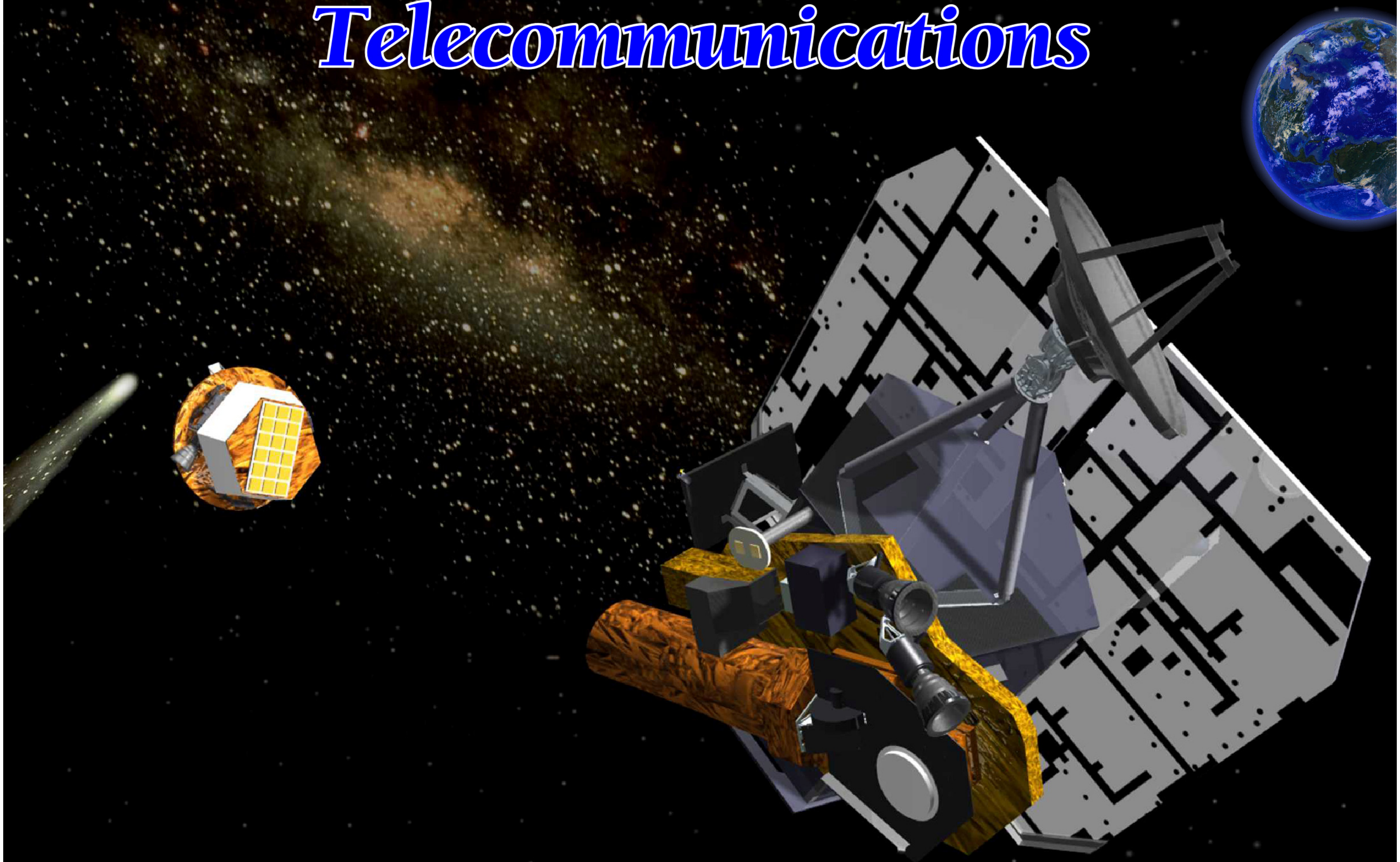
Deep Impact Flyby and Impactor Telecommunications



Jim Taylor and David Hansen

September 2005

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Deep Space Communications and Navigation Systems Center of Excellence

Design and Performance Summary Series

DESCANSO Design and Performance Summary Series

Article 9

Deep Impact Flyby and Impactor Telecommunications

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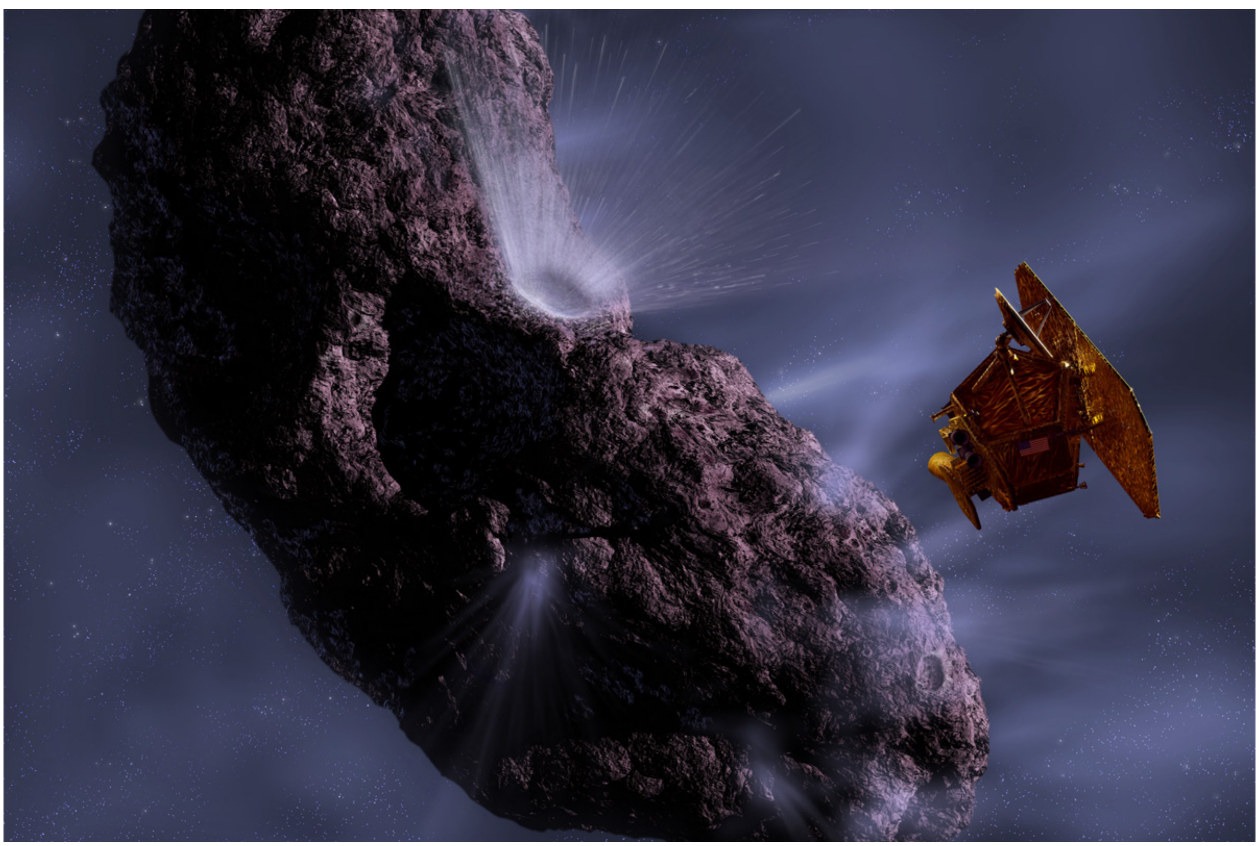
Prologue

Deep Impact: First Look Inside a Comet

On the cover is an artist's rendition of the Deep Impact (DI) flyby spacecraft releasing the impactor, 24 hours before the impact event. Pictured from left to right are comet Tempel 1; the impactor, which communicated via a relay link to and from the flyby; and the flyby spacecraft, which communicated with the National Aeronautics and Space Administration's (NASA's) Deep Space Network (DSN) on Earth.

The impactor is a 370-kg mass with an onboard guidance system. The flyby includes a solar panel (large flat area at right, far background, with cells mounted on side facing away), a high-gain antenna (top), a debris shield (between the antenna and the solar panel), and science instruments for high- and medium-resolution imaging, infrared spectroscopy, and optical navigation (orange cylinder and box, lower left). The flyby is about 3.3 m long, 1.7 m wide, and 2.3 m high. The launch payload had a mass of 1020 kg.

In the illustration below, artist Pat Rawlings gives us a look at the formation of the crater at the moment of impact with comet Tempel 1.



Artwork by Pat Rawlings, courtesy of National Aeronautics and Space Administration/ Jet Propulsion Laboratory/University of Maryland.

DESCANSO DESIGN AND PERFORMANCE SUMMARY SERIES

Issued by the Deep Space Communications and Navigation Systems
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Table of Contents

List of Figures

List of Tables

Foreword

This Design and Performance Summary Series, issued by the Deep Space Communications and Navigation Systems Center of Excellence (DESCANSO), is a companion series to the DESCANSO Monograph Series. Authored by experienced scientists and engineers who participated in and contributed to deep-space missions, each article in this series summarizes the design and performance for major systems such as communications and navigation, for each mission. In addition, the series illustrates the progression of system design from mission to mission. Lastly, it collectively provides readers with a broad overview of the mission systems described.

Joseph H. Yuen
DESCANSO Leader

Preface

This article describes data transmission and reception between the Deep Impact flyby spacecraft and the DSN ground systems for communications and navigation. It also describes data transmission and reception between the impactor spacecraft and the flyby spacecraft for communication of commands and telemetry data.

Throughout the mission, the X-band communications between the DSN and the flyby were on the high-gain antenna (HGA) whenever its orientation allowed this gimbaled antenna to point toward Earth. Commands were transmitted predominantly at 2 kbps, with 7.8125 bps on the low-gain antenna (LGA). Telemetry back to Earth was predominantly transmitted at 200 kbps, and eventually at 100 kbps and 40 kbps to the smaller ground stations, with 10 bps on the LGA.

For the 24 hours between separation and impact, the S-band antenna on the flyby, like its instruments, faced the comet and the approaching impactor. The impactor's antenna faced toward the flyby, opposite from its direction of flight. The impactor sent data to the flyby at 64 kbps and received commands from the flyby at 16 kbps.

The main goal of the article is to provide a reasonably complete single source for the specifics of DI radio communications. The description is at a functional level and includes information on the commands to configure the subsystem, engineering telemetry to monitor its configuration and performance, power consumption, and the mass of telecom subsystem components. The article includes communications parameters in the form of design control tables, subsystem performance during flight, and a set of lessons learned.

The article describes DI mission telecommunications from launch through the end of the primary mission in July 2005. The impactor successfully completed its mission on July 4; the flyby continues on a course that preserves the possibility of an extended mission, if funded.

Much of the telecom design information comes from the System Engineering Reports (SERs) for flyby and impactor telecommunications provided by Ball Aerospace under contract to the Jet Propulsion Laboratory (JPL). Some information about the mission and other subsystems comes from the DI public Web site [1]. Most numerical quantities are from the project's functional requirements documents.

Acknowledgements

The authors are grateful to Andre Makovsky of JPL for the X-band modulation parameters he developed and tested and to Chi Lau of JPL for the X-band prediction models he implemented and tested.

The authors especially appreciate the information provided by Larry Murphy, the X-band and S-band telecom system development lead at Ball Aerospace; and to Wayne Harvey of JPL, who delivered the traveling-wave tube amplifiers (TWTAs) to Ball and later analyzed their behavior as reported in engineering telemetry.

In the writing of this article, the authors also appreciate the helpful reviews by David Spencer and Jeff Srinivasan, the DI Project Mission Manager and the JPL Flight Communications systems Section Manager, respectively.

Section 1

Spacecraft and Mission Summary

1.1 Deep Impact Spacecraft Summary

As launched, DI consisted of two joined spacecraft, the flyby and the impactor. In this article, the individual spacecraft will be called the flyby or the impactor, and together they will be called the spacecraft. This article is current as of July 2005, after the completion of the prime mission, with the impactor having intercepted comet Tempel 1 and the flyby continuing on course for a possible extended mission.

1.2 Flyby

About the size of a sport-utility vehicle but with better fuel economy, the flyby (Figure 1-1) is three-axis stabilized and uses a fixed solar array and a small NiH_2 battery for its power system. The flight system is about 3.3 m long, 1.7 m wide, and 2.3 m high. The structure is aluminum and aluminum-honeycomb construction. Blankets, surface radiators, finishes, and heaters passively control the temperature. The propulsion system is a blowdown hydrazine design that provides 190 m/s of change in velocity (delta-V). The flyby spacecraft mass is 515 kg plus 86 kg of fuel at launch.

The flyby carries two of the three primary instruments: the High-Resolution Instrument (HRI) and the Medium-Resolution Instrument (MRI), for imaging, infrared spectroscopy, and optical navigation. The impactor carried the third instrument. Like the impactor, the flyby has an S-band transceiver and S-band antenna. Prior to the impactor's demise, commands to the impactor and data back from the impactor went through the S-band links.

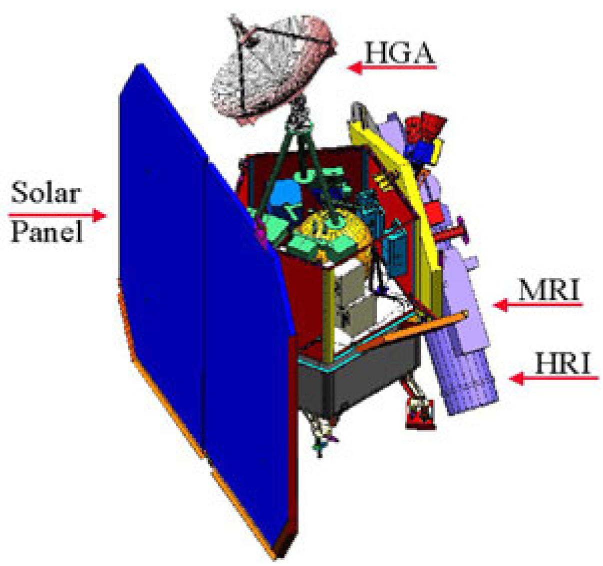

Figure 1-1. Deep Impact flyby.

The flyby's command and data handling functions use a high-throughput RAD750 CPU with 1553-data-bus-based avionics architecture. The flyby has a high-stability pointing control system for instrument operation and for orienting the HGA to the Earth.

Debris shielding is a key part of the flyby design. As the spacecraft passed through the inner coma of the comet it was in danger of being hit by small particles that could damage the control, imaging, and communication systems. To minimize this potential damage, the flyby was rotated before it passed through the inner coma, allowing debris shielding to provide complete protection to the flyby engineering and instrument elements. The flyby emerged from its close passage on July 4 with no particle damage apparent to any subsystem or either instrument.

1.3 Impactor

The impactor (Figure 1-2) was made primarily of copper (49%) as opposed to aluminum (24%) because copper minimized corruption of spectral emission lines that are used to analyze the nucleus of comet Tempel 1.

The impactor was mechanically and electrically attached to the flyby spacecraft for all but the last 24 hours of the mission. During the last 24 hours, the impactor ran on internal battery power. The impactor carried an S-band transceiver and antenna to receive commands from the flyby and to transmit science and engineering data back to it.

The impactor delivered 19 gigajoules of kinetic energy (equivalent to 4.8 tons of TNT[1]) to excavate the crater. This kinetic energy was generated not by a chemical explosion but by the combination of the mass of the impactor (~370 kg) and its velocity when it impacted (~10.2 km/s). Targeting and hitting the comet in a lit area was one of the mission's greatest challenges since the impactor was traveling at 10 km per second and it had to hit an area less than 6 km in diameter from about 864,000 km away. To accomplish this feat, the impactor used a high-precision star tracker, the Impactor Targeting Sensor (ITS), and auto-navigation algorithms

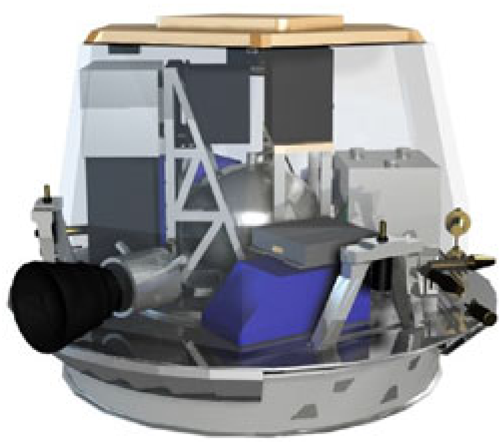

Figure 1-2. Deep Impact impactor.

[1] TNT is 2,4,6-trinitrotoluene, a chemical explosive. A gram of TNT by definition for arms-control purposes produces 1000 thermochemical calories, which equals 4.184 kilojoules.

(developed by JPL for the Deep Space 1 mission) to guide it to the target. Three minor trajectory corrections and impactor attitude control used the impactor's small, hydrazine propulsion system. The propulsion system used hydrazine that could provide up to 25 m/s of delta-V for targeting.

1.4 Instruments

The DI instruments (Figure 1-3) served two purposes. They guided the impactor onto a collision course with the comet and the flyby safely past the comet, and they collected the science data before, during, and after the impact. The instruments were designed to satisfy the following science requirements:

- Pre-Impact Imaging Requirements: Observe the comet and targeted impact site prior to impact, acquiring spatial and spectral data.
- Ejecta Imaging Requirements: Observe the ejecta and track the movement of the ejecta curtain from crater to coma.
- Crater Evolution Data Requirements: Observe the crater and surface evolution.
- Pristine Crater Data Requirements: Observe the exposed pristine crater surface features via spectral imagers with increasing resolution.
- Modular Design Requirements: Have optomechanically interchangeable focal-plane modules.

The HRI, one of the largest space-based instruments built specifically for planetary science, is the main science camera for DI. The HRI was optimally suited to observe the comet's nucleus. The MRI was intended as a functional backup for the HRI, and was slightly better at

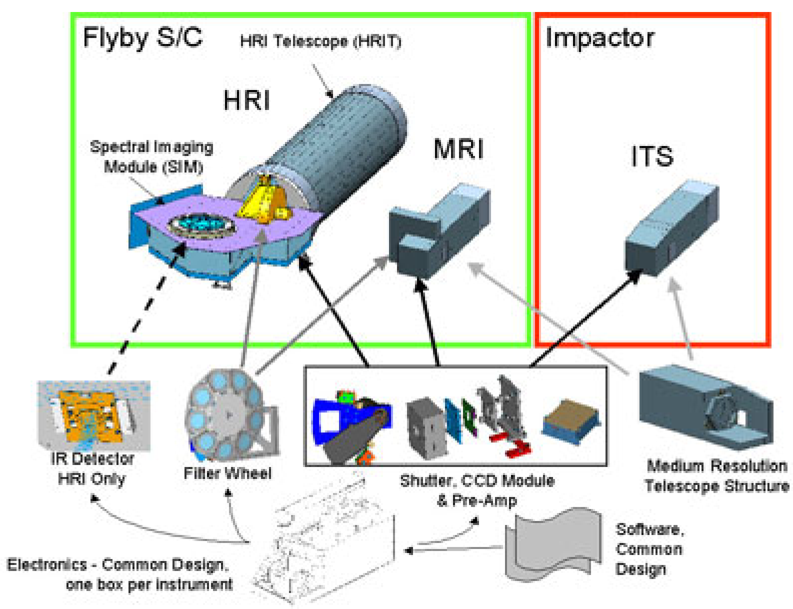

Figure 1-3. Instruments on flyby and impactor.

navigation for the last 10 days of travel before impact because its wider field of view (FOV) allowed it to observe more stars around the comet than could the HRI.[2] The difference between the two instruments is their respective telescopes, which set the FOV and the resolution of each.

The ITS on the impactor was nearly identical to the MRI as it uses the same type of telescope as the MRI as well as the same type of charge-coupled device (CCD) that is in the MRI's Multi-Spectral CCD Camera. It differed only in that it lacked a filter wheel.

