30	32.5	0.3	0.2	0.1	HGA
1999-016 03:15–07:39	15	6.4	5.85	0.6	–132.75	–133.6	0.8	29	29.3	0.0	0.5	0.8	HGA
1999-016 16:30–017 00:29	65	6.3	5.5	0.8	–133.4	–133.6	0.2	26	30.5	0.7	0.1	–0.5	HGA
1999-017 00:15–05:44	15	5.5	5.65	–0.2	–133.2	–133.65	0.5	29	30	0.1	–0.3	0.3	HGA
1999-017 16:30–018 00:44	65	5.3	5.3	0.0	–133.6	–133.85	0.3	25	30.5	0.9	–0.9	–0.6	HGA
1999-018 00:15–09:29	15	5.9	5.45	0.5	–133.25	–133.8	0.6	29	29.5	0.1	0.4	0.5	HGA
1999-019 02:45–07:39	25	5.25	5	0.3	–133.45	–133.85	0.4	30.7	32.9	0.3	–0.1	0.1	HGA
1999-022 01:00–09:59	15	5.5	4.7	0.8	–133.5	–134.7	1.2	29.25	30	0.1	0.7	1.1	HGA
1999-022 19:30–023 00:24	54	4.7	4.1	0.6	–134.2	–134.7	0.5	31	33.1	0.3	0.3	0.2	HGA
1999-023 16:15–23:45	65	5	4.15	0.9	–134	–135	1.0	30	30	0.0	0.9	1.0	HGA
1999-024 02:45–11:44	25	4.6	4	0.6	–134.25	–135	0.8	30	32.9	0.4	0.2	0.3	HGA
1999-24 19:30–025 00:09	54	4.2	3.7	0.5	–134.7	–135.1	0.4	30	33	0.4	0.1	0.0	HGA
1999-025 03:15–11:14	25	4.45	3.75	0.7	–134.4	–135.05	0.7	30	33	0.4	0.3	0.2	HGA
AVERAGE				0.5			0.5			0.4	0.1	0.1	
MIN				–0.2			–0.1			0.0	–1.1	–1.1	
MAX				0.9			1.2			1.1	0.9	1.1	
Variance, assuming Gaussian				0.0			0.0			0.0	0.1	0.1	
Sigma				0.2			0.2			0.2	0.3	0.4	

Table 9. Encoding Modes/Data Rates Verified in Noncoherent Downlink Mode

Data Rate	Convolutional Code
40	(7,1/2)
2100	(7,1/2)
3150	(15,1/6)
13272	(15,1/6)
19908	(15,1/6)

4.8 Nonlinear Phase Modulator Performance

Because of the intermodulation effect, the SDST's ranging and telemetry-carrier suppression deviates significantly from what the established theory of linear phase modulation would predict. For this reason, DS1's telecom team constructed a special nonlinear phase-modulation-loss model, which was used to predict ranging-induced carrier suppression for the SDST.

The validity of this model was tested on day of year (DOY) 1998-344 when the ranging modulation was applied to the downlink with and without telemetry modulation as part of the Xrange test. The plot of downlink carrier power (Pc) versus time (see Figure 3) shows the carrier suppression at low ranging mod index (17.5°) to be approximately 1.0 dB (Pc= –124.4 dBm for ranging OFF, –125.4 dBm for ranging low at 38 data number [DN]). At 35 degrees ranging mod index and a telemetry mod index setting of 32 DN, the carrier suppression was measured to be 7.6 dB. The contribution from telemetry modulation at 32 DN is 5 dB, based on ground-test data. The ranging induced carrier suppression is, therefore, approximately 2.6 dB at 35 ° ranging modulation setting, which agrees well with pre-flight test data (see Table 10) and shows that the X-band phase modulator has not deviated in performance since pre-launch tests. The pre-flight measurement data are contained in section 2.7.2 of the flyable engineering model (FEM) test report dated 12/18/97.

At Ka-band (see Table 11), the phase modulator is linear, the suppression due to telemetry modulation is modeled as 20*log(cos(telemetry mod index)), and the suppression due to ranging is 20*log(J_0(ranging mod index)). A plot of Ka-band carrier power as a function of time at different ranging mod index settings is shown in Figure 3.

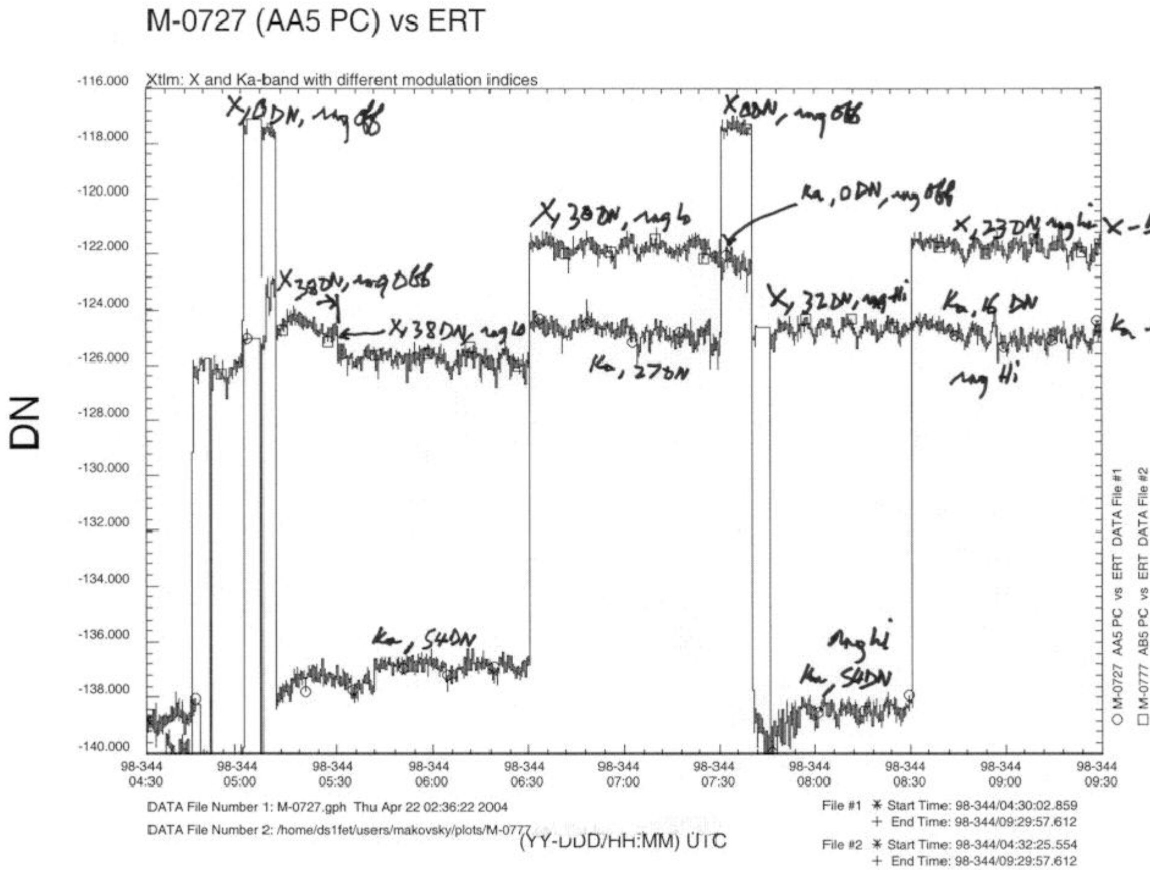


Figure 3. Measured X- and Ka-band Carrier Power as a Function of Time During DOY 1998-344, Showing Various Ranging Carrier Suppression Values (Note: ERT = Earth-Received Time)

4.9 Coherent Doppler Tracking

Coherent Doppler tracking was conducted as part of the Xstable test. The intent was to validate the coherent frequency stability of the SDST both for Doppler tracking and for future radio science applications. During the test, the SDST generated both X-band and Ka-band downlinks that were coherent to the X-band uplink, with coherency ratios of 880/749 and 3360/749, respectively. The X-band and Ka-band downlink signals were received at DSS-25 using the BVR and at DSS-13 using the experiment tone tracker (ETT). The frequency measurements from both the BVR and the ETT were then used to measure the phase deviation and Allan deviations of the X-band and Ka-band downlinks. The stability of the downlink carrier as received at the tracking station should not be affected by the presence of command or ranging modulation on the uplink, or telemetry modulation on the downlink.