1.5 Mission Summary and Objectives

This summary is from the DI mission plan [2]. The purpose of the DI mission, the trajectory of which is shown in Figure 1-4, was to explore the interior of Comet Tempel 1 by using the impactor to excavate a crater in the comet's surface and then taking data on the newly-exposed cometary interior from the companion flyby spacecraft. DI is the eighth mission in NASA's Discovery Program, following Near-Earth Asteroid Rendezvous (NEAR), Pathfinder, Lunar Prospector, Stardust, Genesis, Comet Nucleus Tour (CONTOUR), and Mercury Surface, Space Environment, Geochemistry, and Ranging (MESSENGER). The project team was organized around the principal investigator, Dr. Michael A'Hearn of the University of Maryland; the science team of eleven other prominent experts on comets, remote sensing, and impact

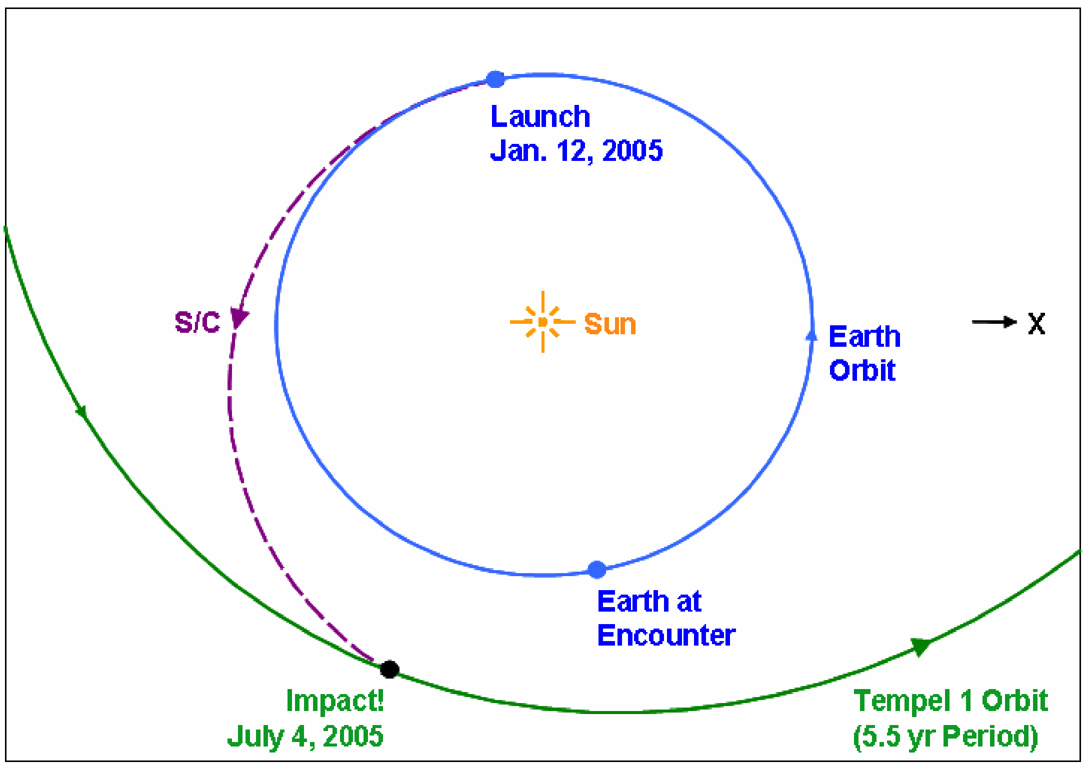

Figure 1-4. Deep Impact trajectory, showing encounter geometry.

[2] After extensive in-flight bake-out, the HRI remained still somewhat out of focus. To separate engineering and science planning functions for the encounter, the project decided about three months before encounter to use the MRI exclusively for optical navigation and to develop deconvolution algorithms for use on the HRI science images.

physics; the industrial partner, Ball Aerospace & Technologies Corp.; and JPL as the lead NASA Center for DI project management and flight operations.

The objectives of the DI mission, from Appendix 8 of the Discovery Program Plan, were as follows:

1. Dramatically improve the knowledge of key properties of a cometary nucleus and, for the first time, assess directly the interior of a cometary nucleus by means of a massive impactor hitting the surface of the nucleus at high velocity.
2. Determine properties of the surface layers such as density, porosity, strength, and composition from the resultant crater and its formation.
3. Study the relationship between surface layers of a cometary nucleus and the possibly pristine materials of the interior by comparison of the interior of the crater with the preimpact surface.
4. Improve our understanding of the evolution of cometary nuclei, particularly their approach to dormancy, from the comparison between interior and surface.

1.6 Mission Synopsis

1.6.1 Overview

Figure 1-5 gives an overview timeline for the mission. The figure and this synopsis are from the mission plan [2]. The two joined spacecraft (flyby + impactor) were launched from the Kennedy Space Center (KSC) on January 12, 2005, to approach the comet in early July 2005.

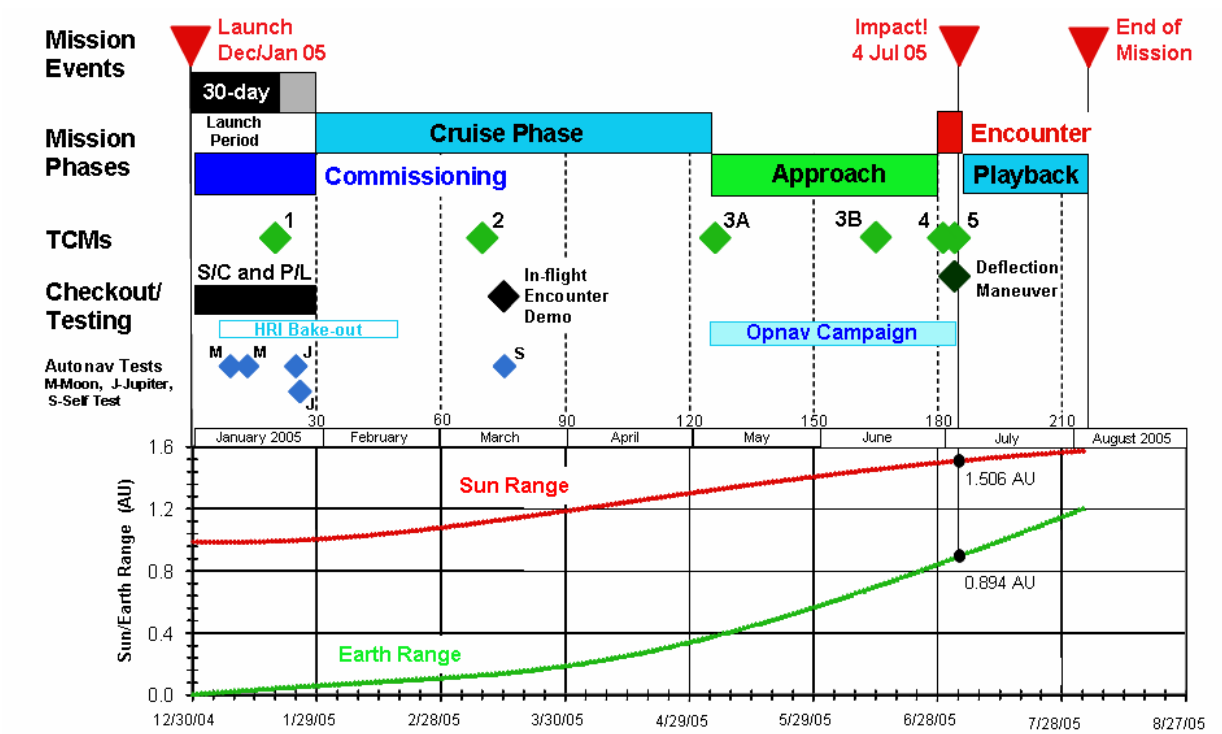

Figure 1-5. Mission phases.

Using spacecraft optical observations of the comet and conventional ground-based navigation techniques, the joined spacecraft were maneuvered as closely as possible to a collision trajectory with the nucleus of Tempel 1. The impactor was released 24 hours before impact. The flyby performed a divert (from collision with the nucleus) maneuver a few minutes after separation.

The impactor, operating on its battery, observed the approaching nucleus with an optical camera and maneuvered itself to a collision course toward the lighted portion of the nucleus. The flyby's divert maneuver delayed and deflected its flight path toward the nucleus so that it could observe the impact, ejecta, crater development, and crater interior during a 500-km flyby of the nucleus that occurred about 14 minutes after the impact. Close-in observations of the nucleus by the impactor camera were sent to the flyby spacecraft by a radio link in the last minutes before impact. The flyby spacecraft sent the highest-priority scientific and engineering data to the ground in real time during the encounter and also recorded the primary data sets for later playback. Simultaneous observations of the comet before, during, and after the impact were also conducted from ground and space-based observatories as an essential part of the total experiment. All scientific and supporting engineering data are being archived for future use by the scientific community.

The DI mission was originally proposed to launch in January 2004, using a one-year Earth-to-Earth trajectory and an Earth flyby to initiate a direct six-month transfer to intercept the comet. In March 2003, NASA approved a one-year launch delay to allow more time for delivery of the spacecraft hardware and system-level testing. The mission as flown used essentially the same six-month direct trajectory to the comet that was the final trajectory segment of the 2004 mission. Although some of the launch conditions changed from the previous plan, the required launch energy and launch mass capability were nearly identical, allowing continued use of the Delta II 7925 launch vehicle. The approach conditions at Tempel 1 are unchanged as well, so the designs for the approach and encounter phases of the mission were unaffected.

The telecom subsystems operated in only a few modes through the mission phases.[3] On the flyby, small deep-space transponder (SDST)-1 and TWTA-1 were prime. Through all phases, SDST-2 (backup) had the receiver powered on and the exciter powered off. TWTA-2 (backup) was powered off. S-band (on both flyby and impactor) was powered off except for an S-band checkout on February 24 during commissioning, an S-band data-flow test on May 6, a final S-band checkout on June 25 during approach, and the actual use of the S-band beginning shortly after separation in the encounter phase.

1.6.2 Launch Phase

The SDST-1 (primary) exciter was off and TWTA-1 was powered off at launch. The LGA was selected for both uplink and downlink. Coherency was enabled, and the flyby ranging channel was on in the low-modulation-index mode. As part of the onboard postlaunch sequence, the TWTA was powered on and warmed up, and the exciter was powered on before scheduled initial downlink acquisition. The uplink rate was sequenced to be 125 bps and the downlink rate

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[3] The flyby subsystem elements are described in detail in Section 3 and the impactor elements in Section 5. The LGA is a system of two antenna elements passively connected together and pointing in different directions. The term "LGA" used in this article refers to both LGAs as a system, not to one element or the other.

to be 2 kbps at initial acquisition.[4] After recovery from safe mode before the end of the initial acquisition pass, the downlink rate was commanded to 20 kbps for playback of launch data, and the uplink rate was commanded to 2 kbps. For the first three passes (24 hours) after launch, the stations transmitted at 200 W, and thereafter at their normal 20 kW.

1.6.3 Commissioning Phase

For commissioning, the downlink rate was increased to 200 kbps. Also during commissioning (beginning five days after launch), the HGA gimbals were unlocked, and HGA ability to move as commanded was checked out. After that, the HGA was Earth-pointed and became the primary antenna for uplink and downlink. The uplink rate on the HGA remained at 2 kbps.

1.6.4 Trajectory-Correction Maneuvers

The project scheduled 70-m stations for trajectory-correction maneuvers (TCMs). Coherency was left enabled and the ranging channel left on for all TCMs. Coherency provided two-way Doppler during the TCM burn for comparison with predictions. As of July 2005, the following TCMs have been performed:

- TCM-1 took place on February 11, 30 days after launch. The required burn attitude precluded the HGA from Earth-point. The TCM was on the LGA for uplink and downlink. The LGA could support the 2-kbps uplink rate[5] and 2-kbps downlink rate.
- TCM-3a and TCM-3b (May 5 and June 23) were done on the HGA 2-kbps uplink and 200-kbps downlink.
- TCM-5 (July 2, 30 hours before encounter) and the divert maneuver (just after separation) required the LGA 7.8125-bps uplink and 10-bps downlink.
- TCM-8 (July 20) to preserve the possibility of an extended mission to comet Boethin required the LGA 7.8125-bps uplink and 10-bps downlink.

1.6.5 Cruise and Approach

The HGA downlink supported 200 kbps over 70-m and 34-m tracks until the Earth-spacecraft range became too large for 200 kbps over 34-m stations. The downlink rate for 34-m stations became 100 kbps after mid-May 2005 and 40 kbps after mid-June. The recommended dates for switching were based on the standard telecom criterion of mean-minus-2-sigma link performance. Because impactor telemetry data could be transmitted only when the downlink rate was 100 kbps or higher, telecom made several near-real-time decisions on the supportability of 100 kbps for specific 34-m passes based on then-current performance.

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[4] The Universal Space Network's tracking station in western Australia received the 2-kbps downlink for a short period before safe mode occurred. The first DSN station, near Canberra, Australia, to have DI in view after launch initially received the 10-bps safe-mode downlink rate and commanded at the 7.8125-bps safe-mode uplink rate.

[5] Because of a station-related problem two days earlier, the TCM-1 was performed with a conservative 125-bps uplink rate using an overlay absolute-timed sequence to override the already sequenced 2-kbps uplink rate.

1.6.6 Encounter

The telecom configuration was iterated and reiterated through several operational readiness tests (ORTs) as well as an in-flight encounter demonstration test on March 24. Telecom configurations included tracking station support. For example, encounter (impact) was planned for a nominal time of 06:00 spacecraft event time (SCET) (06:07 Earth received time [ERT]) on July 4 in part because that time allowed both Canberra and Goldstone stations to track the spacecraft. In addition, a four-station array of 34-m stations was long planned to provide backup to the 70-m stations at Canberra and Goldstone at encounter. A few weeks before encounter, the same four-station array was scheduled to support the separation event, 24 hours before encounter. The encounter flyby spacecraft telecom configuration was as follows:

- Standard convolutional code (length 7, rate 1/2) for all phases, including encounter

  Rationale: Standard code had predicted performance sufficient for both the scheduled 70-m station and the scheduled four-station array to support 200 kbps on the day of encounter. Also, SDST "clear carrier" condition (see subsections 4.3.2, 4.5, and 10.2.3 below) cannot occur if the SDST encoding mode is not changed away from (7,1/2).

- HGA uplink and downlink until July 2 (day of year [DOY] 184), 02:13 Universal Time Coordinated (UTC) ERT, then LGA uplink

- 2-kbps uplink and 200-kbps downlink until July 2 (DOY 184) 02:13 ERT, then 7.8125-bps uplink

  Rationale: Maximize commandability against possible attitude mispointing.

- Coherency enabled and ranging on until July 3 (DOY 185) 01:42 ERT, then coherency disabled and ranging off

  Rationale: Protect the high-value downlink images from uplink problems (such as station transmitter problems). This close to encounter, optical navigation images were of greater value to navigation than were two-way Doppler or ranging (radio navigation) data.

1.6.7 Post-Encounter Activity

For two and a half days after encounter, the flyby performed a total of 15 cycles of alternating "look-back" sequences and playback. Each look-back precluded pointing the HGA toward Earth, so the LGA uplink and downlink (7.8125 bps and 10 bps) were sequenced. Playbacks returned HGA pointing to Earth (2 kbps uplink and 200 kbps downlink).

1.6.8 Delta–DOR

Delta-DOR (delta differential one-way ranging) was a special mode during cruise and approach. Each one-hour instance of this radio navigation mode required simultaneous tracking of the flyby by a pair of stations, with the antennas at both sites pointing alternately at the flyby and a quasar, and recording very-long-baseline interferometry (VLBI) data from the spacecraft or quasar. The *delta* in the name of the mode refers to the difference between downlinks from the spacecraft and the quasar. The *differential* refers to the use of downlinks to two stations.

One or two delta–DORs were planned for each week. During the hour, plus a preceding 15-minute warm-up time for the SDST auxiliary oscillator, the stations did not receive telemetry. Neither station uplinked during the delta–DOR warm-up or recording period. After the recording, an onboard telecom block would activate to return to standard telemetry downlink mode and rate.

The flyby telecom mode for delta-DORs was as follows:

- HGA downlink, coherency disabled (auxiliary oscillator on), and ranging off
- SDST DOR module on
- 375-kHz telemetry subcarrier on, with a 30° carrier modulation index
- Telemetry rate set to 10 bps (7,1/2)[6]

1.6.9 Safe Mode

A fault-protection response first put the flyby into safe mode shortly after launch. Safe mode was also used intentionally for flight software reboots. Safe mode has both uplink and downlink on the LGA, with an uplink rate of 7.8125 bps and a downlink rate of 10 bps. Safe mode for the flyby also has coherency enabled and the SDST ranging channel turned off.

[6] The delta-DOR activity needs the 375-kHz subcarrier as one of the delta-DOR tones. Ideally for delta-DOR, there would be no telemetry symbols on the subcarrier. However, telemetry symbols at a low rate do not degrade the delta-DOR measurement. Not switching the telemetry symbols off provides a means to avoid risk of the SDST "clear carrier" condition by leaving the SDST encoding mode in (7,1/2).

Section 2

Telecom Subsystem Requirements

2.1 Flyby Telecom

Table 2-1, from SER DI-SC-COM-020G [3], defines the principal requirements for the flyby X-band and S-band systems.

2.2 Impactor Telecom

The impactor telecom subsystem [4,5] provides the following functions:

- Receives as an S-band link from the flyby a modulated 16-kbps carrier, demodulates it, and outputs clock and command data to the impactor command and data handling (C&DH)
- Inputs science and engineering telemetry data from the impactor C&DH, modulates and transmits the telemetry at 64 kbps on an S-band link to the flyby

2.3 Deep Space Mission System Telecom

The Deep Space Mission System (DSMS) is a consolidated system of two multimission systems that provide support to flight projects and science investigations: NASA's DSN and JPL's Advanced Multi-Mission Operations System (AMMOS). DSMS is also called the Ground Data System (GDS).

The term "network" [6] refers to the combined ground system control and monitor functions that are carried out by the Deep Space Communications Complexes (DSCCs), Network Operations Control Center (NOCC), Central Communications Terminal (CCT), and AMMOS.

At top level, the GDS provides for

- Generation and radiation of an uplink carrier (which can be modulated with commands or ranging), and detection of and lock to a downlink carrier (which can be modulated with telemetry, ranging, or delta-DOR tones)
- Generation, storage, and transmission of commands from the project real-time mission controller (call sign ACE) to the station for radiation on the uplink carrier
- Reception, demodulation from the downlink carrier, decoding, routing, storage, and delivery of telemetry to the project from the station
- Processing from the downlink carrier and delivery of two-way Doppler data, ranging data, and delta-DOR data for navigation

Table 2-1. Key Deep Impact telecom requirements from SER-DI-SC-COM-020G.

Requirement	Capability	Verification
The flyby shall be DSN-compatible.	JPL-provided SDST transponders.	SDST unit-level verification and compatibility test.
The flyby shall be capable of simultaneously receiving and executing commands and transmitting telemetry continuously in all spacecraft modes.	Gimbaled HGA and LGA antennas located to provide continuous uplink and downlink coverage. Command rates from 7.8125 to 2000 bps; nominal rates 7.8125, 125, and 2000 bps; telemetry-rate capabilities from 10 to 400 kbps.	Verification by antenna model testing. Verification of spacecraft signal levels and performance. Test verification of all spacecraft modes. Verification by analysis using spacecraft and antenna test data.
The flyby shall have a peak downlink transmission capability through encounter of at least 174.9 kbps* (net, 70-m DSN) with lower data rates spaced at 1.5 ±0.3 dB or 50 kHz, and higher rates up to double the above.**	Telecom capability during encounter is at least 200 kbps (174.9 net, 3-dB margin). C&DH provides software-loadable divide ratios from a 24-MHz clock.	Primary data rates verified during integration and test (I&T) and final integrated system test (IST). Nominal set of data rates verified during functional test.
The flyby shall be capable of receiving data transmissions from and commanding the impactor during encounter.	S-band crosslink system, 64-kbps telemetry, 16-kbps command to max. 8,900 km.	Verification by antenna model testing. Verification of spacecraft signal levels and performance. Verification by flyby/impactor crosslink test. Verification by preseparation test.

* Bit error rate (BER) of less than 1*10-6, downlink ranging channel off, a maximum HGA offpoint from the Earth of 0.25°, a station antenna elevation angle 20°, and a 90% year-average weather model. The 174.9-kbps bit rate includes frame headers. With Reed-Solomon error-correction code blocks added, the channel bit rate is 200.0 kbps.

** The lower rates (down to 10 bps) are to allow transmission to a 34-m DSN station, to counter very adverse weather conditions, or to use the LGA. Higher rates (up to 400 kbps) are to allow transmission of more data but with lower link margins.

Section 3

Flyby X-Band Communications

3.1 Subsystem Block Diagram

Figure 3-1 is a functional block diagram of the X-band telecom system in the flyby.

The two low-gain antennas (LGA-1 and LGA-2) have their directions of maximum gain (boresights) along the flyby +Y axis and –Y axis, respectively. Through the hybrid coupler, they present a single antenna system at either the SDST receiver or the TWTA output. Between the antennas, within about +/-20° of the plane of the solar array, the LGA system gain is significantly lower than at boresight, with numerous nulls.

Either the LGA system or the HGA is connected to one of the SDST receivers via the coaxial transfer switch, and the other antenna is connected to the other receiver. Similarly, either the LGA system or the HGA is connected to the output of one of the TWTAs, and the other antenna is connected to the other TWTA. It is possible, as was done in the encounter mode, for the active receiver to be connected to the LGA and the active TWTA to be connected to the HGA. The normal mode prior to encounter was HGA for both uplink and downlink if the HGA could be pointed to Earth, and LGA for both uplink and downlink otherwise.

Throughout the flight mission, both SDST receivers have been powered, with the SDST-1 exciter also powered. TWTA-1 has been powered, and TWTA-2 has been off. As the diagram shows, either exciter can drive either TWTA.

For a downlink antenna swap, the following sequence of commands to the waveguide transfer switch (WTS) and the TWTA momentarily removes radio frequency (RF) from the

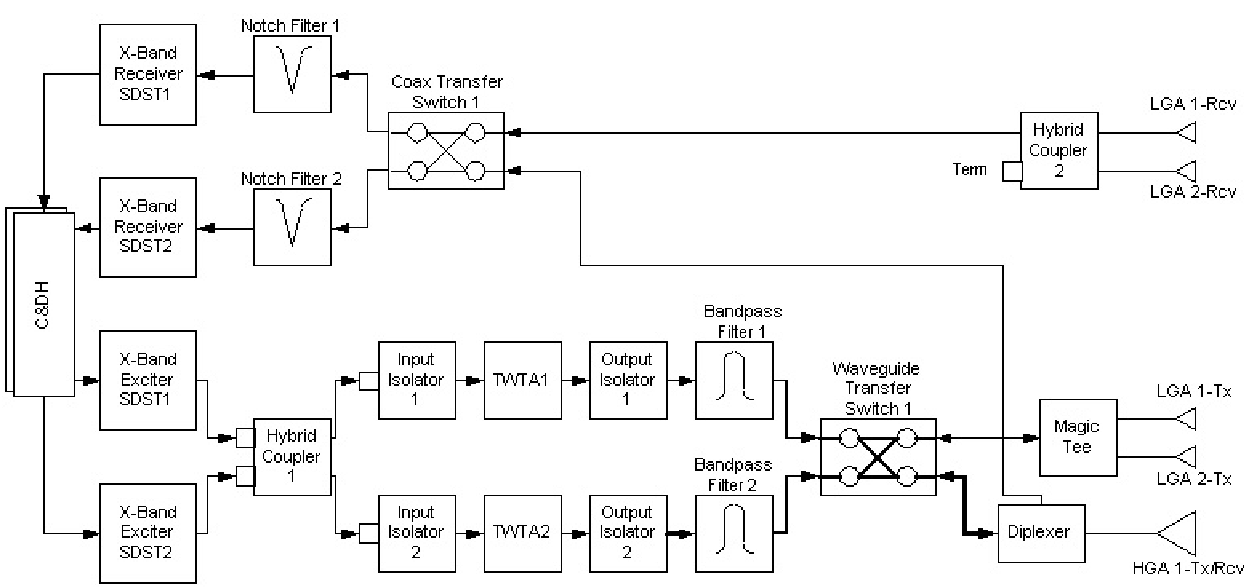

Figure 3-1. Flyby X-band telecom subsystem.

switch to prevent "hot switching": WTS powered on, TWTA beam to standby (RF output halted), WTS selected to desired antenna, TWTA beam to on (RF output resumed), WTS powered off.

3.2 Mechanical and Thermal Design

Figure 3-2 shows the mechanical design for X-band communications. The active TWTA with its electronic power converter (EPC) has drawn 54 W during flight, with an RF output averaging 42.6 decibel-milliwatts (dBm) (18.2 W). SDST-1 has drawn 13.5 W (exciter on), and SDST-2 11.2 W (exciter off). The TWTA baseplate temperature ran as high as 40°C a few days after launch and as low at 19°C near encounter. The SDST baseplate temperature varied from 45°C shortly after launch to 25°C near encounter.

3.3 X-Band Antennas

The flyby X-band antenna suite consists of the LGA pair and an HGA. The antenna polarization is right-hand circular. The antenna selected for spacecraft operations is dependent

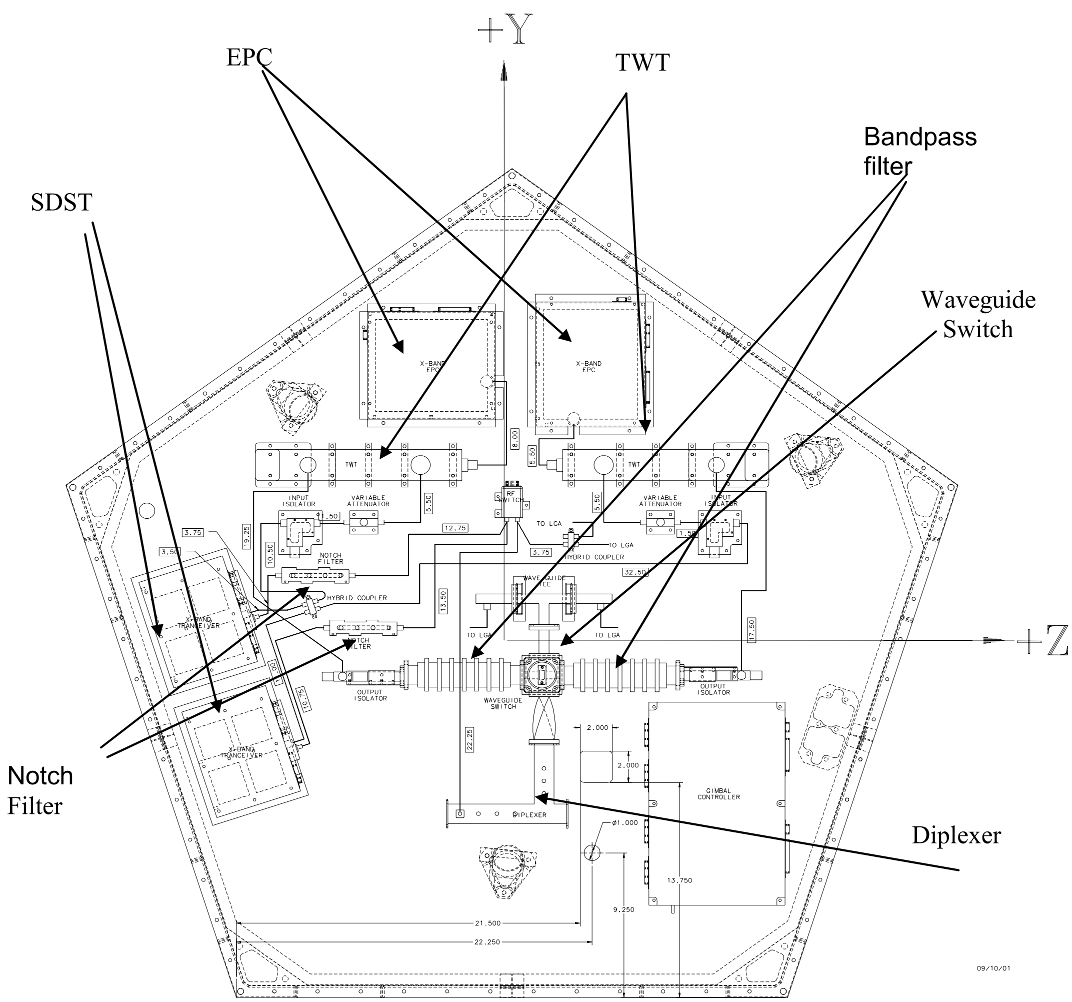

Figure 3-2. Mechanical layout of X-band components.

upon the orientation of the spacecraft in the mission, and the scheduling of the 34-m and 70-m ground antennas.

The LGA is similar to antennas used on past Ball Aerospace spacecraft. The LGA is composed of two coupled hemispherical microstrip patches radiating in opposite directions, +Y and –Y, providing a near-omnidirectional antenna pattern. Each of the two elements includes a receive patch and a transmit patch. The receive patches and the transmit patches are each connected via 3-dB couplers. The LGA system has a receive gain and transmit gain of approximately 3 dB isotropic (dBi) in the +Y and the –Y directions.

The HGA is a 1-m-diameter parabolic dish antenna providing 35.6 dBi circular (dBic) gain and 2.36° beamwidth at 8.435 GHz for the downlink, and at least 34.25 dB and a 2.76° beamwidth at 7.179 GHz for the uplink.

3.4 Telemetry Modulation

The C&DH subsystem accepts telemetry source packets from the flight software, forms telemetry transfer frames or fill frames, performs Reed-Solomon coding, attaches the synchronization word, and sends the resulting data stream to the telecom subsystem.

The C&DH subsystem provides telemetry data, data clock and symbol clock to the telemetry modulator in the SDST exciter at rates that are programmable. There are three sources of C&DH clock rates available: high-, mid-, and low-rate. Dividing a base frequency by a 20-bit divisor generates the high-rate clock. The mid-rate clock runs at 1/3 the rate of the high-rate clock. The low-rate clock runs at 1/6 the rate of the high-rate clock.[7] These rates correspond to SDST convolutional code rates of 1/6, 1/2, and uncoded.[8]

Tables 3-1 and 3-2, in a form often referred to as mi_look or modulation look-up tables, present the results of the compatibility testing between the flyby and the DSN in August 2004. The DSN was represented by the compatibility test trailer parked outside the DI test facility at Ball Aerospace. The tested data rates are in bright green (deep shading), and the modulation index values for SDST-1 used in flight are in pastel green (light shading).[9] SDST-1 is serial 204, and SDST-2 is serial 205.

The modulation index data number (for example 48) is the available value (0 to 63) that produces a modulation index closest to the optimum value in degrees (for example 72). Each data rate is intended to modulate a 25 kHz subcarrier, a 375 kHz subcarrier or the downlink carrier directly.

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[7] The choices for telemetry data clock are high- or low-rate. If the high-rate clock is used for the data clock, the symbol clock is not used (this is to support the S-band link on the impactor). If the low-rate clock is used for the data clock, the choices for symbol clock are high-, mid-, or low-rate.

[8] In flight, only the (7,1/2) convolutional code was used. The (15,1/6) capability was tested during assembly, test, and launch operations (ATLO), including in the DSN compatibility test (August 2004) and the MIL-71 test (November 2004).

[9] In the prime mission, through encounter, the flyby has downlinked at 10 bps, 2 kbps, 20 kbps, 40 kbps, 100 kbps, and 200 kbps.

The values in the three columns to the right are the thresholds for each data rate (expressed in the ratio of total received power to noise spectral density [Pt/No]).[10] The threshold for a given data rate is the lowest if only telemetry modulates the downlink. The threshold is slightly higher is the ranging channel is also on, sharing the downlink at its low index value of 0.185 radians, and higher yet if the ranging channel is on at high index value of 0.37 radians.

Table 3-1. (7,1/2)-Code telemetry modulation table for SDST-1 and SDST-2.

rates compatibility tested 8/2004
modified by A. Makovsky 11/18/04

(7,1/2) convolutional code			SDST-1 (s/n 204)		SDST-2 (s/n 205)		tlm only	tlm + rng LO	tlm + rng HI
conv. code	data rate, bps	sub-carrier frequency kHz	mod. index, degrees optimum	mod. index, DN integer	mod. index, degrees optimum	mod. index, DN integer	threshold Pt/No dB-Hz	threshold Pt/No dB-Hz	threshold Pt/No dB-Hz
(7,1/2)	**10**	25	46	31	46	31	18.75	19.05	19.95
(7,1/2)	16	25	48	32	48	34	19.15	19.45	20.35
(7,1/2)	32	25	55	36	55	38	20.93	21.23	22.13
(7,1/2)	**64**	25	60	40	60	41	22.96	23.26	24.16
(7,1/2)	128	25	65	44	65	45	25.24	25.54	26.44
(7,1/2)	512	25	72	48	72	49	30.35	30.65	31.55
(7,1/2)	1000	25	72	48	72	49	33.06	33.36	34.26
(7,1/2)	**2000**	25	72	48	72	49	36.06	36.36	37.26
(7,1/2)	4000	375	72	48	72	47	39.07	39.37	40.27
(7,1/2)	8000	375	72	48	72	47	42.08	42.38	43.28
(7,1/2)	12048.2	375	72	48	72	47	43.86	44.16	45.06
(7,1/2)	16000	375	72	48	72	47	45.09	45.39	46.29
(7,1/2)	**20000**	375	72	48	72	47	46.06	46.36	47.26
(7,1/2)	24096.4	375	72	48	72	47	46.87	47.17	48.07
(7,1/2)	31746	375	72	48	72	47	48.07	48.37	49.27
(7,1/2)	**40000**	375	72	48	72	47	49.07	49.37	50.27
(7,1/2)	50000	375	72	48	72	47	50.04	50.34	51.24
(7,1/2)	62500	375	72	48	72	47	51.01	51.31	52.21
(7,1/2)	80000	carrier	72	48	72	49	52.08	52.38	53.28
(7,1/2)	**100000**	carrier	72	48	72	49	53.05	53.35	54.25
(7,1/2)	**125000**	carrier	72	48	72	49	54.02	54.32	55.22
(7,1/2)	153846.2	carrier	72	48	72	49	54.92	55.22	56.12
(7,1/2)	**200000**	carrier	72	48	72	49	56.06	56.36	57.26
(7,1/2)	250000	carrier	72	48	72	49	57.03	57.33	58.23
(7,1/2)	285714.3	carrier	72	48	72	49	57.61	57.91	58.81
(7,1/2)	333333.3	carrier	72	48	72	49	58.28	58.58	59.48
(7,1/2)	400000	carrier	72	48	72	49	59.07	59.37	60.27

[10] Pt/No is the ratio of total signal power (W) and the noise power density (W/Hz). The ratio has units of Hz. When this ratio is expressed in decibel form, the units dB-Hz indicate the units of the ratio.

Table 3-2. (15,1/6)-Code telemetry modulation table for SDST-1 and SDST-2.

rates compatibility tested 8/2004

modified by A. Makovsky 11/18/04

(15,1/6) convolutional code			SDST-1 (s/n 204)		SDST-2 (s/n 205)		tlm only	tlm + rng LO	tlm + rng HI
conv. code	data rate, bps	sub-carrier frequency kHz	mod. index, degrees optimum	mod. index, DN integer	mod. index, degrees optimum	mod. index, DN integer	threshold Pt/No dB-Hz	threshold Pt/No dB-Hz	threshold Pt/No dB-Hz
(15,1/6)	10	25	49	33	49	34	19.39	19.69	20.59
(15,1/6)	16	25	51	34	51	35	19.74	20.04	20.94
(15,1/6)	32	25	54	36	54	37	20.41	20.71	21.61
(15,1/6)	64	25	57	38	57	39	22.12	22.42	23.32
(15,1/6)	128	25	61	41	61	42	24.15	24.45	25.35
(15,1/6)	512	25	69	46	69	47	28.87	29.17	30.07
(15,1/6)	1000	25	67	45	67	46	31.39	31.69	32.59
(15,1/6)	2000	375	71	48	71	47	34.34	34.64	35.54
(15,1/6)	4000	375	72	48	72	47	37.07	37.37	38.27
(15,1/6)	8000	375	72	48	72	47	40.08	40.38	41.28
(15,1/6)	12048.2	375	72	48	72	47	41.86	42.16	43.06
(15,1/6)	16000	375	72	48	72	47	43.09	43.39	44.29
(15,1/6)	20000	375	72	48	72	47	44.06	44.36	45.26
(15,1/6)	24096.4	375	72	48	72	47	44.87	45.17	46.07
(15,1/6)	31746	carrier	72	48	72	49	46.06	46.36	47.26
(15,1/6)	40000	carrier	72	48	72	49	47.07	47.37	48.27
(15,1/6)	50000	carrier	72	48	72	49	48.04	48.34	49.24
(15,1/6)	62500	carrier	72	48	72	49	49.00	49.30	50.20
(15,1/6)	80000	carrier	72	48	72	49	50.08	50.38	51.28
(15,1/6)	100000	carrier	72	48	72	49	51.05	51.35	52.25
(15,1/6)	125000	carrier	72	48	72	49	52.02	52.32	53.22
(15,1/6)	153846.2	carrier	72	48	72	49	52.92	53.22	54.12
(15,1/6)	**200000**	carrier	72	48	72	49	54.06	54.36	55.26
(15,1/6)	**250000**	carrier	72	48	72	49	55.03	55.33	56.23
(15,1/6)	**285714.3**	carrier	72	48	72	49	55.61	55.91	56.81
(15,1/6)	333333.3	carrier	72	48	72	49	56.27	56.57	57.47
(15,1/6)	400000	carrier	72	48	72	49	57.07	57.37	58.27

3.5 X-Band Transponder

The SDST provides the command and telemetry interface between the DI flyby and the NASA DSN. Figure 3-3 shows one of the "group buy" SDSTs (see subsection 10.2.3).

Both flyby SDSTs operate on DSN channel 29. The channel 29 center uplink frequency is 7179.650464 MHz. The channel 29 center downlink frequency is 8435.370371 MHz.

The SDST is the functional interface between the spacecraft antennas and the spacecraft C&DH. The X-band uplink signal is directed to the SDST receiver from the antenna subsystem via the coaxial transfer switch and other microwave components. The receiver acquires and tracks the uplink carrier by means of a phase-locked loop and produces a voltage-controlled oscillator (VCO) signal whose phase is coherent with the uplink carrier. With the aid of a phase-locked loop demodulation process, the ranging and command components of the composite uplink signal are demodulated. The ranging component is coupled to a turnaround ranging channel for downlink modulation. The command subcarrier is demodulated, and the command bits are sent to a bit synchronizer for data extraction

When coherent downlink transmission is enabled and the SDST receiver is in lock with an uplink carrier from the station, the receiver VCO frequency is utilized in the exciter to obtain a coherent X-band downlink carrier. When coherency is not enabled or the receiver is not in lock, the downlink carrier is derived from an alternate internal frequency source, the auxiliary oscillator.

Figure 3-3. Small deep-space transponder (typical).

The downlink carrier can be modulated by the turnaround ranging signal or the DOR tones, and the composite telemetry signal from the spacecraft telemetry signal from the spacecraft telemetry subsystem. The spacecraft telemetry data can be convolutionally or bi-phase encoded in the SDST and phase modulated directly on the X-band downlink carrier. Depending on data rate (see Table 3-1 or 3-2), the encoded telemetry data may also be modulated on a subcarrier in the SDST before phase modulation on the X-band downlink carrier.

3.6 X-Band Traveling-Wave Tube Amplifier

The DI system has redundant X-band TWTAs (see Figure 3-4). The X-band TWTAs amplify the exciter RF output to 20 W for downlink transmission. The RF input to the TWTAs is via an RF coupler from the SDST, regardless of which SDST is powered on. Though it was not planned, both TWTAs could have been powered at the same time without damage.

The TWTA requires an RF signal input of approximately -2 to 0 dBm for saturation drive. The SDST exciter outputs from the 3-dB coupler were targeted to approximately 4 dBm. Discrete component attenuators are used to establish the RF level at the TWTA input.

3.7 Uplink and Downlink Frequencies

Four frequencies associated with each SDST have needed to be adjusted or accounted for during flight, as would be true with any mission.

- The nominal channel 29 center uplink frequency is changed to the SDST actual best-lock frequency (BLF) to generate frequency predicts for station uplink operation. The BLF varies with temperature, as Figure 3-5 shows for SDST-1. Also, the BLF for SDST-2 differs from that for SDST-1.

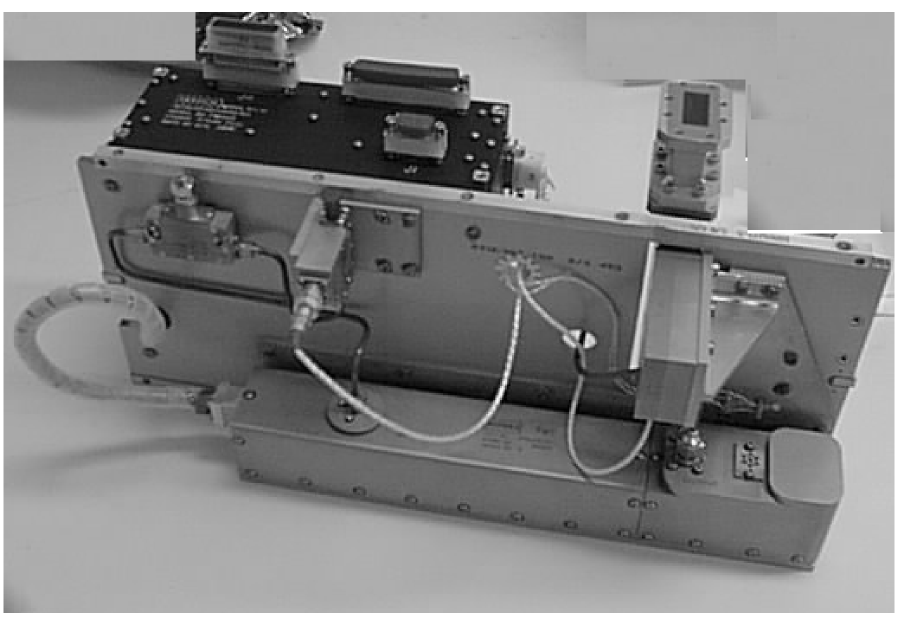

Figure 3-4. Flyby traveling-wave tube amplifier.

- The channel 29 center downlink frequency is changed to the SDST actual auxiliary oscillator transmit frequency (TFREQ) to generate predicts for station receiver operation. The TFREQ varies with temperature, as Figure 3-6 shows for SDST-1. The two SDSTs also have different TFREQs.
- The command subcarrier frequency is 16000.0 Hz. When the lowest command rate, 7.8125 bps, is used, it's necessary for the subcarrier frequency reaching the SDST receiver to be 16000.0 +/- 0.2 Hz. To compensate for the Doppler frequency shift on the uplink during 7.8125 bps operations, the transmitted command subcarrier frequency is set to a value dependent on the relative velocity between station and spacecraft. At encounter a value of 16000.9 Hz was used.[11]
- The SDST telemetry subcarrier frequency is produced by dividing down a reference frequency. While the "high" subcarrier frequency is 375000.0 Hz, the "low" frequency is actually 25000.33 Hz rather than the nominal 25 kHz referenced elsewhere in this article.