Shown in Figure 4 are the X-band and Ka-band frequency residuals taken at DSS-13 using the ETT, after correcting for Earth rotation and spacecraft Doppler effects. It is seen that periodic frequency variations of ±5 millihertz at X-band (Figure 4a) and ±20 millihertz at Ka band (Figure 4b) were visible in the X-band and Ka-band downlink-frequency residuals. These variations are common to both the X-band and Ka-band, and are believed to be due to deadbanding of the spacecraft. When the common mode is removed by subtracting the X-band frequency residual and a Ka-band residual scaled down by a factor of 3360/880, no periodic variation is visible in the data (see Figure 4c). The 0.1-hour (6-minute) period shown in Figure 4 (a–b) was similar to the deadband cycle frequency of the spacecraft.

The two-way Allan deviation performance of the SDST is illustrated in Figure 5. Both X-band and Ka-band downlinks showed an Allan deviation of better than 1 part in 10^{13} with 10 seconds integration time. This translates to a Doppler measurement accuracy of 0.8 millihertz at 10 seconds integration time (or 0.015 mm/s). When the common mode variation was removed, the X/Ka-band downlinks showed a delta frequency stability of better than 1 part in 10^{14} with 10 seconds integration time, or 0.0015 mm/s in Doppler measurement.

4.10 Noncoherent Downlink Frequency Stability

This test verified that the SDST generates downlink frequencies (X-band and Ka-band) from its auxiliary oscillator that have sufficient stability as downlink carriers to be received by the tracking station. The stability of the X-band downlink in the SDST's noncoherent mode was not expected to be affected by reception of an uplink carrier. The test (Xstable) was conducted on DOY 1998-344, when DS1 pointed the +X axis to Earth and transmitted both X-band and Ka-band downlinks. The test measured the frequency of the X-band and Ka-band downlinks over a period of two hours. Shown in Figure 6 is a plot of downlink frequency as a function of time for both the X-band and Ka-band. It is seen from this plot that, under nominal operating conditions (including spacecraft deadbanding), the X-band downlink varies by approximately 75 Hz, whereas the Ka-band downlink varies by a corresponding ratio of (3360/880) and has a maximum frequency deviation of approximately 300 Hz. The close resemblance of the X-band and Ka-band downlinks is expected since they are coherent with the same multiplication ratio. A check of pre-flight temperature data showed that the SDST has a frequency rate of change of over 200 Hz/°C. Therefore, the perceived frequency change can be due to small thermal variations at the spacecraft.

4.11 Ranging Functional Verification

The SDST is designed to provide turnaround ranging simultaneously with uplink command and downlink telemetry. Since the SDST has a nonlinear phase modulator, which effectively causes excessive inter-modulation losses when ranging modulation is applied simultaneously with telemetry modulation at high mod indices, ranging performance validation is limited to the modulation indices planned for routine mission operations. That is, X-band telemetry modulation is limited to 38 DN (approximately 65 degrees) at 17.5 degrees ranging mod index setting and to 32 DN (approximately 58 degrees) at 35 degrees ranging mod index setting. At Ka-band, the phase modulator behaves linearly; it is expected that ranging modulation effects can be correctly predicted using well-established equations.

Both X-band uplink/X-band downlink (X/X) and X/Ka ranging have been successfully demonstrated. Downlink ranging mod indices of 17.5° and 35° have been used at both the X-band and the Ka-band. The actual ranging signal-to-noise ratio (Pr/No) agrees with the predicted within 1 dB at X-band and 1.5 dB at Ka-band. The ranging residuals are larger than one-way (downlink or uplink) residuals because ranging is a two-way link: both a stronger than predicted uplink (typically, 0.7 dB) and a stronger than predicted downlink (typically 0.7 dB) contribute to a larger residual.

Shown in Figure 7 are typical examples of ranging Pr/No values at the X-band and Ka-band; predicts are also shown for comparison to actuals for the X/Ka-band track on 2/4/99. It is seen that the actual downlink Pr/No values are in good agreement with the predicted values. Similar X/Ka-band data, collected for DOY 1999-096 (4/6/99), are shown in Figure 8. It is seen that the X-band Pr/No is within 2 dB of the predicted value, whereas the Ka-band Pr/No is within 3 dB of the predicted value.

Ranging residuals, after accounting for the spacecraft's trajectory, are shown in Figure 9. The ranging residuals (measurement errors when corrected for spacecraft trajectory effects) are typically on the order of 0.5 m when the HGA is used. Larger residuals are seen when the LGA is selected and when the spacecraft is pointed away from Earth. This fact correlates with the weaker uplink and downlink signals.

Table 10. X-band Ranging Suppression Due to Nonlinear Phase Modulator, Measured Versus Predicted on the Basis of Pre-flight Data

Carrier Suppression	Measured In Flight	Pre-Flight Test Data	Delta, In-Flight to Pre-Flight	Link Analysis, Model	Delta, Measured-Model
17.5° ranging (telemetry 38 DN)	1.0	0.9	0.1	−0.79	−1.0
35° ranging	2.6	2.7	−0.1	−2.94	−2.6

Table 11. Measured Ranging Suppression at Ka-band

Telemetry Modulation	Ranging Modulation	Pc, Measured	Pc, Predicted	Delta, Measured-Predicted
0 DN (0°)	0°	−122 dB (1 mW)		
54 DN	35°	−138 dB (1 mW)	−137.8 dB (1 mW)	0.2 dB