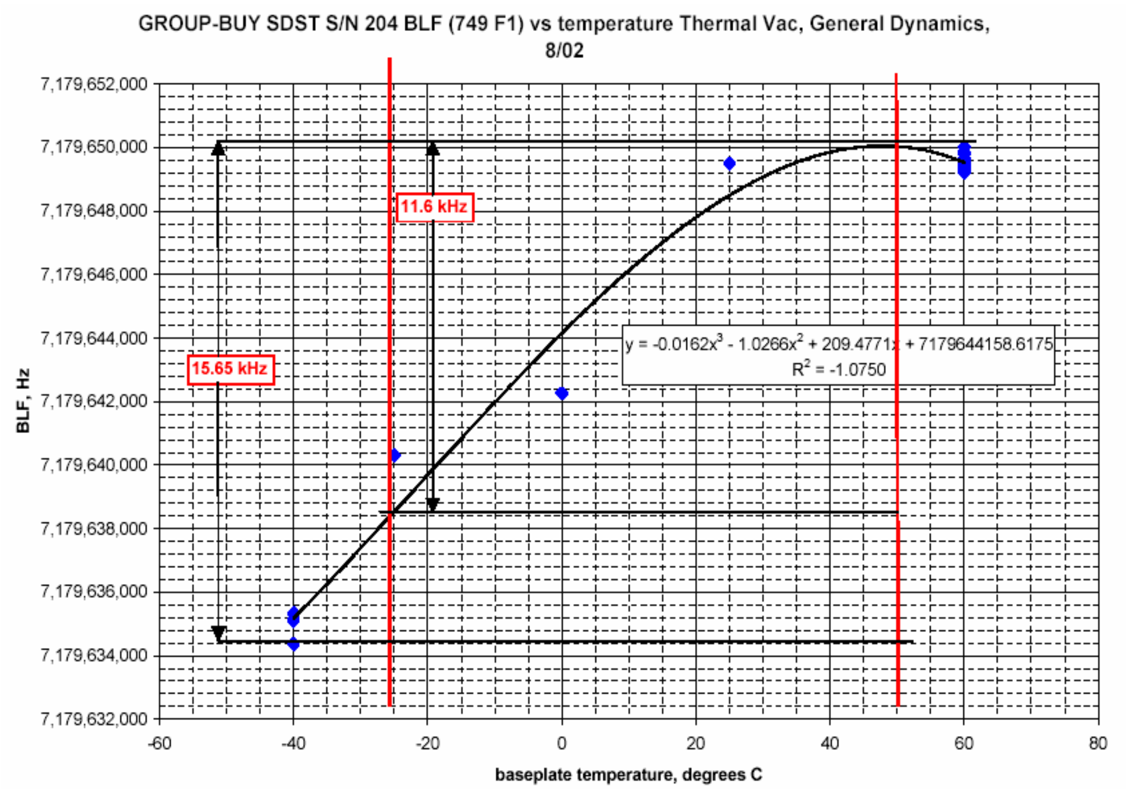

Figure 3-5. SDST-1 BLF vs SDST baseplate temperature.

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[11] The 7.8125-bps command rate is affected by Doppler in the same proportion as the subcarrier frequency. However, the SDST and C&DH require no compensation to the transmitted command rate for Doppler shift.

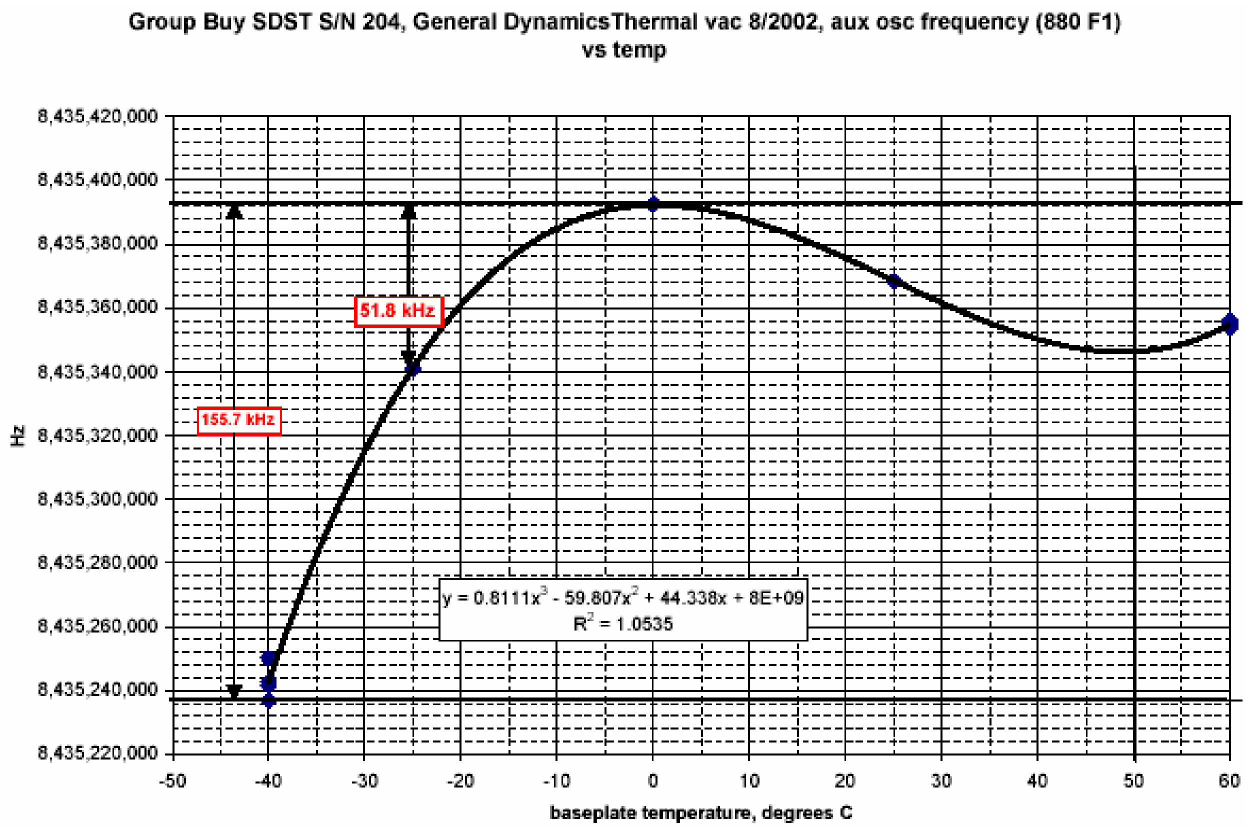

Figure 3-6. SDST-1 auxiliary oscillator TFREQ vs SDST baseplate temperature.

Table 3-3 shows the values of BLF and TFREQ that were specified to the DSN during flight.

Table 3-3. Changes made during flight in BLF and TFREQ for SDST-1 due to changing SDST temperature.

Change Made	BLF (MHz)	TFREQ (MHz)	Baseplate Temp.
Prelaunch	7179.648000	8435.372000	25°C
Jan 21, 2005	7179.649500	8435.355000	35°C
Jan 31, 2005	7179.649500	8435.343000	44°C
Mar 14, 2005	7179.646500	8435.351000	36°C
May 13, 2005	7179.644500	8435.360000	28°C
July 20, 2005	7179.642500	8435.370000	23°C

3.8 Mass and Power Summary, Flyby Telecom Subsystem Elements

Table 3-4 compiles the spacecraft power for the flyby telecom subsystem, both the X-band and the S-band for convenience. (The S-band section of the table duplicates that in Section 5.)

Table 3-4. Flyby telecom subsystem input power and mass (X-band and S-band).

	No. of units	Input Power[12] (W)	Mass/unit (kg)	Total mass (kg)
X-band				
SDST	2	11.2 receive mode 13.5 transmit mode	2.7	5.4
X-Band TWTA	2	54.0	4.5	9.0
HGA	1	-	2.8	2.8
X-Band Receive (RCV) LGA	2	-	0.06	0.12
X-Band Transmit (Xmit) LGA	2	-	0.06	0.12
WTS	1	-	0.49	0.49
Coax Transfer Switch	1	-	0.114	0.114
Microwave Components: 2 notch filters, 2 baseplate (BP) filters, 2 hybrid couplers, 1 diplexer, 1 waveguide (WG) tee, attenuators		-		2.17
X-band total				**20.2**
S-band—flyby				
Transceiver	1	1.6 receiver 8.2 transmitter	1.1	1.1
Medium-Gain Antenna (MGA)	1	-	1.2	1.2
Coupling Antenna		-		0.1
20 dB Coupler		-		0.03
Cabling		-		3.0
S-band flyby Total				**5.4**
Flyby total				**25.6**

[12] The two values for SDST input power are for receive mode (SDST exciter off) and transmit mode (exciter on). Transmit mode is defined here for the predominant mode of coherency enabled, ranging channel on. SDST-1 is in transmit mode, and SDST-2 in receive mode. The two values for the S-band transceiver are for the separately controlled transmitter and receiver.

Section 4

Operating the Flyby X-Band Communications Subsystem

4.1 Major Flyby Telecom Subsystem Commands

Table 4-1 provides an overview of the command names (mnemonics or "stems"), together with their main arguments, that were available to control the modes and states of the SDST and TWTA. (Commands for the flyby and impactor S-band transceivers are in Section 6.)

Many of the abbreviations and acronyms used in the tables of this section have been defined in the text above and in the list at the end of the article. Some acronyms frequently used in the tables are also defined in this paragraph for convenience: CTB is the command and telemetry board; RFF means radio frequency flyby; XBT stands for X-band transponder (XBT1 stands for SDST-1; XBT2 stands for STST-2); and LSB and MSB are least and most significant bits, respectively. (Abbreviations and acronyms that shed little light on the meaning of the tables in this context have been left undefined.) The terms "prime select," "prime," and "backup" refer to controllable values for redundant elements or functions used by fault protection. At a given time, TWTA-1 or TWTA-2 is designated as prime; SDST-1 or SDST-2 is designated as prime, and HGA or LGA is designed as prime.

Table 4-1. Flyby telecom subsystem commands and command arguments.

Command stem	Command function	Main argument values
RFFXBT_FREQ_25	Set telemetry subcarrier to 25 KHz.	
RFFXBT_FREQ_375	Set telemetry subcarrier to 375 KHz.	
RFFXBT_SC_FREQ	Set telemetry subcarrier frequency	LSB, MSB (each a data number)
RFFXBT_XMTR_ST	Turn SDST transmitter on or off.	On, off
RFFXBT_CMD_RT	Set SDST command rate.	1/CMDRT_7_8125, 2/CMDRT_15_625, 3/CMDRT_31_25, 4/CMDRT_62_5, 5/CMDRT_125, 6/CMDRT_250, 7/CMDRT_500, 8/CMDRT_1000, 9/CMDRT_2000
RFFXBT_MOD_INDX	Set SDST transmit modulation index.	0-63 (data number)
RFFXBT_ENC_MD	Set SDST encoding mode. Affects symbol clock rate on CTB.	0/OFF, 1/ENC_15_5, 2/ENC_7_5, 4/ENC_15_167, 10/BYPASSED
RFFXBT_RNG_MOD	Set SDST ranging modulation index.	0/RNGMOD_70, 4/RNGMOD_35, 5/RNGMOD_17_5, 6/RNGMOD_8_75, 7/RNGMOD_4_375
RFFXBT_BB_RNG	Select baseband ranging for indicated SDST.	Primary, backup, XBT1,XBT2
RFFXBT_MOD_MD	Set modulation mode. Enable subcarrier or carrier mode.	Subcarrier, carrier
RFFXBT_DOR_ST	Turn differential one way ranging (DOR) on or off.	On, off
RFFXBT_RNG_ST	Turn ranging on or off.	On, off

Command stem	Command function	Main argument values
RFFXBT_COHER_ST	Enable or disable the transmitter to be coherent with the receiver.	Disable, enable
RFFXBT_RMTR_TO	Enable or disable the remote terminal timeout.	Disable, enable
RFFXBT_NORM_TO	Enable or disable the timeout function for normal mode.	Disable, enable
RFFXBT_CLR_ERR	Clears SDST error message.	
RFFXBT_WBTLM_ST	Turn wideband telemetry mode on or off.	On, off
RFFXBT_PRIMESEL	Selects which SDST is considered prime for routing of commands	LGA, HGA
RFFCTB_TLM_SRC	SDST telemetry source select on CTB	XBT_1, XBT_2
RFFXBT_RBT	Reboots selected SDST. Command sent to CTB	Primary, backup, XBT1, XBT2
RFFNIC_PRIMESEL	Selects which NIC is considered prime for routing of TWTA & switch commands and telemetry.	NIC_A, NIC_B
RFFTWT_PRIMESEL	Selects which TWTA is considered prime for routing of commands	TWT_1,TWT_2
RFFTWT_XMT_ST	TWTA beam voltage. Set indicated TWTA to transmit state.	Standby, on
RFFTWT_HGA	Sets waveguide switch position. Connect indicated TWTA to indicated antenna	Primary, backup, LGA, HGA
RFFRCV_HGA	Sets transfer switch position. Connect indicated SDST to indicated antenna	Primary, backup, LGA, HGA
RFFXLNK_CONFIG	Configuration of crosslink hardware. Packet sent to NIM-ICB	0/DISABLE_ALL, 1/HARDLINE, 2/SBAND, 3/SBAND_HDLINE, 4/GSE, 5/GSE_HDLINE, 6/GSE_SBAND, 7/ENABLE_ALL
RFFXLINK_RST	Reset crosslink. Packet sent to NIM-ICB	
RFFCTB_SYNC_WD	Set command sync word length on CTB	
RFFCTB_CLK_DIV	Set high rate clock divisor. No state enumeration exists.	
RFFCTB_TLM_RT	Set high rate clock divisor for telemetry rate.	8/RT_500000, 10/RT_400000, 12/RT_333333, 16/RT_250000, 20/RT_200000, 26/RT_153846, 32/RT_125000, 40/RT_100000, 50/RT_80000, 64/RT_62500, 80/RT_50000, 100/RT_40000, 126/RT_31746, 166/RT_24096, 200/RT_20000, 250/RT_16000, 332/RT_12048, 500/RT_8000, 1000/RT_4000, 2000/RT_2000, 4000/RT_1000, 7814/RT_512, 31250/RT_128, 62500/RT_64, 125000/RT_32, 250000/RT_16, 400000/RT_10, 14/RT_285714
RFFXBT_RST	Reset command sent to SDSTs via 1553	

Command stem	Command function	Main argument values
RFFCTB_CMD_SRC	Command source select on CTB. SDST A or SDST B on flyby	Primary, backup, XBT1, XBT2
RFFSCB_WGSEC_PW	Select waveguide switch power to on or off	Off, on
RFFANT_PRIMESEL	Select a prime antenna for fault-protect response.	LGA, HGA
RFFMONENABLE	Enable or disable a monitoring-function	SBND, SDST, TWTA

4.2 Major Flyby Telecom Subsystem Engineering Telemetry

Table 4-2 provides an overview of the telemetry channels that were used to monitor the modes and performance of the SDST and TWTA. S-band telemetry for both flyby and impactor is in Section 6. In general, the channels listed below are for SDST-1 only and TWTA-1 only. The backup units (not used in flight) have corresponding telemetry measurements (not included).

Table 4-2. Flyby X-band telecom subsystem engineering telemetry measurements.

Telemetry name	Subsystem function	Channel No.	Values
PWFXBT1CUR_A	SDST-1 input current	E-0685	converted to A
PWFHGACUR_A	HGA input current	E-0698	converted to A
PWFTWTA1CUR_A	TWTA-1 input current	E-0699	converted to A
THFT_HGAGB2	HGA gimbal temperature	T-0314	converted to C
THFT_SDST1BP	SDST-1 baseplate temperature	T-0323	converted to C
THFT_TWTA1BP	TWTA-1 baseplate temperature	T-0332	converted to C
THFT_EPC1BP	TWTA-1 EPC temperature	T-0365	converted to C
RFFXBT1_CAR_LK	Carrier Lock	R-0155	0/unlock, 1/lock
RFFXBT1_CDU_LK	CDU lock	R-0156	0/unlock, 1/lock
RFFXBT1_RT_TO	RT Timeout	R-0157	0/disabled, 1/enabled
RFFXBT1_HL_CMD	Hard-line command	R-0158	0/disable, 1/enable
RFFXBT1_XMTR_ST	X-Band exciter status	R-0160	0/off, 1/on
RFFXBT1_XDOR	XDOR Tlm status	R-0162	0/off, 1/on
RFFXBT1_RNG_ST	Ranging status. 0/Off, 1/On	R-0164	0/off, 1/on
RFFXBT1_VCO_TMP	VCO Temperature	R-0165	converted to C
RFFXBT1_OSC_TMP	Aux Osc Temperature	R-0166	converted to C
RFFXBT1_VCO_TRF	SDST 1 Word A3; VCXO/Aux Osc Transfer.	R-0168	0/enable, 1/inhibit
RFFXBT1_COHEREN	Coherency	R-0169	0/enable, 1/disable

Telemetry name	Subsystem function	Channel No.	Values
RFFXBT1_ENC_MD	Telemetry encoding mode	R-0173	0/Off, 1/Rate 15.5 conv encoded, 2/Rate 7.5 conv encoded, 3/Rate 15.25 conv encoded, 4/Rate 15.167 conv encoded, 5/Rate 15.5 conv encoded + manchester, 6/Rate 7.5 conv encoded + manchester, 7/Rate 15.25 conv encoded + manchester, 8/Rate 15.167 conv encoded + manchester, 9/Manchester encoding only, 10/Encoding bypassed
RFFXBT1_MOD_MD	Modulation mode	R-0174	0/SUBCARRIER, 1/CARRIER
RFFXBT1_WB_TLM	Wideband telemetry status	R-0175	0/OFF, 1/ON
RFFXBT1_MOD_IND	Telemetry modulation index	R-0176	Converted to degrees
RFFXBT1_SC_FRQM	Subcarrier frequency MSB	R-0177	Data number
RFFXBT1_SC_FRQL	Subcarrier frequency LSBs	R-0178	Data number
RFFXBT1_RNG_GS	Ranging gain setting	R-0180	0/DEG_70, 4/DEG_35, 5/DEG_17_5, 6/DEG_8_75, 7/DEG_4_375
RFFXBT1_RNG_AGC	Ranging AGC	R-0183	
RFFXBT1_DIG_AGC	Digital AGC. Current signal strength of signal entering the transponder.	R-0186	Converted to dBm
RFFXBT1_CAR_STR	Carrier lock accumulator	R-0187	Converted to dBm
RFFXBT1_PC_CURR	PC Input current	R-0188	Data number
RFFXBT1_PC_VOLT	PC +5 V unswitched voltage	R-0189	Data number
RFFXBT1_DATA_RT	Command data rate	R-0184	0/NOT_USED, 1/RT_7_8125, 2/RT_15_625, 3/RT_31_25, 4/RT_62_5, 5/RT_125, 6/RT_250, 7/RT_500, 8/RT_1000, 9/RT_2000
RFFXBT1_SPE	Static phase error (SPE)	R-0185	Converted to degrees
RFFTWT1_CCURR	TWTA 1 Cathode current	R-0250	Data number (volts)
RFFTWT1_HCURR	TWTA 1 Helix current	R-0251	Data number (volts)
RFFTWT1_INCURR	TWTA 1 Input current	R-0252	Data number (volts)
RFFTWT1_RFIN_PW	TWTA 1 RF Input Power	R-0253	Converted to dBm
RFFTWT1_RFOU_PW	TWTA 1 RF Output Power	R-0254	Converted to dBm
RFFCTB_SYNC_WD	CTB start sequence word length. 0/16 bit, 1/32 bit	R-0240	0/LEN_16, 1/LEN_32
RFFCTB_CMD_SRC	Command source select on CTB.	R-0241	0/RECEIVER_1, 1/RECEIVER_2
RFFXBT1_TLM_SRC	SDST 1 telemetry source select	R-0243	0/SCU_B, 1/SCU_A
RFFCTB_SYM_CLK	Symbol clock rate	R-0261	0/LOW, 1/MID, 2/HIGH, 3/UNKNOWN
RFFXBT1_HGA	SDST 1 connection to the HGA.	R-0232	0/LGA, 1/HGA
RFFTWT1_HGA	TWTA 1 connection to the HGA	R-0236	0/LGA, 1/HGA

Telemetry name	Subsystem function	Channel No.	Values
RFFXBT1_EVT_CTR	SDST Event Counter	R-0262	Data number
RFFXBT1_WB_AGC	Wideband receiver automatic gain control.	R-0284	Converted to dBm
RFFXBT1_CD_AGC	Command Detector AGC	R-0285	Data number
RFFXBT1_SNR	Signal/Noise Ratio	R-0286	Data number
RFFXBT1_LO_SPE1	1st LO Static Phase Error	R-0287	Data number
RFFXBT1_LO_SPE2	2nd LO Static Phase Error	R-0288	Data number
RFFXBT1_EXC_SPE	Exciter LO static phase error	R-0289	Data number

4.3 Flyby Telecom Contingency Procedures

The two flyby telecom contingency procedures [7,8] are to guide the flight team to identify and recover from either loss of commandability ("no uplink") or loss of telemetry ("no downlink").[13]

4.3.1 Loss of Uplink Capability

Loss of uplink capability can be caused by one or more of the following:

- Processing or transmission problem on the ground (ground command system, transmitter, antenna)
- Spacecraft attitude that is improper or unknown (most likely would affect the downlink similarly in received signal level variation as a function of time)
- Spacecraft power loss (most likely would affect the downlink as well)
- Rarely, local environmental or solar problem such as heavy rain at the station or a burst of charged particles from the sun crossing the downlink path (would affect the downlink more severely)
- Loss or degradation of an onboard telecom uplink or control function
- Sequence error
- C&DH or flight software fault
- Other onboard system failure

The "no uplink" contingency plan is invoked when telemetry indicates that the flyby did not react to a command radiated from the station. Under the lead of the mission manager and the telecom analyst, the flight team steps through the plan methodically to eliminate or pinpoint potential causes and to recommend actions to restore commandability to continue the mission. A summary of the "no uplink" plan is as follows:

- In parallel to this plan, the mission controller (ACE) coordinates the GDS in the use of their own plan to determine if a ground problem is the likely cause.

[13] The impactor had no telecom-specific contingency procedures.

- Coordinate with the GDS to resolve the cause of any alarms in the ground command system or tracking station.
- On the flight team side, recheck the command radiation form and supporting documentation to make sure the command is correct in function and format.
- Confirm that telemetry remained in lock after command radiation. If it didn't, the safe-mode downlink and safe-mode command rate need to be considered.
- If the uplink has ranging modulation, the ACE requests it turned off and the command retried.
- If the SDST telemetry indicates abnormalities in the received uplink signal level or frequency offset, the ACE will request the station to resweep the uplink in preparation for sending the command again. If the uplink sweep is not successful, a likely cause is a problem with the station transmitter or the SDST. Consider using a different tracking station or sweeping to the backup SDST.
- If the resweep is not successful, a likely cause is a problem with the station transmitter or the SDST. Consider using a different tracking station or sweeping to the backup SDST.
- After each change in configuration, radiate a test "no operation" command.

4.3.2 Loss of Downlink Signal

Downlink signal losses of various durations can be caused by one or more of the factors listed below. Abnormal downlink can be caused by any of these as well as a variety of ground processing faults.

- Receiving or processing problem on the ground (antenna, receiver, downstream equipment)
- Local environmental or solar problem such as heavy rain at the station or a burst of charged particles from the sun crossing the downlink path
- Failure or degradation of an onboard downlink or control function, such as the following:
  - If both exciters are inadvertently powered on, the downlink will have subcarrier and telemetry, but garbled. After a transponder reset, the power-on-reset state will turn on the exciter. Fault protection would then run to configure one or the other as prime.
  - If fault protection has switched TWTAs, the second TWTA will need 5 minutes before it will power on the beam and produce an RF output downlink carrier.
  - If the power subsystem voltage drops below 25 V, the TWTA will shut off. When it rises above 26.5 V, the TWTA will restart with a 5-minute warm-up.
  - Also, an encoding command to the SDST may cause "clear carrier" (no telemetry modulation, no subcarrier).
- Sequence error

- Spacecraft attitude that is improper or unknown
- Spacecraft power loss, C&DH, flight software fault, or other onboard system failure

The "no downlink" contingency plan is invoked if a tracking station is unable to lock up telemetry normally at the beginning of a pass, or if telemetry drops lock during a pass. As with the "no uplink" plan, the ACE coordinates the GDS in determining if a ground problem is the likely cause of the outage. If a second receiver at the allocated station, or a second station, is available, this is often the quickest way to lock up the downlink in the case of a station problem.

After the preliminary GDS determination of the state of their equipment, under the lead of the mission manager and the telecom analyst, the flight team walks through the contingency plan to resolve the cause and establish an approach to restore the downlink. The following presumes a normally operating GDS:

- If the station receiver cannot lock to the carrier, the station operator evaluates the carrier and the spectrum around the carrier to determine if there is a difference in frequency, level, or modulation from the expected. If, for example, the subcarrier frequency differs from the expected, the safe mode may be suspected. If the station can lock the carrier, but sees no modulation spectrum, the SDST may have entered the "clear carrier" mode and will have to be rebooted to get back to normal mode.
- If the station is able to lock the telemetry symbols and bits, but the ground system is unable to achieve frame sync on the data, a C&DH problem called "first packet header pointer problem" may have occurred. This problem is remedied by transmitting a "recipe" (a series of commands).

A separate branch of the "no downlink" contingency plan was applied to DI's initial acquisition pass after launch.[14] This branch, which is nearly the same for any deep space mission, addresses possible problems involving the launch vehicle and radio information available from the launch vehicle. For DI, the plan asks the project to coordinate with the launch vehicle team to determine if the S-band downlink from the third state has been seen, what its level is as compared to predictions, and what its stability in level is. This launch vehicle information is compared with what the DSN is seeing from the spacecraft, to try to isolate launch vehicle problems from spacecraft problems. An abnormally varying level may indicate that the launch vehicle did not release the spacecraft at the expected time or orientation.

[14] The first part of the initial acquisition pass by the DSN was not normal. The flyby had entered safe mode by the time the first station in eastern Australia came into view. Fortunately, the project had procured the services of the Universal Space Network (USN) tracking station in western Australia. The USN saw a normal downlink initially and then the transition to safe mode. This information guided the actions of the flight team and the ACE's coordination with the DSN. The flight team recovered the flyby from safe mode and got back on the planned time line during the initial acquisition pass.

4.4 Flyby Telecom Fault Protection

DI fault protection is provided in both the flyby and impactor. Fault protection has monitor and response algorithms. One or more response algorithms are kicked off when a defined fault is detected by the monitor. Repair responses for subsystem elements (SDST, TWTA, waveguide transfer switch, coaxial transfer switch, S-band) generally are in the following four tiers, from mildest to most forceful. "Enforce" means to issue the commands to reestablish the unit to its prefault configuration.

1. Reboot (reboot the faulty unit, then run "enforce"
2. Cycle (power the faulty unit off and back on, then run "enforce")
3. Escape (powers the backup unit on, makes it prime, runs "enforce" on it)
4. Isolate (same as Escape, but also powers off the presumed faulty unit)

When the SDST is rebooted or powered on, it configures itself to a known state, called power-on-reset (POR). Table 4-3 shows the POR states for the DI SDST.

Table 4-3. SDST power-on-reset table for Deep Impact flyby.

SDST Power On Reset States	
parameter	POR State
Transponder Mode	Normal
Auto Coherent/Nocoh. Transfer	Enabled
VCXO/Aux OSC Transfer	Enabled
Command Data Rate	7.8125
X-Band Exciter	On
Normal TLM Mode	Subcarrier
Subcarrier Frequency	25 kHz (nominal)
Normal TLM Mod. Index	50 deg (nominal)
Normal TLM encoding mode	Convolutional 7-1/2
Wideband TLM	Off
Ranging	Off
Ranging Mode	Baseband (turn around)
Ranging Mod.Index	17.5 deg (1/4x) nominal
XDOR	Off
SDST Event Counter	0
RT Event Counter	0
Remote Terminal Time-out	Disabled
State 1 Time-out	Enabled

Section 5

Flyby and Impactor S-Band Communications

5.1 Summary

The S-band crosslink provided communication between the flyby and the impactor during the encounter phase of the mission.[15] Both the flyby and the impactor have an S-band transceiver, diplexer, and antenna. Additional components were needed for the pre-separation tests done three times during the commission, cruise, and approach phases of the mission. These additional components consist of a 20-dB coupler, a 20-dB attenuator, and a coupling ("whisker") antenna on the flyby, and two RF switches, two 30-dB attenuators, and one 3-dB attenuator on the impactor.

Figure 5-1 includes block diagrams of the S-band subsystems for the flyby and impactor. The connector plate on the flyby block diagram is the interface between components on the interior of the spacecraft and components on the exterior of the spacecraft.

The impactor-to-flyby link is at 64 kbps at a frequency of 2105 MHz, and the flyby-to-impactor link is at 16 kbps at a frequency of 2280 MHz. These crosslink carrier frequencies are also listed in Table 5-1.

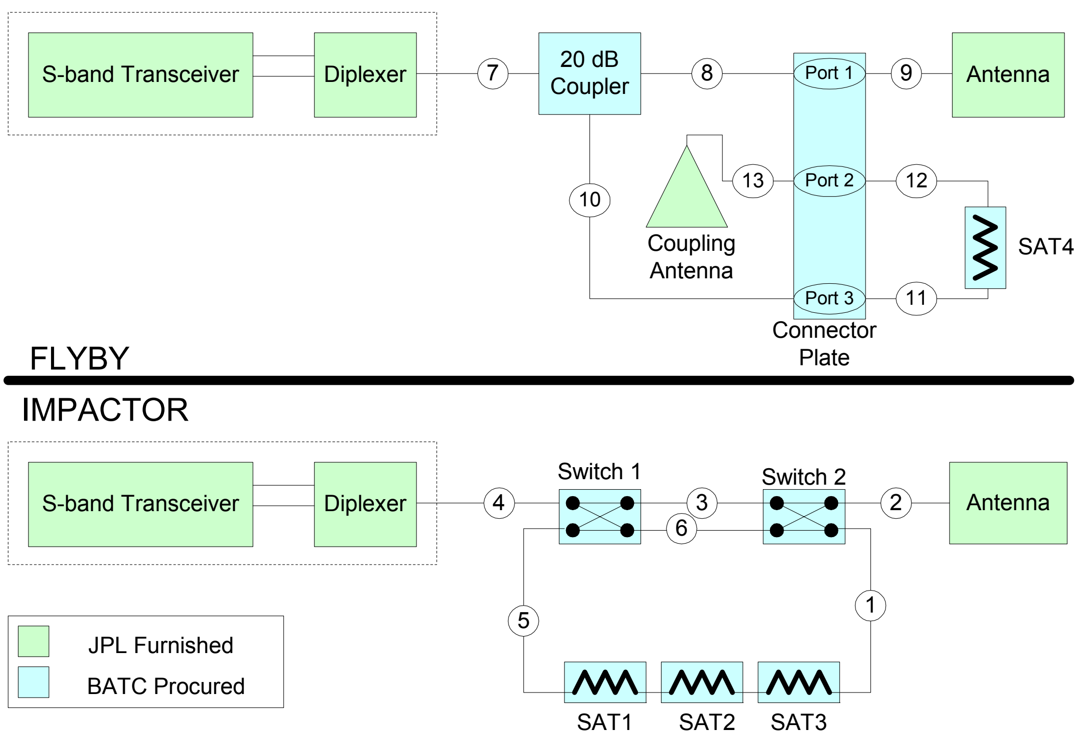

Figure 5-1. Flyby and impactor S-band block diagrams.

[15] This section of the article was written in July 2005 after the last and successful use of the S-band system.

Table 5-1. S-band (crosslink) frequencies.

	Transmit Freq (MHz)	Receive Freq (MHz)
Flyby	2280	2105
Impactor	2105	2280

5.2 S-Band Transceiver, Flyby and Impactor

The Thales S-band transceiver (shown in Figure 5-2) is composed of an electrically isolated transmitter and receiver; and a diplexer, which allows the combination of the two signals in a common antenna. The transmitters put out 2 W of RF power. The transceivers are devices developed for space application with full duplex digital data transmission capability. The receiver and transmitter are fully independent, and each one can be activated separately.

The transceiver transmitters use a communication protocol to achieve fast signal acquisition. The transmitter sends an unmodulated carrier preamble for 0.5 seconds before the digital data transmission starts. During the pure carrier preamble, the receiver's local oscillators lock carrier frequency; then the digital quadrature phase-shift-keyed (QPSK) demodulator phase-locks to the carrier (alternating *1*s and *0*s). Total worst-case receiver acquisition time is

- Less than 8 minutes at 16 kbps (16 seconds typical) if the carrier shift is less than ±12 kHz, and
- Less than 2 minutes at 64 kbps (8 seconds typical) if the carrier shift is less than ±50 kHz.

Local oscillators are locked on internal 10-MHz oven-controlled crystal oscillators (OCXOs). If the receiver loses lock, the receivers will acquire on the modulated RF (carrier-only preamble not required), but acquisition times could be as long as the worst case.

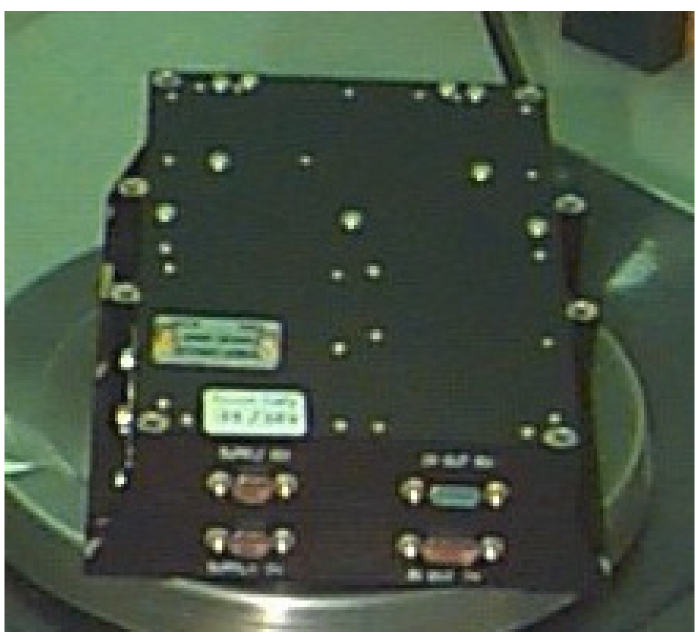

Figure 5-2. S-band transceiver and diplexer.

The receiver and the transmitter are independently operable, each with its own microcontroller.

The impactor will continuously provide clock and data to the transmitter. When the transceiver transmitter is powered on, it will not transmit for one minute, for a warm-up time. After the warm-up time and after the unit receives a data clock signal, the transmitter will transmit an unmodulated carrier for approximately 0.5 seconds and then provide a modulated QPSK output.

The impactor C&DH subsystem provides data and symbol rate clock to the transmitter. The transmitter differentially encodes the input data and then convolutionally encodes the differential data before QPSK modulating the downlink carrier with the convolutional data.

The system provides Consultative Committee on Space Data Systems (CCSDS)-compatible commands to the impactor C&DH.

5.3 S-Band Antenna, Flyby and Impactor

The S-band antenna provided by JPL is shown if Figure 5-3. The antenna has a gain of 18.7 dBi, mass of 1.2 kg, and dimensions of 3.8 cm × 71.12 cm x 35.56 cm. Identical antennas were provided for the flyby and the impactor.

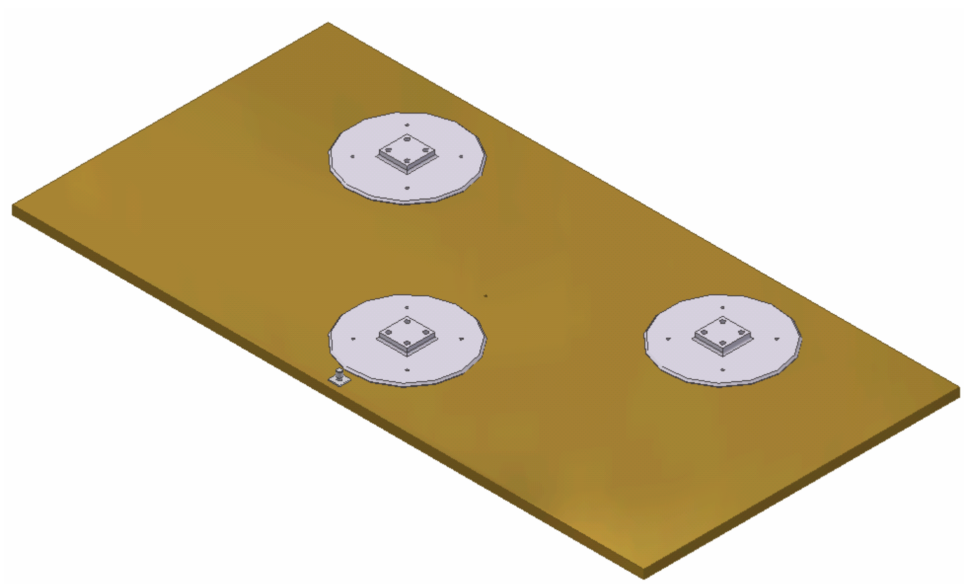

Figure 5-3. S-band antenna (viewed from spacecraft mounting side).

5.4 Impactor Attenuator Switch

The impactor S-band subsystem includes a Slonski switch configuration, which results in two paths directly through the switches to the antenna, and two paths in which the signal is attenuated 63 dB before reaching the antenna. Figure 5-4 shows the four possible switch configurations.

When the two switches are in different positions (SW 1 = Pos 1, SW 2 = Pos 2 or SW 1 = Pos 2, SW 2 = Pos 1), the RF signal is attenuated 63 dB. During the S-band checkouts on February 24, May 6, and June 25, one switch was in the cross position and the other in the through position.

With both switches in position 1 or both switches in position 2, the RF signal goes to the antenna without passing through the attenuators. Shortly before separation, both switches were commanded to the cross position for minimum attenuation.

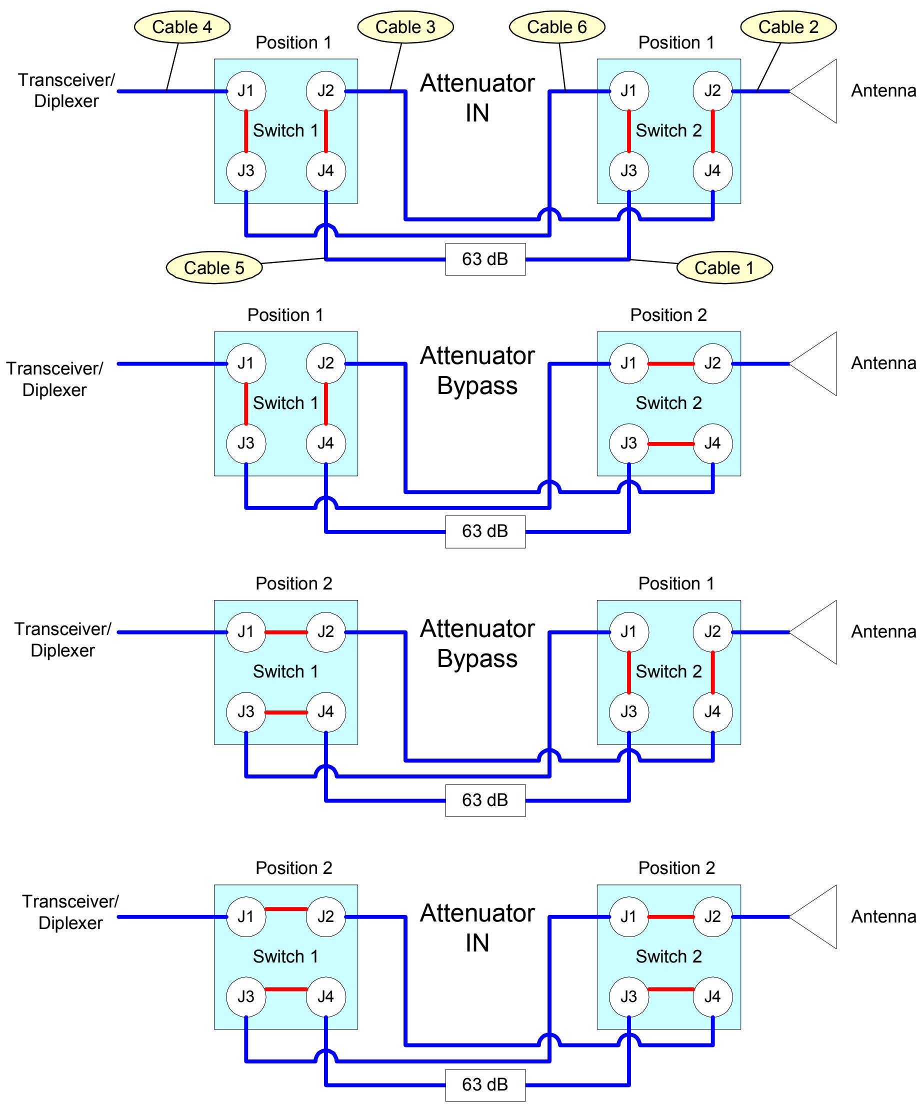

Figure 5-4. Switch configuration options.