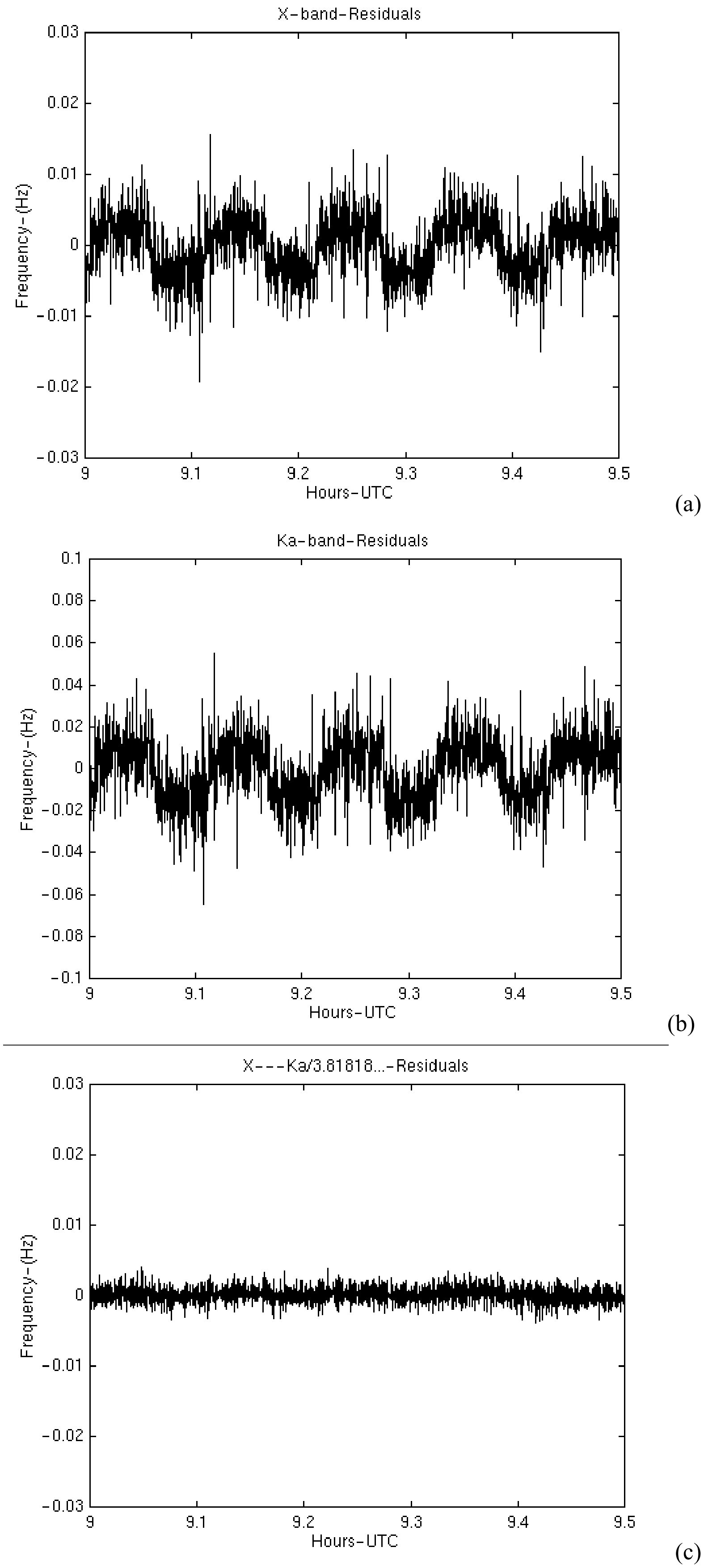
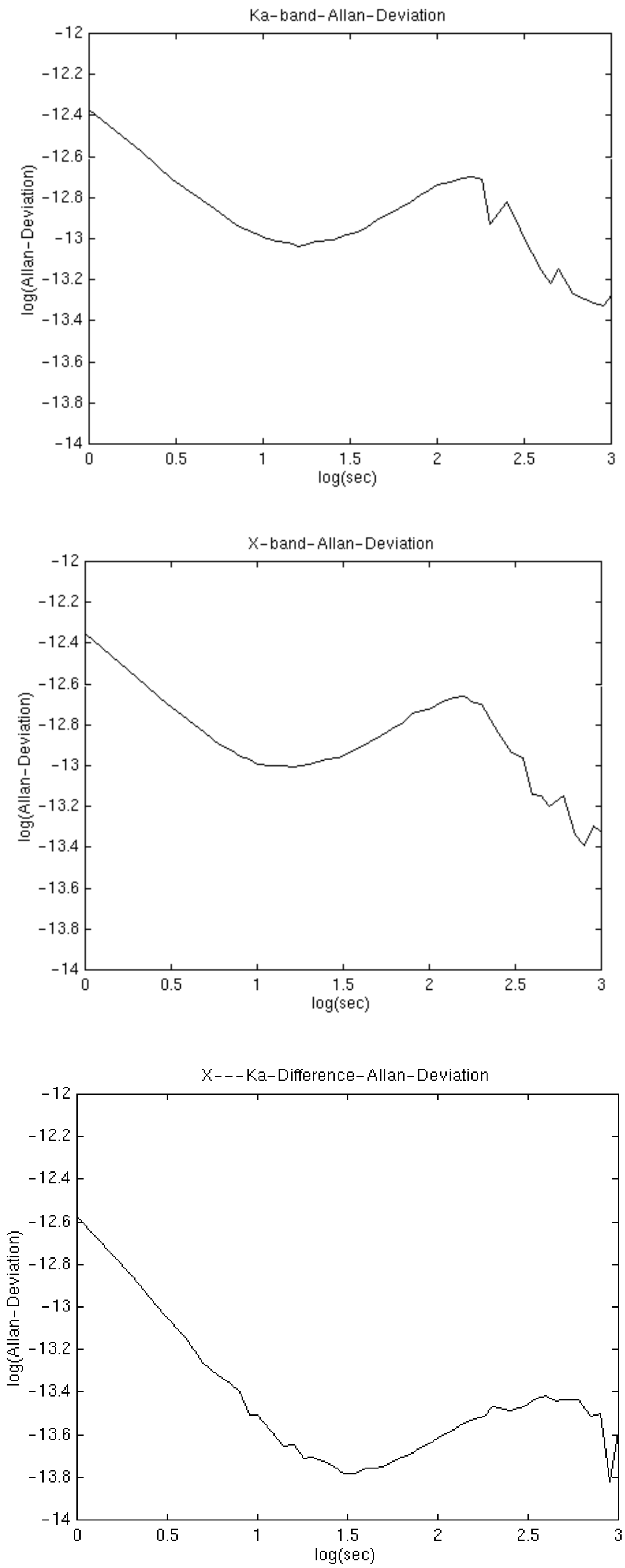


Figure 4. (a) Measured Coherent Frequency Stability at X-band and (b) at Ka-band; and (c) Relative Stability of X/Ka-bands

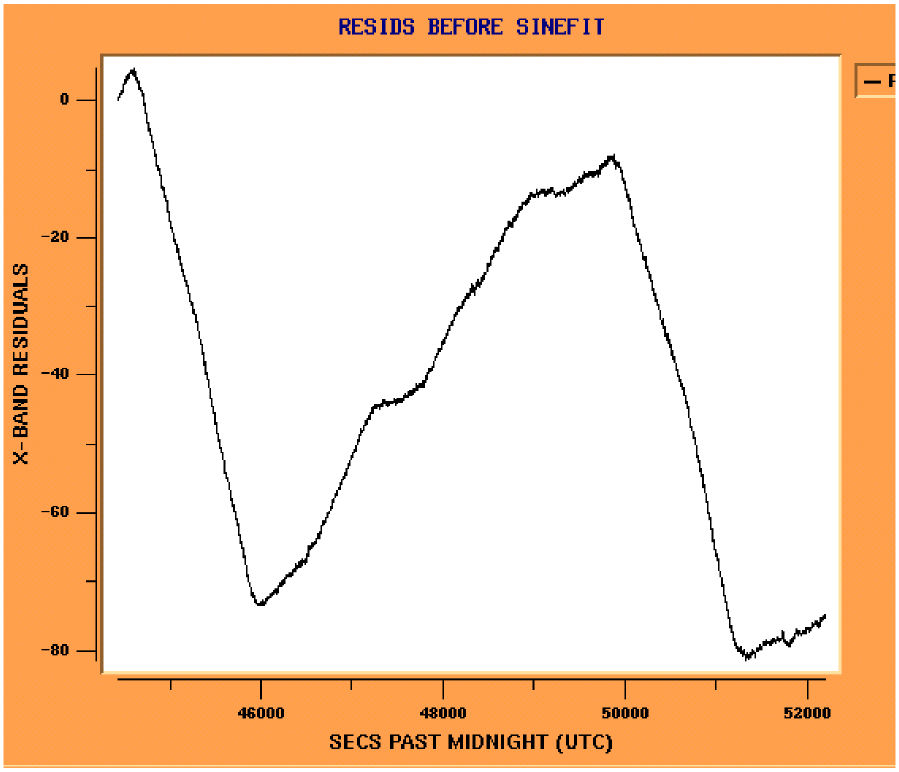


(a)

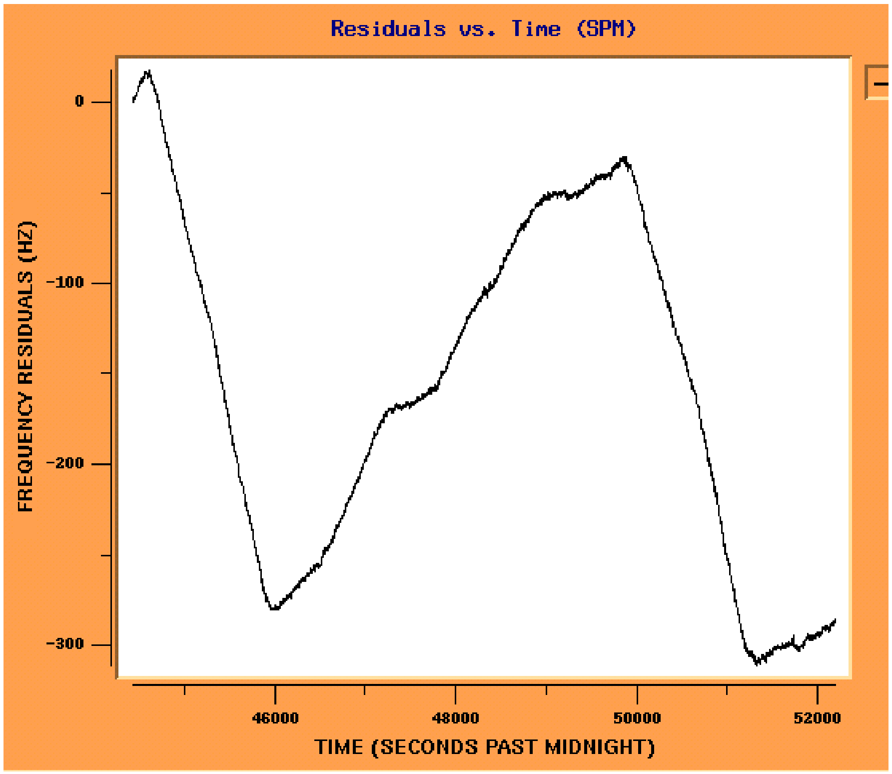
(b)

(c)

Figure 5. (a) Measured Allan Deviations for X-band and (b) Ka-band Downlinks, and (c) Measured X/Ka-band Relative Stability



(a)



(b)

Figure 6. (a) Measured Noncoherent Downlink Carrier Stability at X-band and (b) at Ka-band

4.12 Beacon Tone Generation and Tone Tracking
The SDST was designed to provide a flexible selection of downlink telemetry subcarrier. This feature was used to provide the beacon tone for noncoherent signaling: the SDST would provide one of four selectable subcarrier frequencies (20, 25, 30 and 35 kHz) at a near-90° modulation index (complete downlink carrier suppression). Detection of the tone frequency can be used to signal one of four possible spacecraft states.

The Xtone activity was designed to show that the beacon downlinks signal from the SDST could be detected effectively, even at low signal power level. The results show that the SDST was able to generate and transmit the four required beacon tones (frequencies of 20, 25, 30, and 35 kHz) at X-band. No beacon experiment was performed at Ka-band.

At the planned modulation index of 54 DN, more than 99% of the power was in the subcarrier sidebands. The expected beacon tones were successfully detected. In order to test the detection of beacon tones on the ground at weaker signal levels, Xtone was successfully performed at much lower modulation indices (1.7, 3.4, 5.1, and 6.8 degrees), a procedure that allowed a much lower signal to be detected. The tone-detection system successfully detected signals as low as SNR=4.5 dB.

4.13 External Telemetry Sampling Functions
The SDST samples external analog and temperature telemetry signals. These channels served, among other functions, to provide the necessary engineering data for KAPA performance validation.

5.0 DSN KA-BAND READINESS VERIFICATION

Since the SDST is the first Ka-band capable deep space transponder, a significant portion of the technology validation activity was conducted for both the X-band and the Ka-band. In addition to the technology validation objectives cited previously, a side benefit of the DS1 Ka-band downlink is direct verification of the operational readiness of the DSN Ka-band subnet and of the performance advantages of the Ka-band relative to the X-band. Although only one of the three subnet stations (DSS-25) was ready in time to support DS1, the performance data gathered using DS1’s Ka-band downlink were useful in evaluating the projected Ka-band performance at other subnets in the future.

DS1 powered on Ka-band during December 9–10, 1998 and again after January 10, 1999 prior to the first thrusting cruise arc. The initial characterization tests (December 1998) supported the following SDST technology validation objectives:

- Demonstrate SDST capability to support simultaneous X-band and Ka-band downlinks at various data rates and modulation indices.
- Measure one-way and two-way frequency stability and X/Ka-band relative frequency stability of Ka-band downlink.

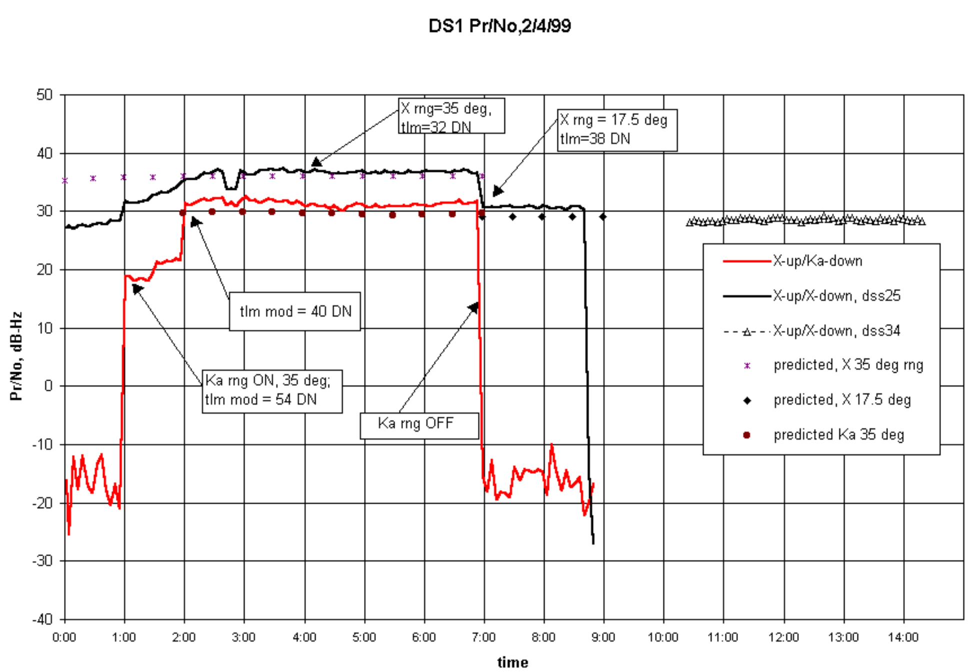


Figure 7. Predicted Versus Actual Pr/No for DOY 1999-035

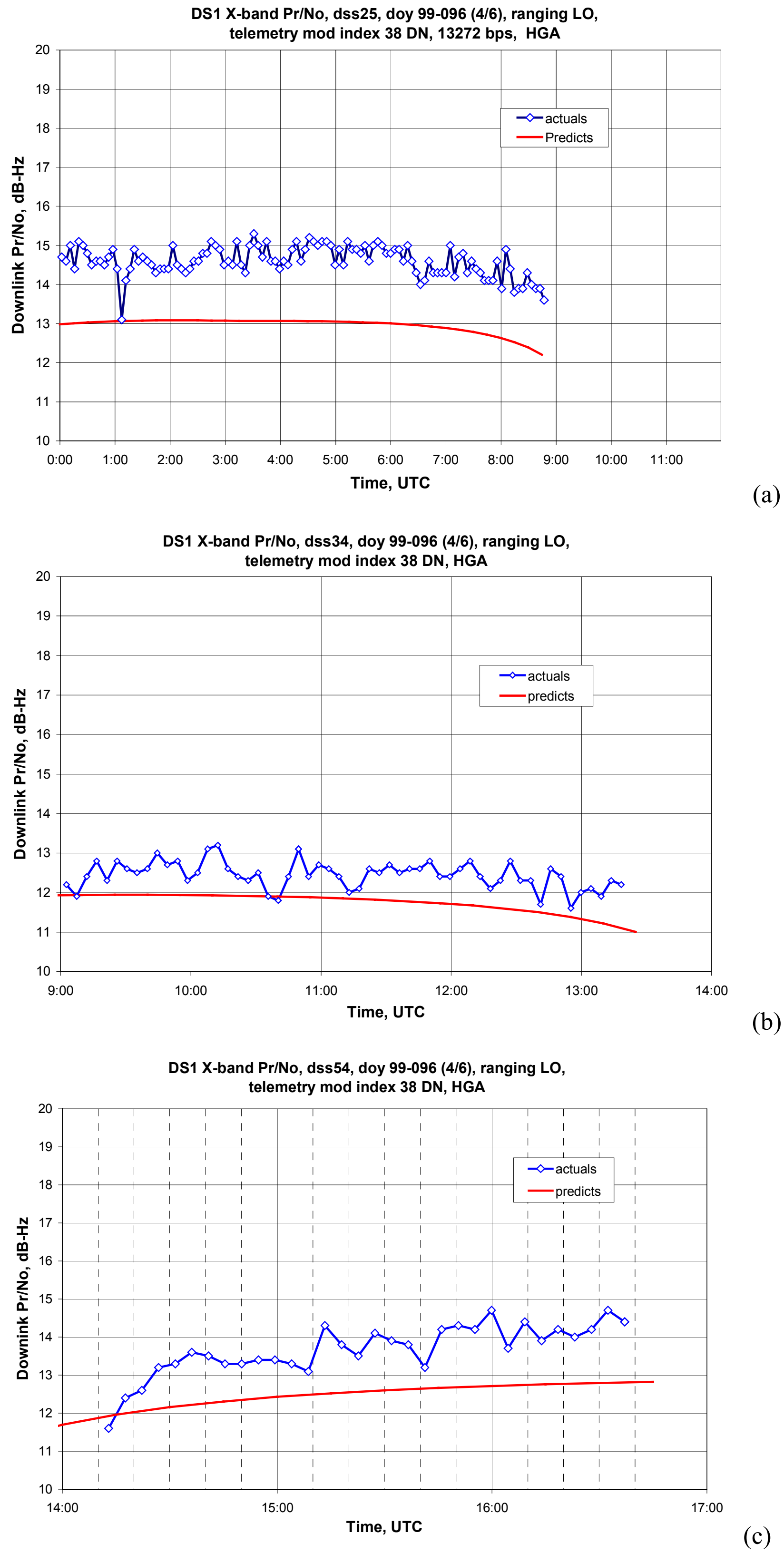


Figure 8 (a–c). Ranging Residuals for DOY 1999-096 (4/6/99): (a) DSS 25, (b) DSS 34, and (c) DSS 46