5.5 S-Band Link Prediction and Assessment

5.5.1 Assessment

Qualitatively, both S-band links worked flawlessly up to the moment of impact. However, neither S-band transceiver provided a quantitative measure of received carrier level or data signal-to-noise ratio (SNR). By design, telemetry from each spacecraft provided only an in/out indication of receiver carrier lock and receiver bit lock.

5.5.1.1 Flyby-to-Impactor. After the links were initially established (both transmitters on) 7 minutes after separation, an S-band lockup "recipe" signal was sent from the flyby to the impactor. The recipe includes a short period of unmodulated carrier, followed by a pseudorandom bit pattern, followed by five "no operation" (NO_OP) commands. Thereafter, single NO_OP commands were radiated hourly from the ground to the flyby, then routed over the S-band link to the impactor. All NO_OPs were confirmed in impactor telemetry.

5.5.1.2 Impactor-to-Flyby. All planned science and engineering data transmitted from the impactor to the flyby was confirmed by flyby telemetry as received.

5.5.2 Prediction

Tables 5-2 and 5-3—reproduced from SER DI-IMP-COM-101 [5]—present the S-band flyby-to-impactor command link and the impactor-to-flyby telemetry link. The link margins[16] are 8.8 dB for the command link and 3.5 dB for the telemetry link.

[16] The link margin was calculated for a 1*10-5 BER for uncoded data. The 1*10-6 BER requirement is met by the Reed-Solomon encoding of the link.

Table 5-2. Flyby-to-impactor S-band link budget.

Flyby-Impactor Command Link S-Band Link Budget, Freq= 2280 MHz, 16 kbps	Value		Comment
Transmitter Power	32.9	dBm	2 Watts
Flyby Line Loss	-1.7	dB	
Antenna Gain	15.9	dBi	16 element patch array
Antenna Pointing Loss	-0.1	dB	+/- 1 deg
Flyby EIRP	47.1	dBm	
Path Loss	-178.4	dB	8700 km
Impactor Antenna Gain	19.3	dBi	16 element patch array
Antenna Pointing Loss	-0.6	dB	+/ 5 deg
Axial Ratio Loss	-0.6	dB	
Impactor Line Loss	-0.8	dB	
Received Power	-114.0	dBm	
Receiver Sensitivity (specified)	-122.8	dBm	BER = 1E-05
System Margin	8.8	dB	

Table 5-3. Impactor-to-flyby S-band link budget.

Impactor - Flyby Telemetry Link S-Band Link Budget, Freq = 2105 MHz, 64 kbps	Value		Comment
Transmitter Power	33.0	dBm	2 Watts
Impactor Line Loss	-0.8	dB	
Antenna Gain	18.8	dBi	16 element patch array
Antenna Pointing Loss	-0.6	dB	+/- 5 deg
Impactor EIRP	50.4	dBm	
Path Loss	-177.7	dB	8700 km
Flyby Antenna Gain	16.0	dBi	16 element patch array
Antenna Pointing Loss	-0.1	dB	+/-1 deg
Axial Ratio Loss	0.0	dB	
Flyby Line Loss	-1.7	dB	
Received Power	-113.0	dBm	
Receiver Sensitivity	-116.5	dBm	BER = 1E-05
System Margin	3.5	dB	

5.6 S-Band Link Doppler Verification

During an encounter-mode operational readiness test (ORT-9) in May 2005, the Generalized Telecom Predictor (GTP) program was used to confirm the link performance and to assess the Doppler frequency change from separation to impact. Input to GTP included flyby and impactor trajectory files (Spacecraft, Planet, Instrument, C-Matrix Events [SPICE] kernel [SPK] files) and the S-band hardware and antenna parameter values from Tables 5-2 and 5-3. The GTP design control tables (DCTs, not shown) confirmed the link margins in Tables 5-2 and 5-3.

Table 5-4 shows the Doppler results from the GTP run. Links L12 and L21 are flyby-to-impactor, and impactor-to-flyby, respectively. The maximum Doppler shift is -774 Hz for the impactor receiver and -714 Hz for the flyby receiver. The specified data lockup time is less than 5 seconds for a Doppler offset of 15 kHz.

Table 5-4. S-band Doppler assessment at impact based on ORT-9 trajectories.

L12 Range	km	8682
L12 Range Rate	km/s	0.10175
L12 Carrier Freq Doppler (delta-F, uncomp)	Hz	-773.8
L12 Observed Carrier Freq	Hz	2279999226
L12 Observed Data Rate	bps	15999.995
L12 Compensated Data Rate	bps	16000.005
L21 Range	km	8682
L21 Range Rate	km/s	0.10175
L21 Carrier Freq Doppler (delta-F, uncomp)	Hz	-714.4
L21 Observed Carrier Freq	Hz	2104999286
L21 Observed Data Rate	bps	63999.98
L21 Compensated Data Rate	bps	64000.02

5.7 Mass and Power Summary, S-Band Telecom System Elements

Table 5-5 compiles the spacecraft input power and the mass of the S-band subsystem elements on the flyby and the impactor. The flyby portion duplicates the information in Section 3.

Table 5-5. S-band telecom subsystem power input and mass (flyby and impactor).

	No. of units	Input Power[17] (W)	Mass/unit (kg)	Total mass (kg)
S-band—flyby				
Transceiver	1	1.6 receiver 8.2 transmitter	1.1	1.1
MGA	1	-	1.2	1.2
Coupling Antenna		-		0.1
20-dB Coupler		-		0.03
Cabling and microwave components		-		3.0
S-band flyby total				**5.4**
S-band—impactor				
Transceiver	1	1.6 receiver 8.2 transmitter	1.1	1.1
MGA	1	-	1.2	1.2
Coax Switch	2	-	0.1	0.2
Attenuators		-	0.01	0.02
Cabling		-		0.5
Impactor total				**3.0**

[17] The two values for the S-band transceiver are for the separately controlled transmitter and receiver. Both transmitter and receiver were normally on at the same time. Prior to separation, the impactor S-band system drew its power from the flyby power subsystem. After separation, it drew its power from the impactor battery.

Section 6

Operating the Flyby/Impactor S-Band Link

6.1 Impactor and Flyby S-Band Subsystem Commands

Table 6-1 (impactor) and Table 6-2 (flyby) show representative power subsystem and telecom subsystem commands that control the S-band transceivers. There are significantly fewer S-band functions to control than there are for the SDST. The first column in the table is the command name (mnemonic or "stem"). "Arguments" are variables or parameters of the command. Compare with the X-band command list in Section 4.

Table 6-1. Impactor S-band telecom subsystem commands and command arguments.

Impactor Cmd stem	Command function	Argument names	Argument values
RFIXLNK_CONFIG	Configuration of crosslink hardware.	XLNK_RCV_SRC XLNK_XMT_SRC FORCE_ACT	Hardline, S-band, ground-support equipment (GSE), Hardline, S-band, GSE Disable, enable
RFIXLNK_RST	Reset crosslink.	NO_OP	
RFICTB_SYNC_WD	Set command sync word length on CTB	SYNC_WD	tc_sync_16, tc_sync_32
RFICTB_CLK_DIV	Set high rate clock divisor. No state enumeration exists.	CLK_DIV	
RFICTB_TLM_RT	Set high rate clock divisor for telemetry rate.	TLM_RT	rt_2000, rt_64000
RFICTB_TF_LEN	Set transfer frame length/reed Solomon interleave depth	TF_LEN	tlm_long_fr, tlm_short_fr
RFIATTN_SW1_POS	Set attenuator switch 1. The switches are in-line when they are set opposite to each other	SWITCH_POS	through, cross
RFIATTN_SW2_POS	Set attenuator switch 2.	SWITCH_POS	through, cross
RFIMONENABLE	Enable or disable a monitoring-function	MONITOR_ID ENABLE_STATUS	Sbnd disable, enable
PWICTL_SBANDRX	S-band Rx Power Switch Control	DEVICE_SELECT ACTION	oc_enable, oc_disable, oc_reset, on, off
PWICTL_SBANDTX	S-band Tx Power Switch Control	DEVICE_SELECT ACTION	oc_enable, oc_disable, oc_reset, on, off

Table 6-2. Flyby S-band telecom subsystem commands and command arguments.

Flyby Cmd stem	Command function	Argument names	Argument values
PWFCTL_SBANDRX	S-Band Rx Power Switch Control	SWITCH_PRIMESEL	0/PRIMARY, 1/BACKUP, 2/SWITCH_A, 3/SWITCH_B
PWFCTL_SBANDRX	S-Band Rx Power Switch Control	ACTION	0/OC_ENABLE, 1/OC_DISABLE, 2/OC_RESET, 3/ON, 4/OFF
PWFCTL_SBANDTX	S-Band Tx Power Switch Control	SWITCH_PRIMESEL	0/PRIMARY, 1/BACKUP, 2/SWITCH_A, 3/SWITCH_B
PWFCTL_SBANDTX	S-Band Tx Power Switch Control	ACTION	0/OC_ENABLE, 1/OC_DISABLE, 2/OC_RESET, 3/ON, 4/OFF
RFFMONENABLE	Enable or disable a monitoring-function	MONITOR_ID	1/CFGSEL, 2/RFCFG, 3/SBND, 4/SDST, 5/TWTA
RFFMONENABLE	Enable or disable a monitoring-function	ENABLE_STATUS	0/DISABLE, 1/ENABLE

6.2 Impactor and Flyby S-Band Subsystem Engineering Telemetry

Table 6-3 lists the engineering telemetry channels used to monitor the performance of the S-band crosslink. Note the correspondence between the impactor channels and the flyby channels. Section 4 lists the engineering channels for the flyby X-band subsystem.

Table 6-3. Impactor and flyby S-band telecom subsystem engineering telemetry.

Telemetry name	Subsystem function	Channel No.	Values
RFFSBT_FORCEACT	Flyby S-band receiver forced active state	R-0374	0/OFF, 1/ON
RFFSBT_RFACT	Flyby S-band transmitter RF output	R-0376	0/OFF, 1/XMT_ON
RFFSBT_RSSI	Flyby Receive signal strength indicator	R-0379	0/NO_RF, 1/RF_LOCK
RFFSBT_BER	Flyby receiver bit error rate	R-0380	0/UNLOCK, 1/LOCK
RFISBT_FORCEACT	Impactor receiver forced active receiver state	R-2374	0/OFF, 1/ON
RFISBT_XMT_PFLT	Impactor transmit power fault	R-2377	0/OVER_CURR, 1/NOMINAL_CURR
RFISBT_RCV_PFLT	Impactor receiver power fault	R-2378	0/OVER_CURR, 1/NOMINAL_CURR
RFISBT_RCV_SIG	Impactor receive signal strength indicator	R-2379	0/NO_RF, 1/RF_LOCK
RFISBT_BIT_ERR	Impactor receiver bit error rate	R-2380	0/UNLOCK, 1/LOCK
RFICTB_TF_LEN	Impactor CTB transfer frame length	R-4009	0/LONG_FR, 4/SHORT_FR
RFICTB_SYNC_WD	Impactor CTB start sequence word length	R-4007	0/LEN_16, 1/LEN_32
RFICTB_CMD_SRC	Impactor CTB command source select	R-4008	0/RECEIVER_1, 1/RECEIVER_2
RFIATT_SW1_XPOS	Status of impactor attenuator switch 1 cross position	R-4010	0/FALSE, 1/TRUE
RFIATT_SW1_TPOS	Status of impactor attenuator switch 1 through position	R-4011	0/FALSE, 1/TRUE
RFIATT_SW2_XPOS	Status of impactor attenuator switch 2 cross position	R-4012	0/FALSE, 1/TRUE
RFIATT_SW2_TPOS	Status of impactor attenuator switch 2 through position	R-4013	0/FALSE, 1/TRUE
PWISBRXCUR	Current: Impactor Sband Rx	E-2700	Engineering units
PWISBTXCUR	Current: Impactor Sband Tx	E-2701	Engineering units
THIT_SBTRBP	Impactor S-Band Transponder temperature	T-2315	Engineering units
THIT_SBNDAT	Impactor S-Band Antenna 1 temperature	T-2276	Engineering units
PWFSBRXCUR_A	Current: Flyby Sband Rx (PI-A)	E-0700	Engineering units
PWFSBTXCUR_A	Current: Flyby Sband Tx (PI-A)	E-0701	Engineering units
THFT_SBNDAT	Flyby S-Band Antenna temperature	T-1794	Engineering units
THFT_SBNDBP	Flyby S-Band Transceiver BP temperature	T-1821	Engineering units

Section 7

Ground Data System for Deep Impact

7.1 DSN Support

The flyby was tracked by scheduled 34-m beam waveguide (BWG), 34-m high-efficiency (HEF), and 70-m antenna stations as determined by the mission phase and the required X-band link performance. Support configurations included the following:

7.1.1 Uplink

- 20 kW transmitter power
- Command modulation (rates 7.8125 bps, 125 bps, or 2000 bps)
- Command subcarrier 16000.0 Hz (except 16000.8 or 16000.9 Hz for 7.8125 bps)
- Ranging modulation 3.0 dB suppression, with parameters defined below

7.1.2 Downlink

- Standard receiver (block V type) in residual carrier mode, except as defined below
- Standard turnaround ranging
- Standard delta–DOR using VLBI system

7.1.3 Special Configurations

- Launch used 26-m X-band AC aid antenna for initial downlink
- 34-m uplink power set at 200 W for first three postlaunch passes
- Telemetry receiver operated in suppressed carrier (Costas loop) mode at 100, 200 kbps
- Four-station Goldstone array: Deep Space Station (DSS)-15 served as the array’s reference station, with DSS-24, DSS-25, DSS-26 as the other three stations.

7.2 Ranging Parameters

These were controlled by the RNG_CFG table and by the DSN keywords file (DKF). The clock component is 4, and the last component is 20. Based on Mars Exploration Rover (MER) experience and DI navigation requirements, the integration times were initially made T1 = 2 sec and T2 = 2 sec (with T3 = 0 sec throughout the mission). Because ranging was required only on the HGA, the predicted ratio of ranging power to noise spectral density (Pr/No) values were high: 30 to 50 dB throughout the mission.

Ranging degradation in the form of a fall-off in Pr/No during the latter hours of long passes began to occur in late March. This was determined to be from a known cause: the change in round-trip light time (RTLT) during a single pass (delta-RTLT). When delta-RTLT became comparable in magnitude to T1 or T2, the algorithm to generate Pr/No and eventually the algorithms used to process range data began to fail. The DSN recommended increasing T1 and T2 to compensate for the delta-RTLT. The only downside to doing this was a slightly longer cycle time to complete a ranging acquisition (point) and therefore fewer range points per pass.

Table 7-1 defines the T1 and T2 values for the mission. Each set of values apply to 70-m and 34-m passes. The June 27 values (T1= 30 sec, T2=8 sec) have continued to be used for HGA passes after encounter.

Table 7-1. Ranging integration times for the flyby.

Start date	T1 (sec)	T2 (sec)	Cycle (sec)	Comments
Launch	2	2	53	for LGA until HGA at L+5 days
Apr 8, 2005	5	5	104	for HGA operations only
June 22, 2005	6	6	121	for HGA operations only
June 27, 2005	30	8	177	for HGA up/HGA down
June 27, 2005	510	30	809	for LGA up/HGA down (encounter)

7.3 Station Telemetry Receiver Configuration for Direct Carrier Modulation

The problem that made the use of the standard station receiver configuration unfeasible is documented in Incident/Surprise/Anomaly (ISA) report Z85490 [10]. This problem caused the loss of portions of uncompressed science image data frames from any of the three image instruments. The problem was referred to as "corrupted image frames" for short. It first occurred in data returned from the flyby on January 15, less than three full days after launch.

The problem was almost immediately suspected to be caused by the direct carrier modulation by symbols that have a particular data structure in uncompressed images.[18]

At the recommendation of the DSMS cognizant development engineer for the station receiver, the project requested the Network Operations Project Engineer (NOPE) to issue a briefing message to the stations for a test that reconfigured a backup receiver as follows:

1. Change receiver carrier loop operating mode from "residual carrier mode" to "suppressed carrier mode" (Costas = 1).
2. Change final symbol loop bandwidth from 25 Hz to 1 Hz.

The first change is to alleviate the effect of an imbalance of "zero" symbols and "one" symbols, which causes the carrier loop to be biased. The second change is to reduce the interaction between carrier tracking loop and symbol loop, both of which used 25-Hz loop bandwidth settings for the strong downlinks shortly after launch.

With two receivers at a station configured for the test as above, side-by-side comparison of station receiver performance plots (monitor data) showed that the prime receiver had large degradation in the following monitor data channels: m-1305, frequency residual; m-1314, static phase error (SPE); m-1315, Pc/No; m-1393, symbol SNR (SSNR); m-1434, bit SNR; and m-1512, ranging Pr/No. Simultaneously, the backup receiver had negligible degradation in SSNR and bit SNR.

Figures 7-1 and 7-2 show SSNR over DSS-55 (34-m in Madrid) on February 5 for receivers in the residual carrier mode and suppressed carrier mode, respectively.

On February 15, the project accepted the above receiver configuration as standard for the remainder of the mission for all downlinks at rates of 200 kbps or 100 kbps. Downlink rates lower than 100 kbps are on a subcarrier, so do not cause a bias in the carrier loop. The project decided against implementing either of two onboard SDST options for the 100-kbps and 200-kbps rates: use of the Manchester (bi-phase L) code, or use of a new higher-frequency subcarrier (750 kHz).

Two tests at Deep Space Communications Complex Test Facility 21 (DTF-21) (March 11 and March 16) and one ground-based test at DSS-26 (March 17) verified the performance of the

[18] Based on this cause, the project knew that there would not be a similar problem with impactor images on the S-band crosslink. The impactor C&DH included a "randomizer" to break up repetitive data patterns. However, any uncompressed image that passed through the flyby C&DH was subject to the corruption because this C&DH did not have a randomizer. See Section 10.2.6 for a lesson learned.

recommended station receiver suppressed carrier mode at SSNR from 20 dB down to -1 dB (which is below threshold). The expected 70-m adverse (mean minus 2-sigma criterion) SSNR at encounter was predicted to be about 2 dB depending on elevation angle.

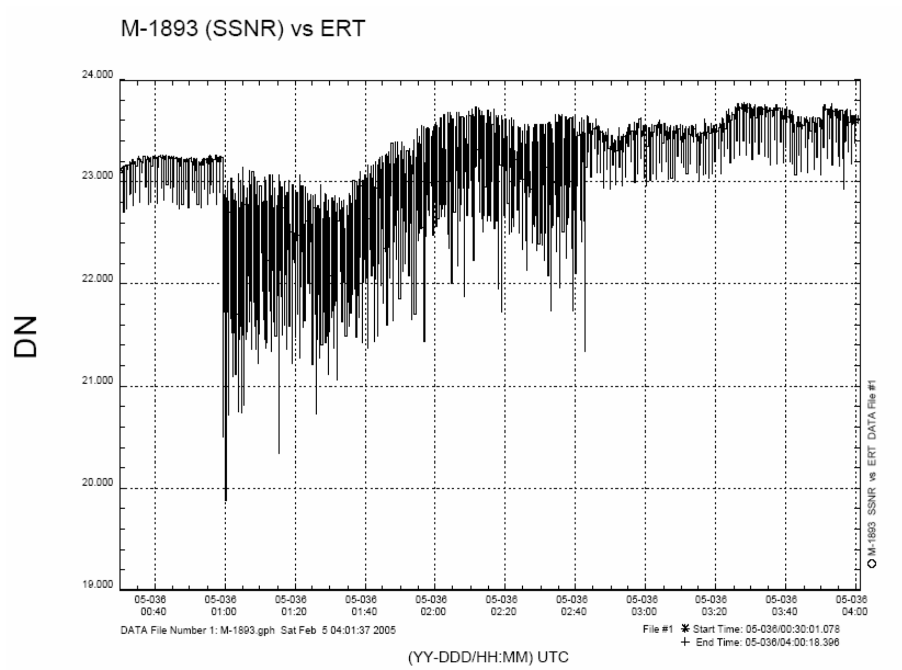

Figure 7-1. 200-kbps SSNR with DSS-55 receiver in residual carrier mode.

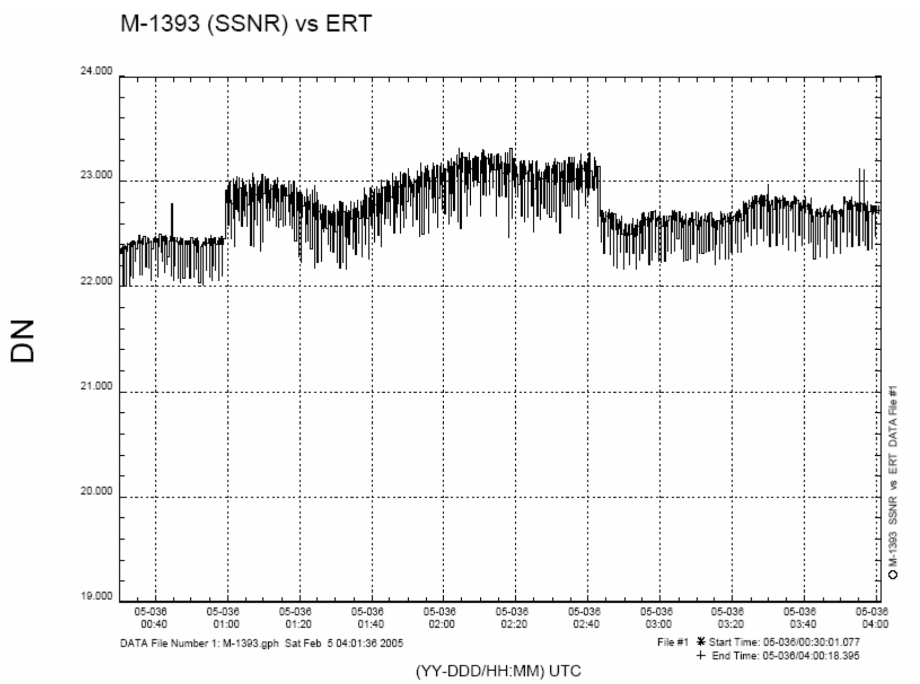

Figure 7-2. 200-kbps SSNR with DSS-55 receiver in suppressed carrier mode.