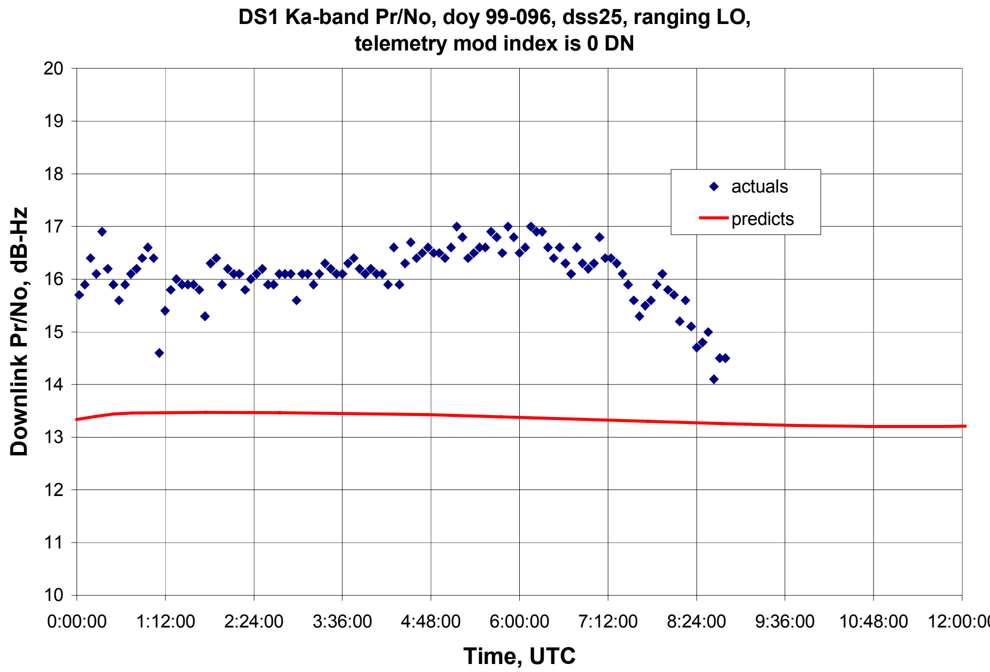


Figure 8 (d). Ka-band Ranging Residuals for DOY 1999-096 (4/6/99)

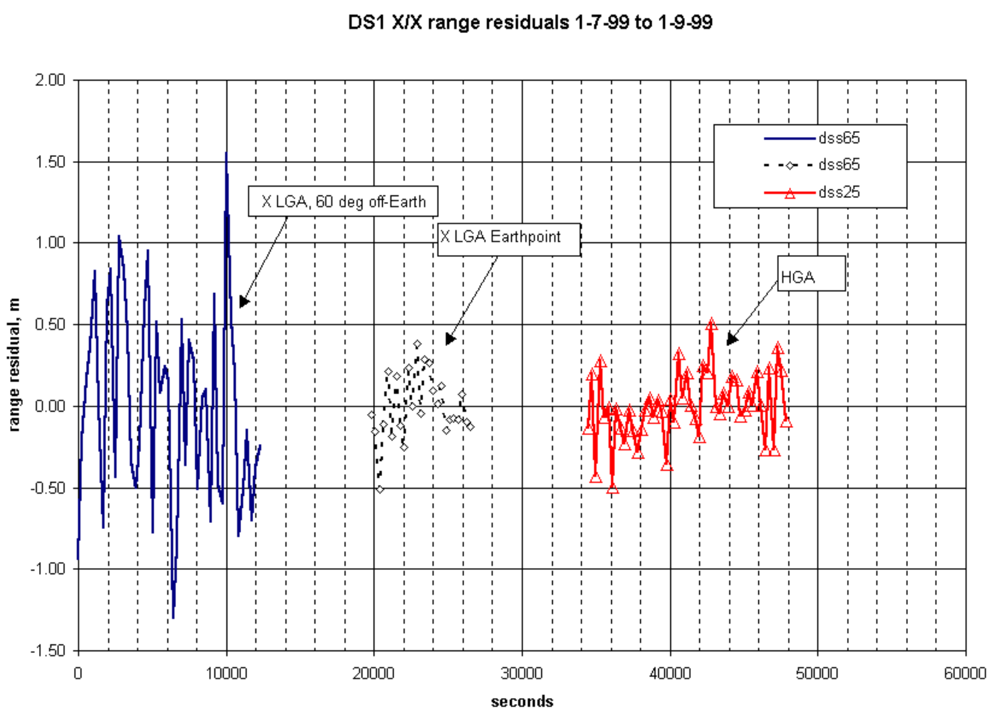


Figure 9. Ranging Residuals (Measurement Errors) after Accounting for Station and Spacecraft Motions

- Verify X/Ka-band radio metrics performance.
- Demonstrate operation of 3-W (2.5-W) Ka-band solid-state power amplifier (SSPA) in space.
- Collect operating data for the Ka-band SSPA (gate current and drain voltage telemetries and operating temperature data) for future analysis.

Additionally, the Ka-band downlink supported the following readiness demonstration objectives:

- Demonstrate DSN readiness to support Ka-band missions.
- Demonstrate dual-band (X/Ka), end-to-end telemetry flow from a spacecraft to the DS1 MSA.
- Demonstrate the capability to generate necessary station predicts for Ka-band tracking.
- Demonstrate the station capability to perform radio metric tracking (Doppler and ranging) on the Ka-band downlink.
- Measure Ka-band system noise temperature and link performance advantages relative to X-band.
- Demonstrate DSS-25 capability to accurately point the 34-m antenna using blind pointing.

Ongoing characterization tests (since January 1999) also demonstrated continuous operation of the Ka-band downlink and supported characterization of the Ka-band downlink threshold and verified link-margin calculation. The DS1 Ka-band downlink was also used to provide a stable signal for measurement/characterization of 70-m DSN station pointing and receiving capability using different techniques (array feed, deformable flat mirror, etc.)

Future plans for the Ka-band downlink from DS1 include:

- Ka-band beacon tone experiment.
- Long-term monitoring of X/Ka-band propagation data with spacecraft Ka-band downlink.
- Characterization of Ka-band performance under very low downlink power.
- Characterization of Ka-band performance during solar conjunction.
- Possible radio science during solar conjunction.

Additionally, the Ka-band downlink is relatively insensitive to solar plasma-induced scintillation. Since DS1's next encounter (with comet Wilson-Herrington) occurs at an Sun-Earth-Probe (SEP) angle of 2 degrees, the availability of the Ka-band downlink can be very valuable as it can be the only direct confirmation of the link at a low SEP angle.

5.1 34-m Antenna Pointing Performance

5.1.1 Blind Pointing Model—There are two blind pointing models for DSS-25. The first is the standard X-band blind pointing model, which was used for the majority of the tracks. The second is a fourth-order Ka-band blind pointing model, which was used on an experimental basis. When the fourth-order Ka-band model was used, it was observed that the Ka-band signal power was generally strong. When Conscan was turned on to bring the antenna on point, only 1 dB of increase in signal-to-noise ratio was observed with the fourth-order Ka-band model. With the X-band pointing model, this was not the case. At times, increases in the signal-to-noise ratio upwards of 5 dB were observed when Conscan was turned on and when the antenna was pointed using the X-band pointing model. This indicates that the Ka-band model is quite accurate and requires a minimum of active correction. For future Ka-band tracks it is recommended that the fourth-order Ka-band blind pointing model be used.

5.1.2 Conscan Mode—As mentioned above, we observed an increase of 1 to 5 dB in the signal-to-noise ratio when Conscan was turned on. This indicates that, given the current set of blind pointing models available, it is advisable to use an active pointing mechanism on the 34-m beam waveguide (BWG) antenna to take full advantage of the Ka-band performance. Furthermore, it was observed that when Conscan was turned on, fluctuations in the BVR symbol signal-to-noise ratio (SSNR) decreased from approximately ±0.3 dB to ±0.03 dB. Figure 10 is a plot of pointing residuals as a function of time for DOY 98-344. It is seen that pointing residuals of less than 4 mdeg were effectively maintained. This indicates that the antenna was on point because fluctuations in antenna pointing cause less degradation at peak. This is due to the fact that the roll-off in gain of the antenna at peak is not too sharp. Another thing to note is that several times Conscan was turned on for a few minutes, and pointing offsets were obtained; then Conscan was turned off, but the offsets were kept. This resulted in several hours of very good tracking. However, as the track proceeded, the pointing degraded and Conscan needed to be turned on to obtain new pointing offsets. This was especially true at high elevations, where the blind pointing model may not be as accurate when fast changes in azimuth occur.

5.2 Ka-band System Noise Temperature and Link Capacity Projection

During our initial tracks at DSS-25, there were problems with the reporting of the Ka-band system noise temperature (SNT). Once this was brought to the attention of DSN operations, there was improvement in the reporting of the SNT and reported SNT values were between 40 K and 50 K, depending on elevation (although some values were as high as 56 K at high elevations) (see Figure 11). Given that the contribution of noise sources other than atmosphere is about 27 K, this indicated a zenith atmospheric noise temperature of about 10 K to 12 K, which corresponds to 50% to 70% weather. It should be noted that these weather percentages are calculated not from the standard 810-5 numbers but from the latest set of water vapor radiometer data collected at Goldstone. These numbers reflect 46 months of observations and are by far the most accurate source of atmospheric-noise-temperature data for the Ka-band at Goldstone.

The validity of the observed SNT values was verified in two ways. First, the theoretical SNT was calculated for a zenith atmospheric noise temperature of 10 K, based on DOY 1998-344 track elevation, and plotted against DOY 1998-344 SNT data (see Figure 11). Then, the Ka-band antenna-gain-to-system-noise-temperature-ratio (G/T) advantage over X-band was calculated, based on the received SNR values for DOY 1998-344 and DOY 1999-035, and plotted against the predicted Ka-band G/T advantage over X-band at 50% and 70% weather (10 K and 12.5 K zenith atmospheric noise temperature), respectively. The following method was used to calculate the G/T advantage. First, it was noted that if the spacecraft had the same amount of transmission power available for the X-band and the Ka-band over the same size antennas, with the exact same efficiency for Ka-band and X-band, the Ka-band Equivalent Isotropic Radiated Power (EIRP) would have been 11.6 dB higher than that for the X-band. However, for DS1, the EIRP for Ka-band is 3.4 dB *less* than that for the X-band. This means that in order to make a fair comparison between Ka-band and X-band performance we need to add 15 dB (11.6+3.4) to the measured Ka-band signal-to-noise ratio. Therefore, we calculated the total signal-to-noise ratio (Pt/No) for each band from the estimates for carrier signal-to-noise ratio (Pc/No), symbol signal-to-noise ratio (Es/No), and, when applicable, ranging signal-to-noise ratio (Pr/No). Then, we added 15 dB to the Ka-band Pt/No and subtracted the X-band Pt/No from the total. The result is the Ka-band G/T advantage over X-band. These results are presented in Figure 12 and Figure 13.

As we can see from Figure 11 , the observed SNT values for DOY 1998-344 closely match the predicted SNT values at the Ka-band. The mismatches that are observed occur at higher elevations, where the theoretical antenna models usually do not quite match the actual antenna performance. In Figure 12 and Figure 13, the G/T advantage for Ka-band over X-band is approximately 10 dB at the higher elevations. This is about 1 to 1.5 dB higher than those predicted for 50% weather for the antenna configuration (dual-frequency, diplexed configuration) that was employed during these tracks. There could be several reasons for the discrepancy between the theoretical and actual results. First of all, the theoretical model may not be accurate. This could lead to inaccurate estimates of antenna gain and system noise temperature for different elevations. This is the most likely source of error due to the large amount of error observed. Other factors, such as miscalibration of the SNT

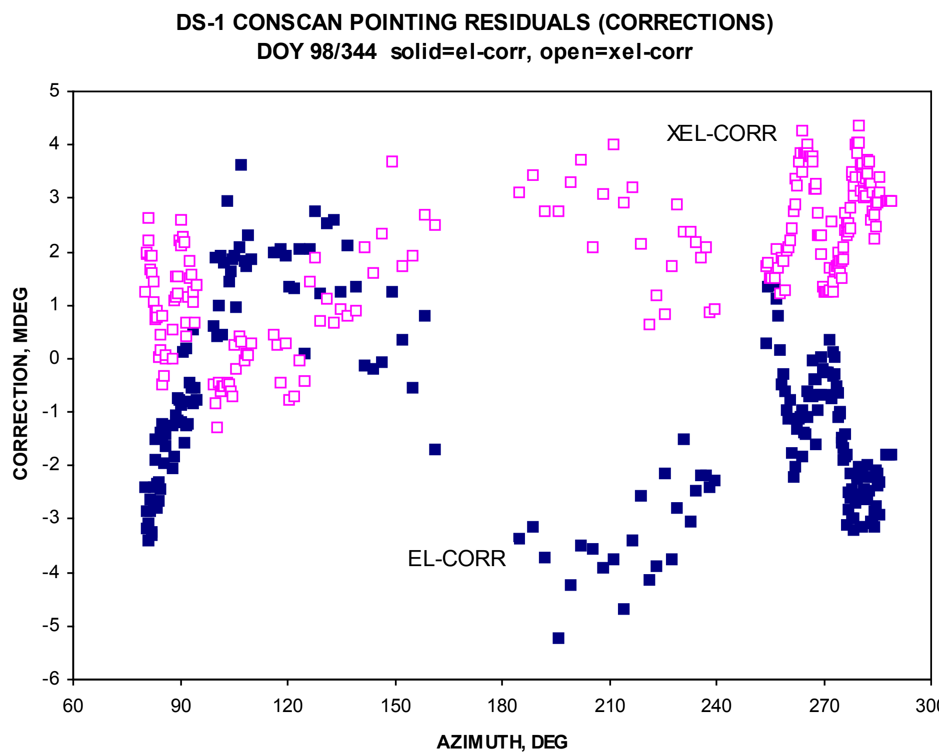


Figure 10. DSS-25 Conscan Pointing Residuals, Showing that Pointing Error is Generally Less than 4 millirads