Section 8

Flyby X-Band Subsystem Performance and Trends

8.1 Overview

The X-band subsystem proved to be stable and trouble-free throughout the mission. The stability was verified by daily queries from the ground system's telemetry data base of most of the performance (non-status) telemetry channels defined in Section 4. Over the six-month span from launch to mid-July 2005, most channels showed no trend at all. The exceptions are shown in Figures 8-1 through 8-8, each with data through July 25.

- Figure 8-1. SDST-1 temperatures through flyby prime mission. Variations in baseplate temperature (higher values) and VCO temperature (lower values) followed one another closely through the mission. The baseplate ran about 4°C higher, and it was used to establish the values of BLF, as discussed in Section 3.
- Figure 8-2. SDST-1 receiver static phase error (BLF is temperature-dependent). The SPE represents the difference between the frequency received by the SDST and the BLF. The BLF is temperature-sensitive. Adjusting the value of BLF used in station predictions can keep the SPE small. Changes in BLF on March 14 (DOY 073), May 13 (DOY 133), and July 20 (DOY 201) are reflected by discontinuities in daily SPE.
- Figure 8-3. SDST-1 output power (reported as TWTA-1 input power; sensor is temperature-dependent). Though the actual input power is the SDST-1 exciter output power, the measurement is made by the TWTA. The TWTA measurements are very temperature-sensitive. Compare the input power trend with the TWTA temperature trend in Figure 8.4 below.
- Figure 8-4. TWTA-1 temperatures through flyby prime mission. The TWTA baseplate averaged as high as 40°C by two weeks after launch (at a particular flyby orientation to the Sun) and lower than 20°C by encounter (DOY 185).
- Figure 8-5. TWTA-1 output power (sensor is temperature-dependent). The telemetry indicates that the output power decreased by somewhat less than 0.2 dB through the mission. Such a small change would be indiscernible by analysis of link performance residuals at the stations. Because the output power sensor is temperature-sensitive, it's likely the TWTA had no output power decrease at all.
- Figure 8-6. TWTA-1 helix current (sensor is temperature-dependent; outliers in next figure). The daily value at 00:00 would seem to have increased by a small amount through the mission. This sensor is also temperature-sensitive. However, what's most interesting about helix current is not the slowly varying average, but rather the presence of outliers (next figure).
- Figure 8-7. TWTA-1 helix current showing outliers (ISA Z85877). This figure displays all of the data of Figure 8-6 and has the vertical axis rescaled, so that more extreme values (larger than 0.9 V or smaller than 0.7 V) also appear. These extreme

values are called outliers, and are the subject of ISA Z85877. Helix current outliers have had no effect on link performance and do not represent a hazard to the TWTA. Outliers are discussed separately at the end of this section.

- Figure 8-8. HGA gimbal temperature through flyby prime mission. The HGA was used starting five days after launch. This measurement had the largest variation of any monitored by telecom during the mission. It was in the region of 40°C for the first few days after first HGA use,and decreased to below -30°C by encounter. These values are both well within the flight allowables, which are -120°C to 110°C for the HGA [3].

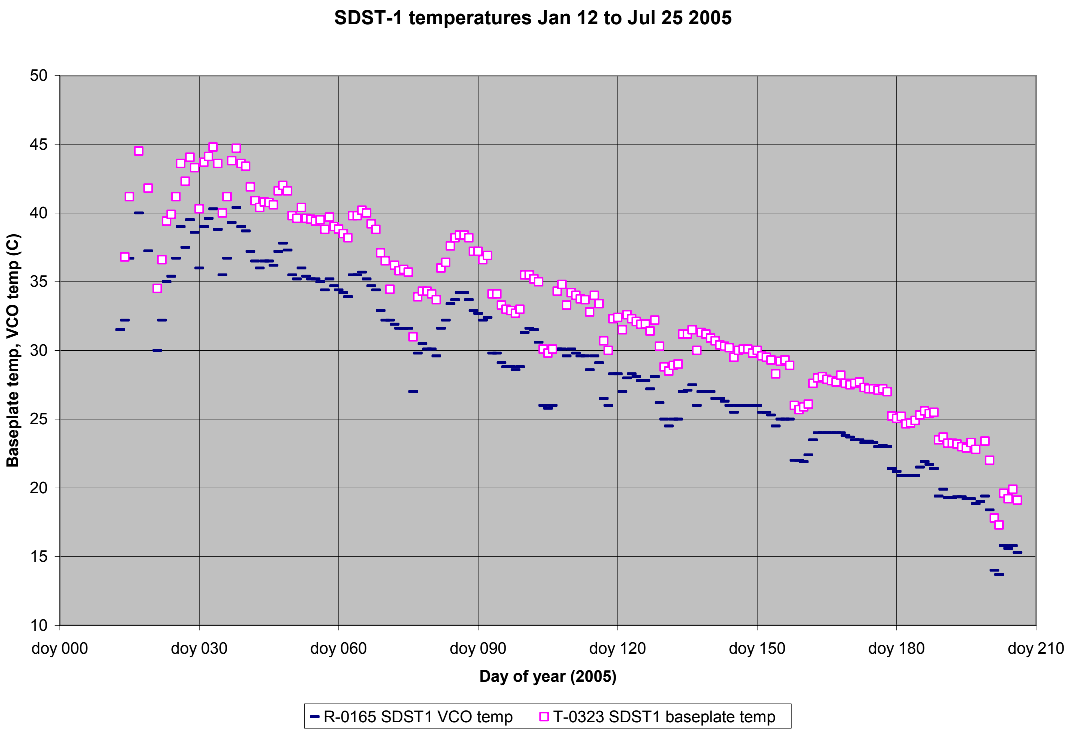

Figure 8-1. SDST-1 temperatures through flyby prime mission.

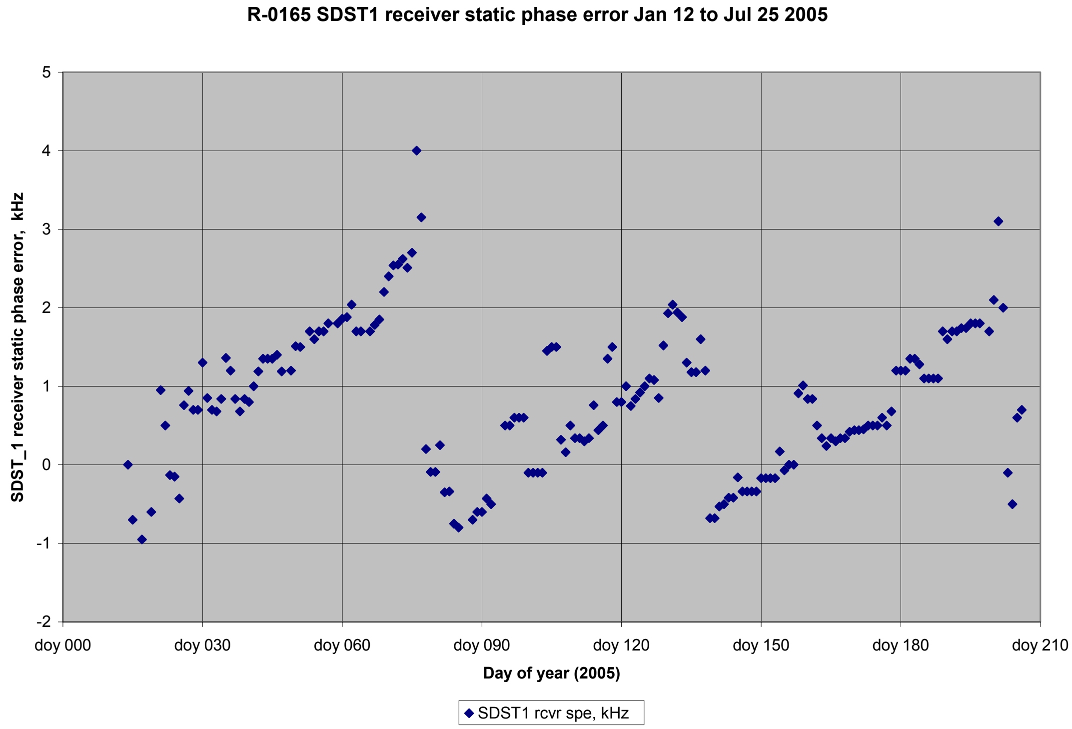

Figure 8-2. SDST-1 receiver static phase error (BLF is temperature-dependent).

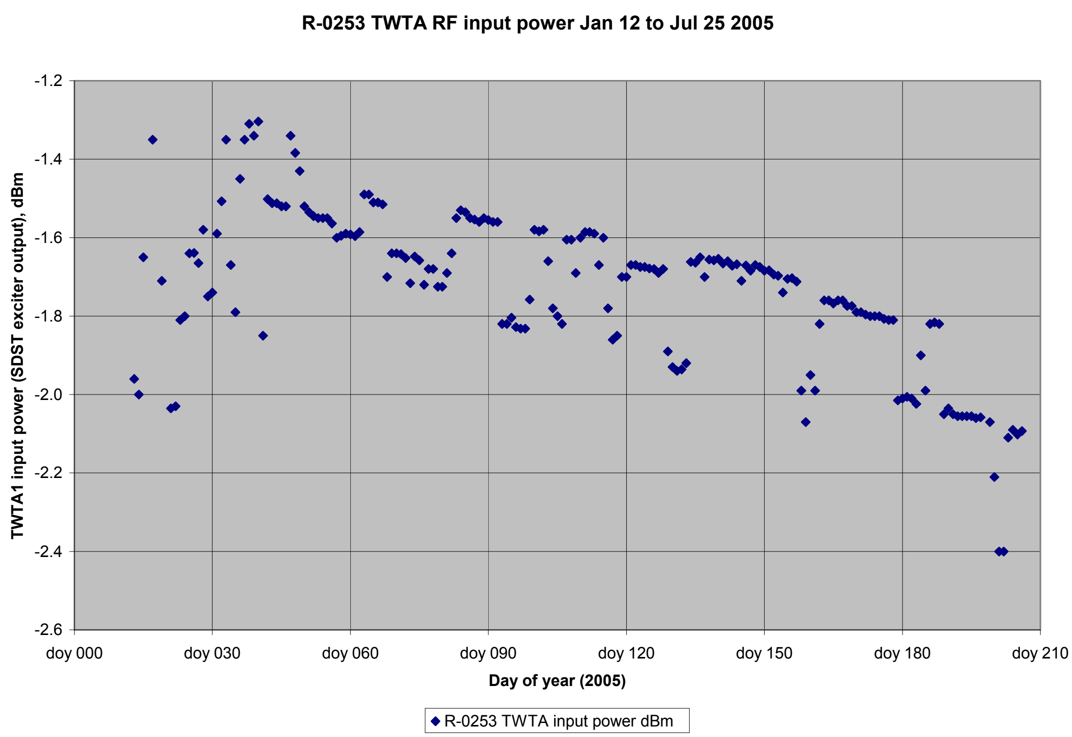

Figure 8-3. SDST-1 output power (reported as TWTA-1 input power; sensor is temperature-dependent).

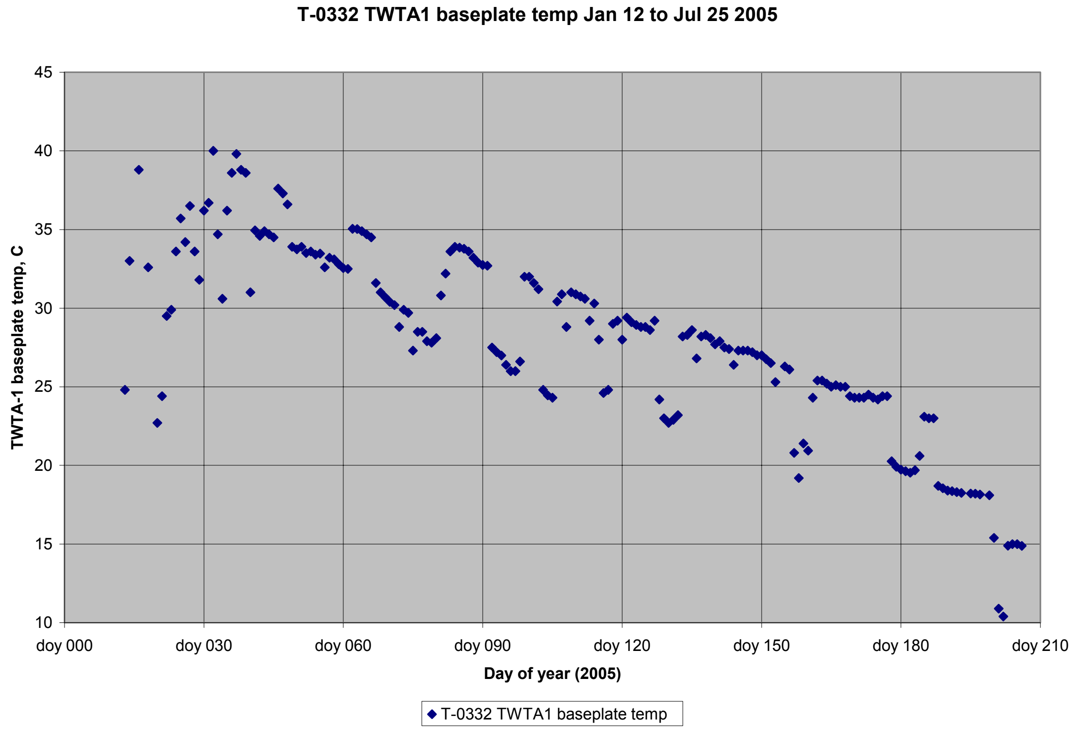

Figure 8-4. TWTA-1 temperatures through flyby prime mission.

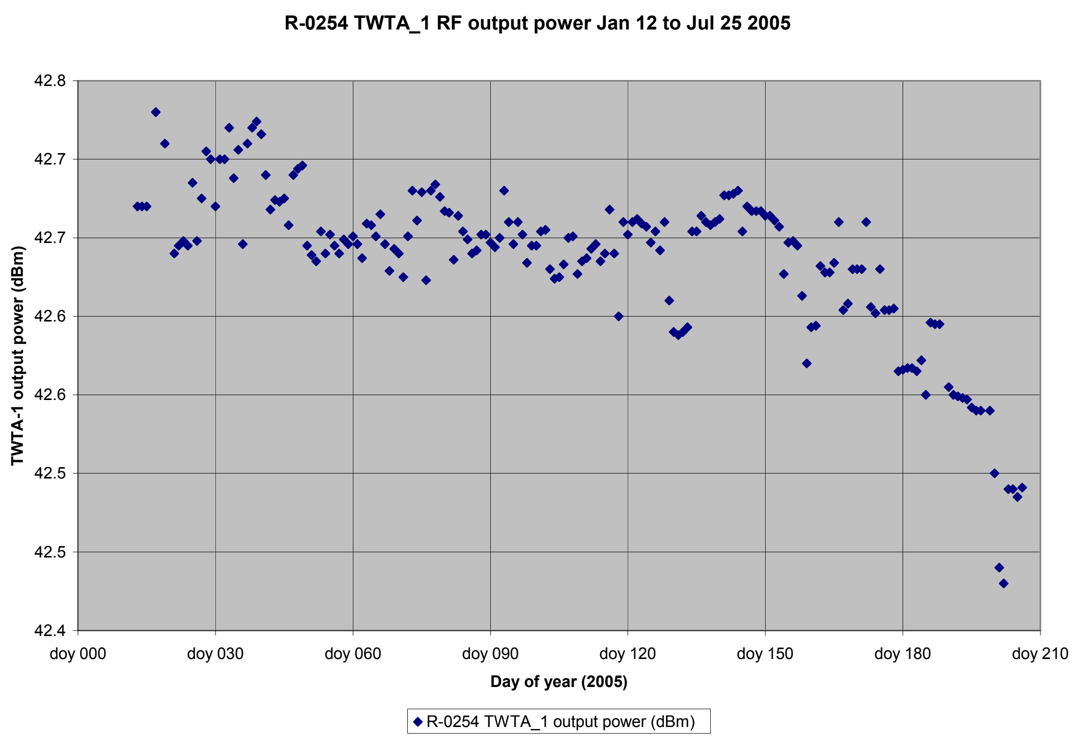

Figure 8-5. TWTA-1 output power (sensor is temperature-dependent).

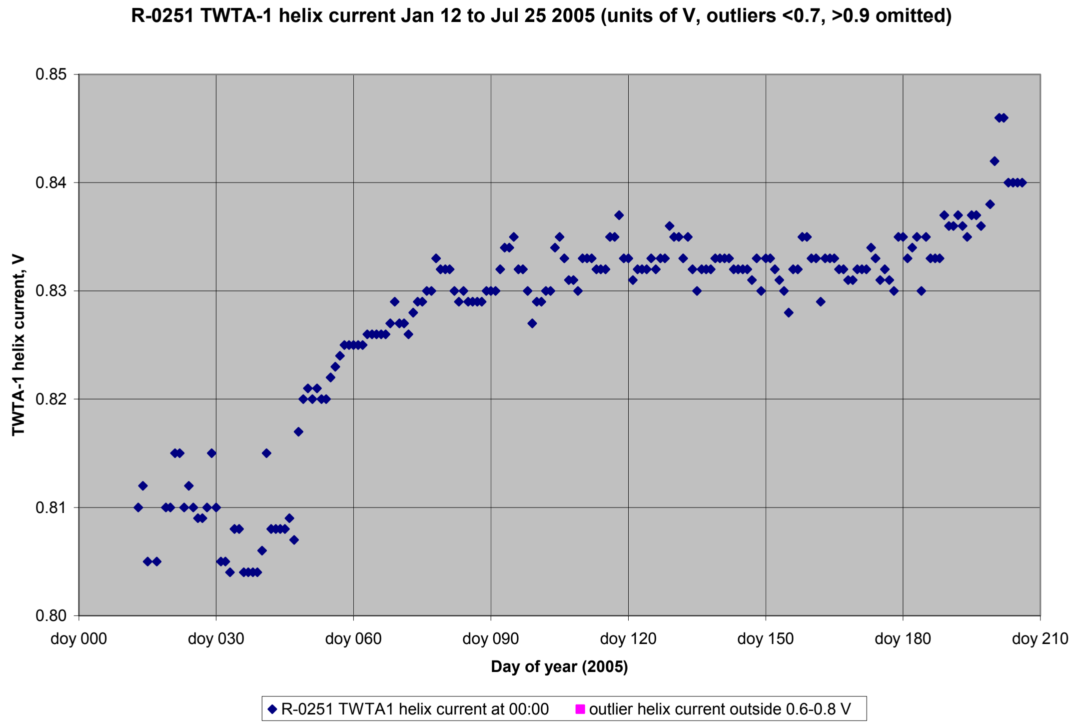

Figure 8-6. TWTA-1 helix current (sensor is temperature-dependent; outliers in next figure).