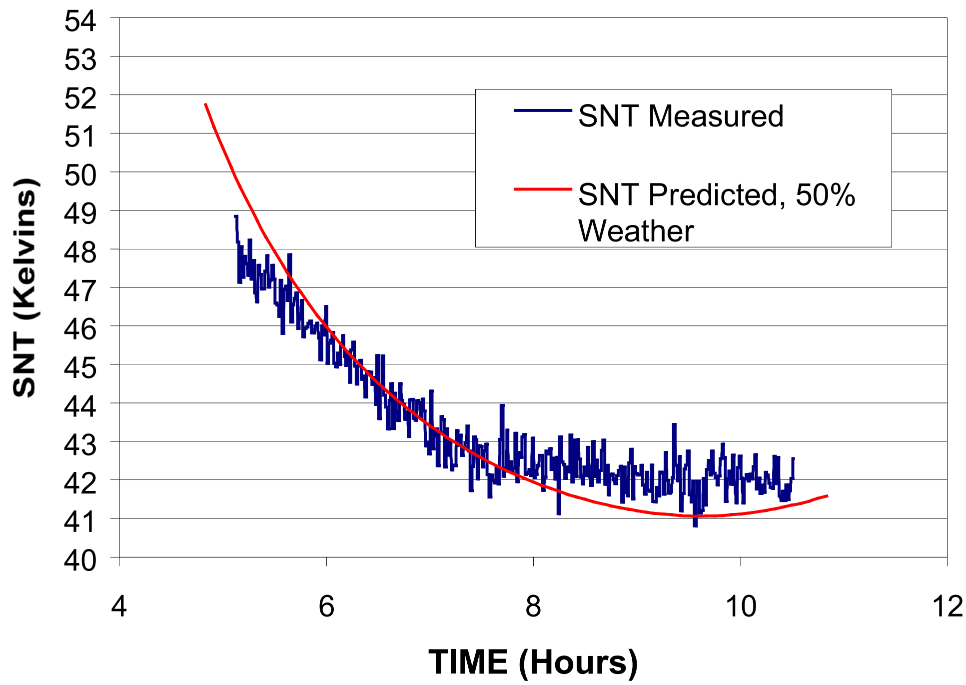


Figure 11. DOY 1998-344 Ka-band Measured SNT and 50% Weather-Predicted SNT

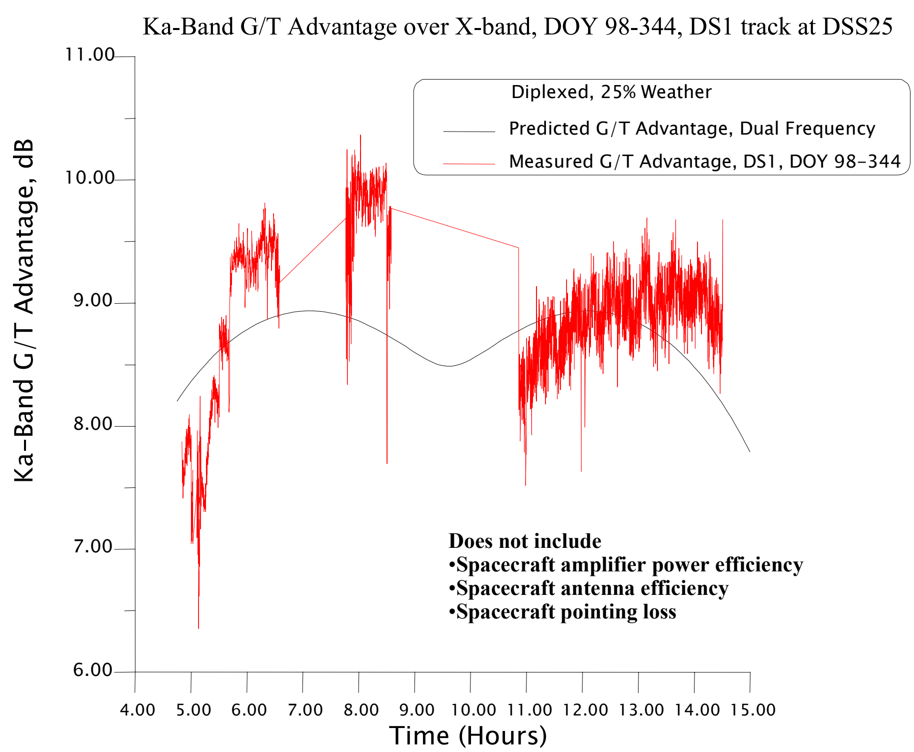


Figure 12. Ka-band G/T Advantage Over X-band, DOY 1998-344, DS1 Track at DSS-25

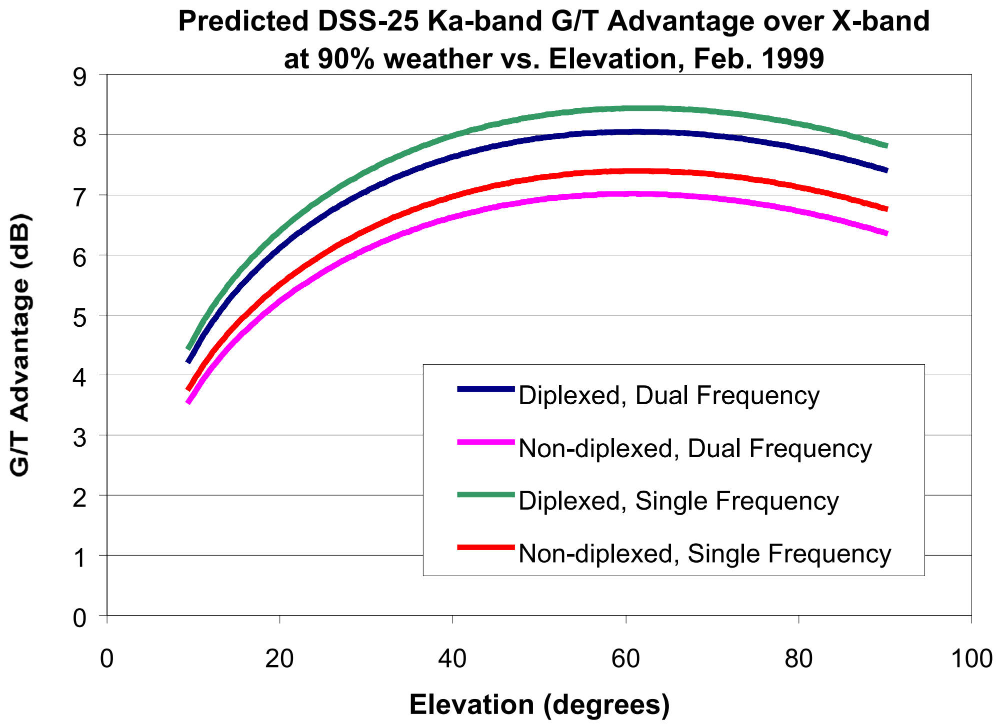


Figure 13. Ka-band G/T Advantage Over X-band, DS1 Track, DOY 1999-035, DSS-25

readouts, nonlinearities in the spacecraft modulator, and changes in the EIRP, could also effect the measurements, as could the pointing of the spacecraft antenna. The performance advantage observed during these tracks for the Ka-band over the X-band indicate that Ka-band could be, if it is not already, an evolutionary step to increase the capacity of the DSN by at least a factor of four.

There are several caveats to these observations. First of all, the tracks were performed under very good conditions. There was very little wind and humidity was low. Further tracks need to be performed, especially during summer, when the humidity at Goldstone is high, to observe the behavior of the Ka-band under adverse conditions. Secondly, DS1 carries a relatively low-gain Ka-band antenna. Due to this, the antenna pointing for DS1 Ka-band is not as stringent as it would be on a spacecraft that carries a higher gain antenna (say a 1-m dish). In that case, the secondary effect of antenna pointing error on the spacecraft, while negligible at the X-band, could drastically affect the performance of the Ka-band. Finally, it should be noted that the performance advantage that was calculated was only for the ground G/T performance. The actual end-to-end performance advantage of the Ka-band link depends also on spacecraft configuration. Lower efficiency of Ka-band amplifiers and lower efficiency of Ka-band antennas should also be factors in determining whether or not Ka-band should be used on a spacecraft.

5.3 Ka-band Performance Threshold

This test was designed to evaluate the quality of the Ka-band telemetry received from DS1. This was done by changing the received bit signal-to-noise ratio at the Ka-band by changing the telemetry mod index and then observing the lock status of the frame synchronizer subassembly (FSS) and the maximum likelihood convolutional decoder (MCD). Furthermore, telemetry gap reports were to be used to evaluate the decoding signal-to-noise ratio threshold for the (15,1/6) convolutional code, concatenated with the Reed-Solomon (255,223) interleaving depth 5 code.

Four days, DOY 1999-025, 027, 028, and 030, were scheduled for these tests. The spacecraft was sequenced so that the mod index would change every five minutes for cycles of 35 to 45 minutes, depending on the day. The mod index is the highest at the beginning of the cycle, producing the highest SNR, and the lowest at the end of the cycle, producing the lowest SNR. These mod indices were selected so that the test would produce SNR values both above and below the expected threshold of 0.65 dB bit SNR (corresponding to –7.05 dB symbol SNR). Shown in Figure 14 is a plot of the receiver SNR as a function of time. The steps in measured SNR result from modulation index changes.

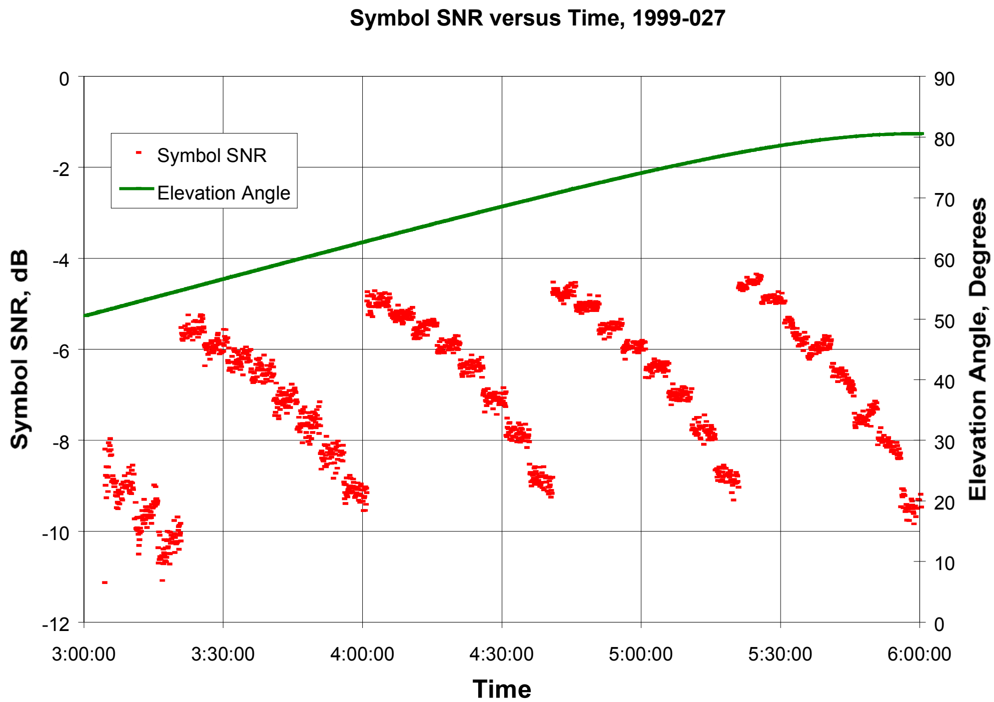


Figure 14. Ka-band Threshold Measurement Data

The FSS and MCD lock statuses were obtained immediately after the pass from the monitor data and correlated with the measured receiver symbol SNR shown in Figure 14. The FSS starts losing lock when the symbol SNR is between –7.5 dB and –8 dB (bit SNR between 0.3 and –0.2 dB). This corresponds with the observations made on the X-band channel during tests for previous missions, where the FSS lost lock at about –7.5 dB symbol SNR. The MCD loses lock when the symbol SNR is between –8 dB and –8.5 dB (bit SNR between –0.2 dB and –0.7 dB). These values also match rather closely those observed for previous missions.

5.4 X/Ka-band Radio Science

X/Ka-band radio science is a potential objective for the solar conjunction. The frequency stability characterization performed during IC showed that a relative frequency stability of better than one part in 10^{13} can be achieved with an integration time of better than 10 seconds. The frequency stability appears to be limited by the relative shift of the X- and Ka-band phase center; the time scale is limited by the deadband of the spacecraft.

5.5 Ka-band Link Threshold at Low Bit Rate

As of this writing, this test has not been performed due to limitations imposed by the mission.

5.6 Ka-band Antenna Pointing and Gravity Compensation at 70 m

The DS1 Ka-band signal was used as part of a task to evaluate the performance of DSS-14 at the Ka-band. A complete report is being prepared by the task force on the experiments performed at DSS-14. Part of the report will address the use of the DS1 Ka-band signal to evaluate DSS-14 performance. As of this writing, the report is not complete. Following is a brief description of the systems that were used to evaluate and improve DSS-14 Ka-band performance, along with a summary of the conclusions presented by the task force.

5.6.1 Purpose of the Ka-band Tests at DSS-14—The purpose of these tests is twofold: (1) measure improvements in the antenna efficiency at Ka-band and (2) measure improvements in the pointing accuracy of the antenna for Ka-band tracking.

In order for DSN to use the 70-m subnet for tracking at Ka-band it must be shown that the antennas have sufficient gains and that they can be pointed accurately enough to justify their use at that frequency. It is, therefore, paramount to test various candidate technologies that improve the gain and pointing of the 70-m antennas to measure the potential performance of the 70-m subnet at Ka-band.

5.6.2 Candidate Technologies—There are three different technologies that are under consideration for use on the 70-m subnet for Ka-band pointing and gain compensation: (1) the monopulse pointing and compensation system, (2) the array feed pointing and compensation system, and (3) the deformable flat plate (DFP) compensation system.

Monopulse uses simple measurements in the antenna focal plane to estimate the peak of the antenna beam and to adjust the pointing of the antenna to help ensure that the beam is centered as the antenna tracks. Monopulse requires a coherent signal on which to peak; therefore, it can be used only on spacecraft signals. Monopulse improves only the pointing of the antenna and does nothing to improve its gain.

Array feed uses seven feed horns in the focal plane to estimate the peak of the antenna beam and to adjust the pointing of the antenna accordingly, so that the beam is centered. In addition, array feed has the potential to combine the output of the seven feed horns to compensate for decreases in the gain of the antenna due to gravity deformations. Array feed works with both coherent sources (i.e., spacecraft signals) and noncoherent sources (i.e., natural radio source such as stars, galaxies, and planets).

DFP is basically an RF mirror that changes its form according to the elevation of the antenna in order to compensate for the decrease in gain due to gravity. DFP compensates only for gravity deformations and does not affect the pointing of the antenna.

Since we need to improve both the gain and the pointing of the antenna, DFP and monopulse cannot be used by themselves. Therefore, there are three configurations that are considered during these tests:

- Array feed.
- Monopulse + DFP.
- Array feed + DFP.

5.6.3 Use of DS1—While natural radio sources could be used to measure the performance of the DFP and array feed systems, it is necessary to measure the performance of each configuration using real spacecraft signals, since the bottom line for the DSN is the quality of the returned data from the spacecraft. In addition, the monopulse system could not be tested with natural radio sources.

Currently, there are only four spacecraft that are operating at the deep space Ka-band (31.8–32.3 GHz): (1) Student Undergraduate Research Fellowship Satellite (SURFSAT), (2) Mars Global Surveyor (MGS), (3) Cassini, and (4) DS1. SURFSAT, which was supposed to act as a Ka-band beacon, orbits the Earth. However, due to SURFSAT's tumbling motion, its Ka-band signal power fluctuates and is, therefore, unreliable for threshold-related experiments, for which a stable downlink is required. The MGS Ka-band signal was turned off during the time these experiments were being performed. Furthermore, implementation of the MGS Ka-band system, with large spurious signals at high modulation indices, resulted in uncertainties in total signal power and, thus, in unreliable threshold measurements. Cassini's Ka-band does not carry telemetry; Cassini is under strict configuration control.

DS1 is the only spacecraft that has a complete, independent, and stable Ka-band telemetry system. In addition, the spacecraft team has been more than helpful in meeting the needs of these tests at DSS-14. Therefore, we have naturally gravitated towards the use of DS1 during these tests.

The DS1 signal is used both to establish a baseline for each configuration and to measure the performance of each configuration when its constituent systems are activated.

5.6.4 Conclusions—The experiment was performed successfully. In addition, the DS1 Ka-band signal was used successfully to evaluate the performance of candidate configurations. It is the opinion of the task force that the combination of array feed and deformable flat plate provides the best option for receiving Ka-band at DSS-14. This is due to the fact that this combination provides the most gravity compensation for DSS-14 while providing accurate pointing. Another conclusion of the task force was that DSS-14 Ka-band performance is not adequately characterized at high elevations. Therefore, in the future, the DS1 Ka-band signal could be used in conjunction with DSS-25 to characterize DSS-14 performance at high elevations for the Ka-band.

6.0 SUMMARY AND CONCLUSION

The in-flight checkout activities and ongoing flight validation of the SDST provided confidence that the transponder functioned as intended. With the exception of nonlinear phase modulation and the temperature sensitivity of receiver best lock frequency, the SDST functioned exactly as intended.

One should also note that both the nonlinearity of the phase modulator and the variation in BLF/SPE have been corrected for the current generation of the SDST, scheduled to be flown on Mars 01 and SIRTF missions. Furthermore, unlike the DS1 SDST, which functioned only with a single-string C&DH, the Mars 01 SDST supports dual-string cross-strapping with the C&DH. These performance improvements and added capabilities, together with DS1's in-flight validation, make the use of the SDST truly low-risk for future flight projects.

7.0 LIST OF REFERENCES

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Appendix A. List of Telemetry Channels and Names

Table A1 is a list of all of the telemetry channels that the SDST team collects and uses. Note the importance of "monitor" channels in this work. (Jim Taylor, 10/20/99.)

Table A1. Channels and Mnemonics

Channel	Mnemonic	Channel	Mnemonic
T-0017	nar_band_AGC	T-3148	xsubcar_freq
T-0018	carlock_accm	T-3180	ksubcar_freq
T-3252	sdst_evnt_ct	T-3100	X_ranging
T-3228	rcvr_spe	T-3101	ka_ranging
T-3116	aux_osc_temp	T-3224	ranging_gain
T-3124	vco_tmp	T-3104	X_Exciter
T-4002	XPA_temp	T-3105	ka_Exciter
P-2061	ess_bus_v	P-3127	XPA_on_off
T-3500	sdst_dc_pwr	P-3160	DAM_on_off
T-3501	xpa_dc_pwr	T-3002	wts1_pos1
T-3316	xpa_in_pwr	T-3004	wts2_pos1
T-3476	X_Exc_SPE		
A-1637	bbc_CtrlErr0	M-0130	MCD1 SNR
A-1621	bbc_CtrlErr1	M-0781	AB5 SS1 SNR
A-1625	bbc_CtrlErr2	M-0773	AB5 PCN0
		M-0777	AB5 PC
T-3144	coherency	M-0775	AB5 SNT
T-3240	cmd_datarate	M-0787	AB5 SPE
T-0025	dnlink_rate	M-0618	RNG PRN0 X
B-3090	DlinkClokRat	M-0304	ANT A EL ANG
T-3156	x_tlm_mod	M-0305	ANT A AZ ANG
T-3188	ka_tlm_mod	M-0308	A CNSCN
T-3132	xtlm_coder	M-0309	A CNSCN LOOP
T-3136	katlm_coder		

Appendix B. Date of Turn-on/off and Frequency of Data Capture

The SDST was turned ON as part of the launch script in fault protection. Per the ACE log, the downlink from the spacecraft was first detected at 98-297/14:35 UTC. The SDST has been on continuously since then, except for short hiccoughs due to spacecraft safing. In fact, one could say that parts of it (e.g., receiver) have been on continuously. (Jim Taylor 10/29/99)