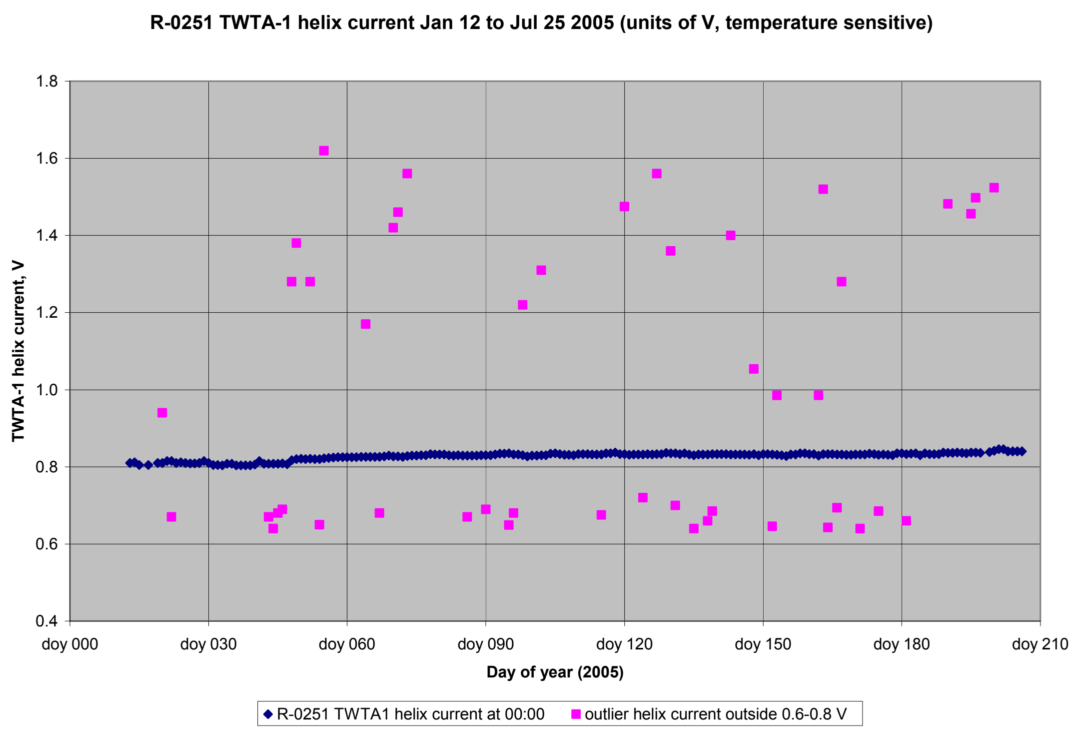

Figure 8-7. TWTA-1 helix current showing outliers (ISA Z85877).

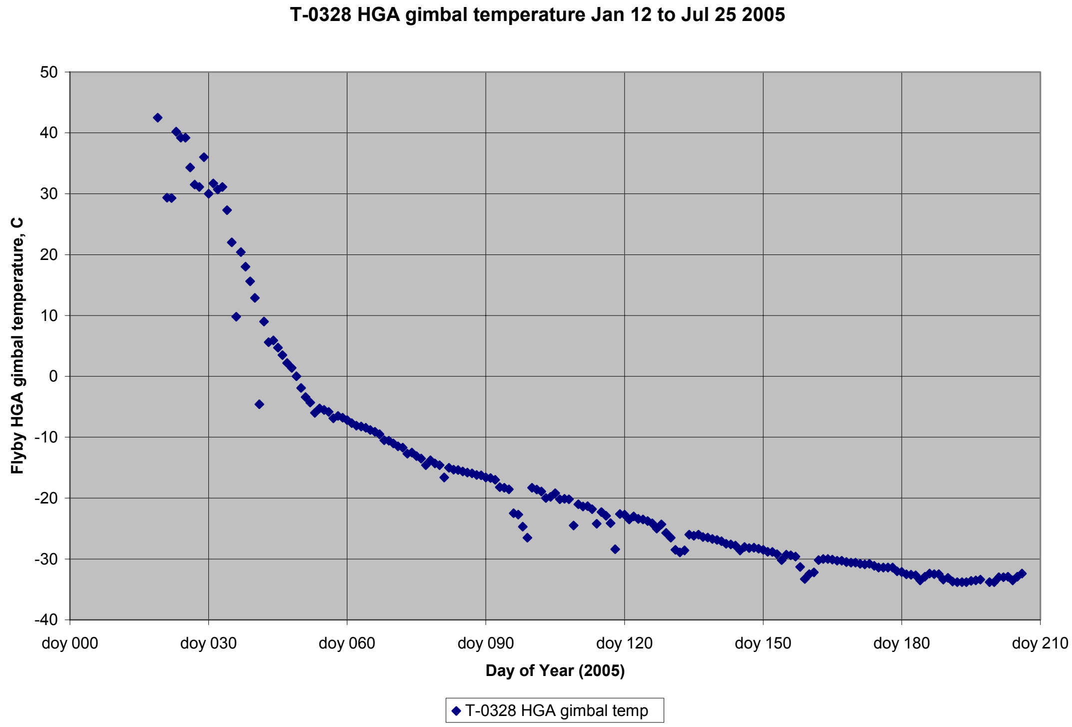

Figure 8-8. HGA gimbal temperature through flyby prime mission.

8.2 TWTA Outliers (ISA Z85877)

Several of the TWTA-1 telemetry channels, but particularly helix current R-0251, have displayed sporadic single values noticeably different from the long-term average of 0.83 V. The other channels, always displaying variation at the same time sample (from the same telemetry packet) as R-0251 are R-0252 (TWTA input current) and R-0254 (TWTA output power). In flight, we defined any helix current sample of less than 0.7 V or more than 0.9 V as an outlier. Outliers occur sporadically, on the order of once per day to once in a couple of weeks. Once a day is once per 6170 samples, when the packet rate is once per 14 seconds.

With two exceptions, on DOY 055 (Feb 24) and on DOY 167 (June 16), outliers have not been correlated with other telemetry. Both Figures 8-9 and 8-10 are for DOY 055; the DOY 167 signature is very similar. On both days, the outlier group included E-0699 (power subsystem TWTA input current telemetry) and R-0252 (TWTA input current telemetry), which each increased 5% for one sample. The significance of this is that both R-0252 (TWTA telemetry) and E-0699 (power subsystem telemetry) are measurements of the current drawn by the TWTA. E-0699 was sampled one second earlier (DOY 055) or one second later (DOY 167) than R-0252. Normally the packets containing E-0699 and R-0252 do not line up in time closely enough for both the power subsystem and the TWTA to report the outlier.

As Figure 8-6 shows, there have been almost equal numbers of negative-going outliers (with values of 0.6 to 0.7 V and positive-going outliers (with values of 0.9 to 1.6 V).

The outliers cause no change in TWTA operation that can be seen in the resulting X-band downlink to the station. There have been no unexplained signal outages that could be attributed to the TWTA momentarily going to the standby mode from the transmit mode, and certainly no outages of the 5-minute warm-up duration that would occur if the TWTA went to power-off and then power-on. The TWTA goes to standby each time there is a switch of downlink antennas (HGA to LGA or LGA to HGA) or an enforcement of the selection of the existing antenna. The size of the largest outlier, the DOY 055 one, in TWTA RF output (R-0254) was equivalent to a 0.06-dB increase. This is far too small a change to be detectable in station-received signal level.

The JPL cognizant engineer for these TWTAs (which were originally made for the Cassini project) reviewed the telemetry. He documented his conclusions in [11] and [12]. On March 27, the DI project recommended the closure of the ISA on the basis of this evaluation. Alarm limits were set on maximum helix current (2.5 V) and minimum output power at levels (42.55 dBm) that would bear watching. Except for temperature-caused hits in output power after encounter, all above 42.46 dBm (Figure 8-5), no alarms occurred on either channel as of July 2005.

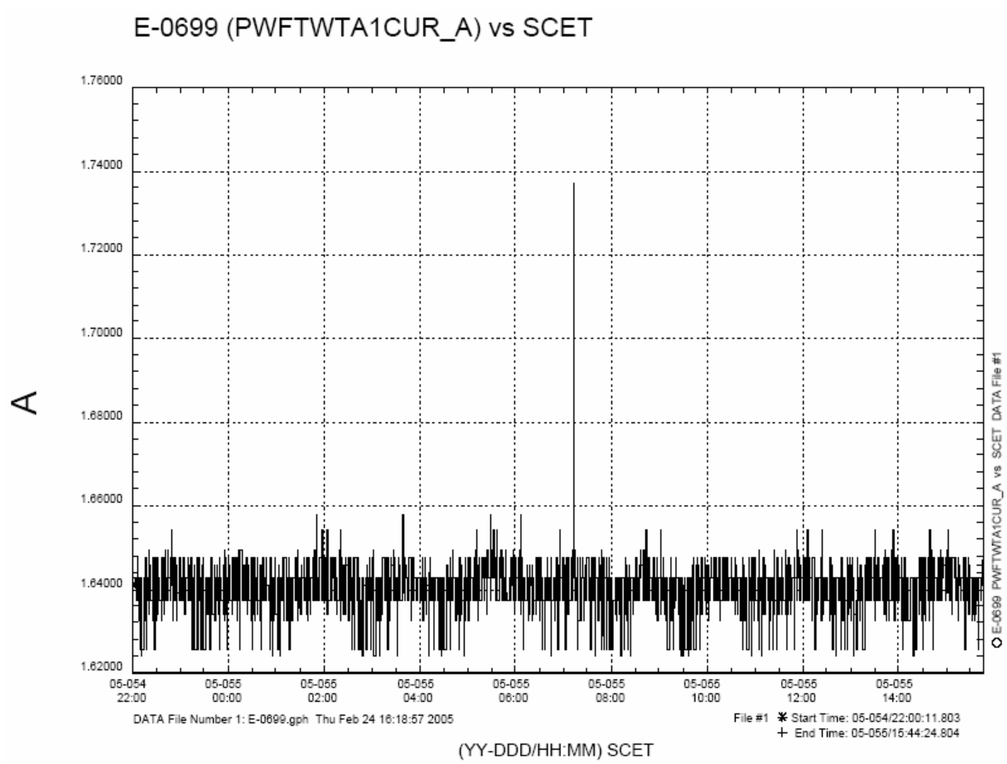

Figure 8-9. DOY 055 (Feb. 24) TWTA outlier as telemetered by power subsystem.

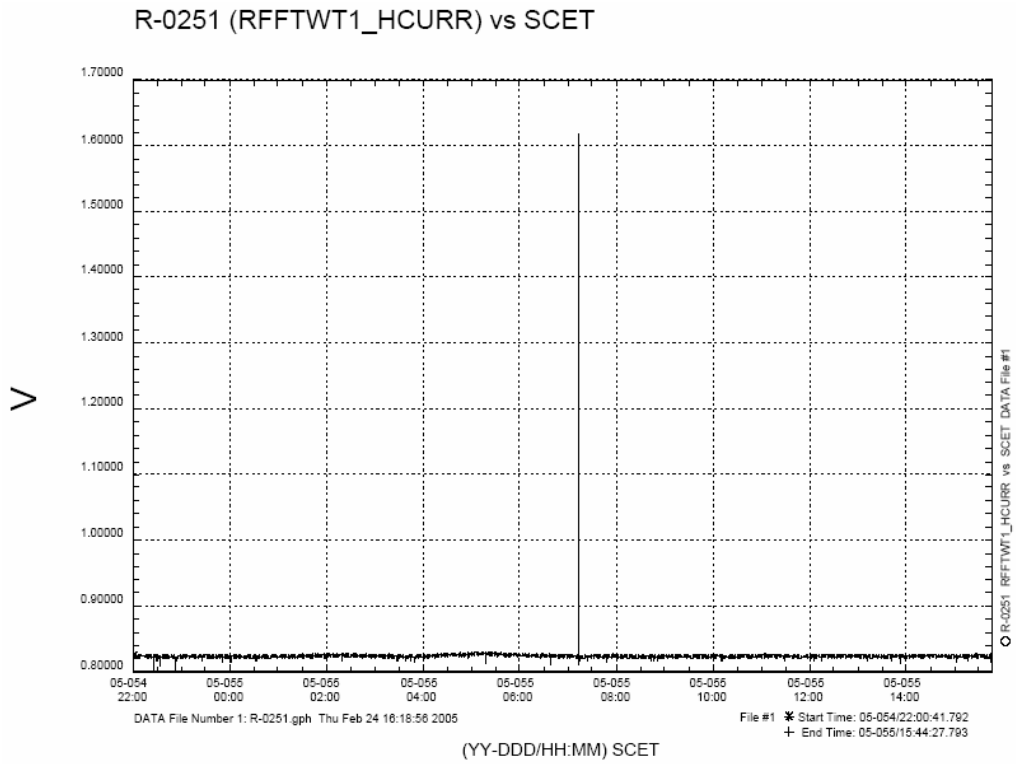

Figure 8-10. DOY 055 (Feb. 24) TWTA outlier as telemetered by TWTA.

The closure of ISA Z85877 [13] on May 20 (written before the DOY 167 (June 16) correlated outlier event), as based on [11] and [12], states:

> The vast majority of the DI events (outliers) are the result of TWTA telemetry noise, without appropriate correlation to other observable telemetry information and without consistency with TWTA behavior mechanisms other than telemetry noise. One outlier, however, on 2005 Day of Year (DOY) 055, is corroborated with independent telemetry information from the spacecraft power distribution subsystem and could in fact be a real event involving a transient pressure change within the TWTA's traveling-wave tube (TWT). Such an event would have lasted for at least one second, but not more than 14 seconds, and the TWT and TWTA apparently returned immediately to normal, with no sign of degradation or indeed any change in performance. Transient pressure events, such as this, are known to be possible with the operation of TWTAs. Such events, however, generally become less likely with accumulated TWTA operating time and result in no permanent degradation.
>
> The type of event within the TWTA that roughly matches the DOY 055 observations would be a gas "burst" within the TWT itself. The TWT is evacuated to a pressure on the order of 10^{-9} Torr to facilitate formation and control of the electron beam formed within the TWT. This electron beam provides the power to support amplification of the RF signal. The electrons in the beam collide with any gas molecules within the RF circuit region of the tube. One of the results of such collisions is the helix current monitored by the TWTA. An implication of that helix current is power dissipated within the RF circuit area. If there should occur a transient increase in internal pressure in the RF circuit

region (a gas "burst"), increased collisions ensue and helix current and dissipation increase. Since helix dissipation increases, effective TWTA efficiency temporarily drops and an increase in TWTA DC input current (and power) should be observed.

Section 9

Telecom Subsystem and Link Performance

9.1 Low-Gain Antenna System Gain Pattern

Patterns from SER DI-SC-COM-020G [3] were the starting point to modeling the pattern in a way that it could be used for uplink and downlink predictions given the angle between the +Y axis (LGA-1 boresight) or the –Y axis (LGA-2 boresight).

Figure 9-1 shows the uplink pattern (7179 MHz) and Figure 9-2 the downlink pattern (8415 MHz).

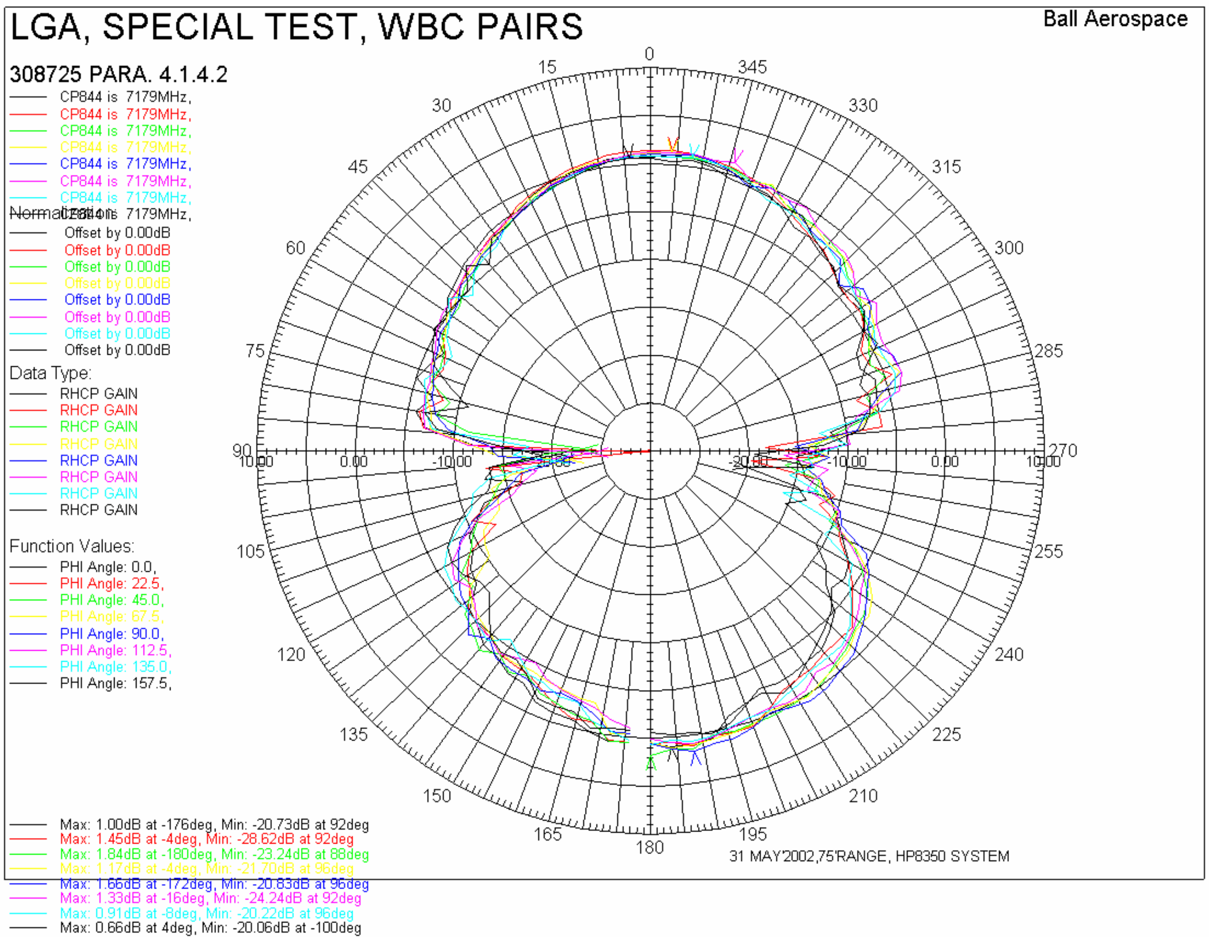

Figure 9-1. LGA system uplink pattern, measured at 7179 MHz.

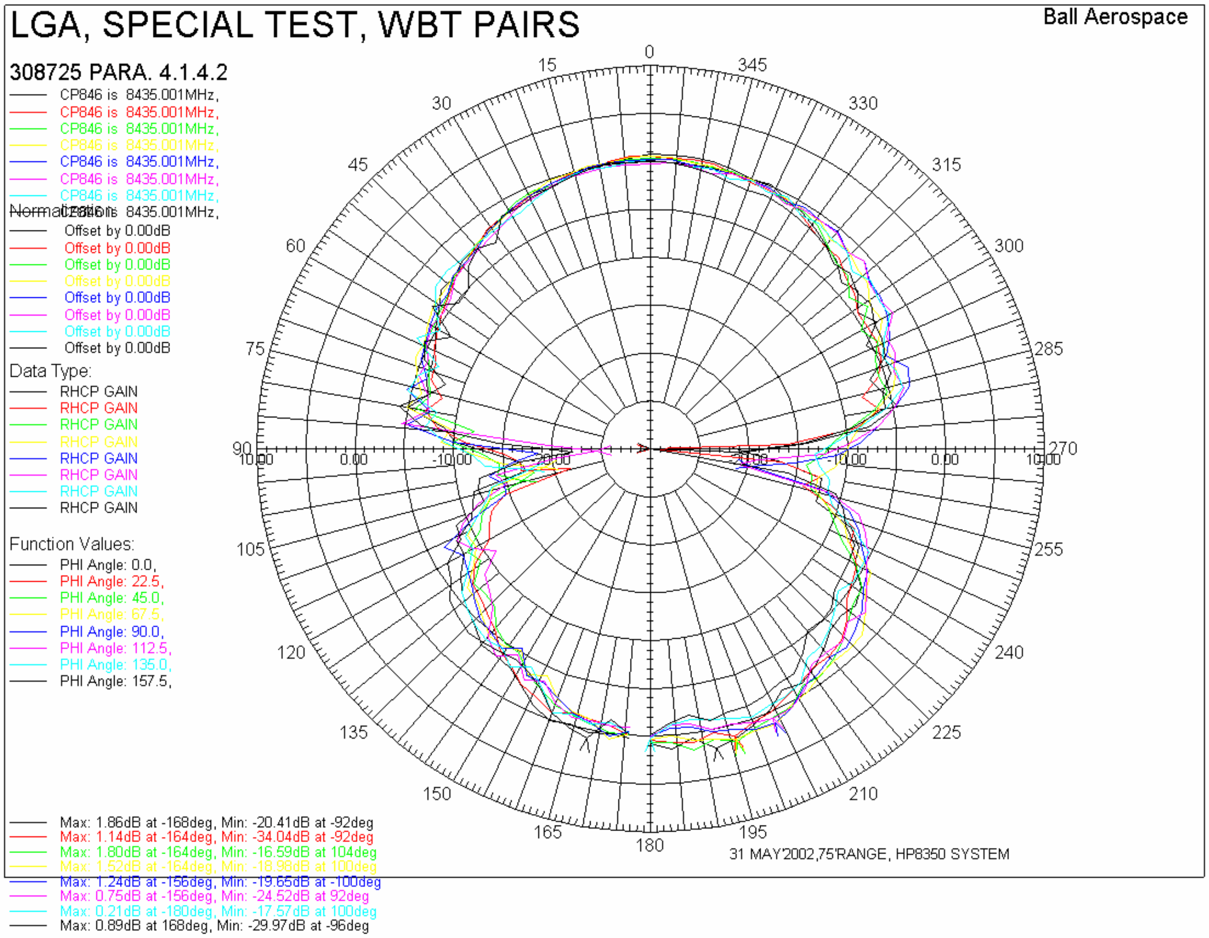

Figure 9-2. LGA system uplink pattern, measured at 8435 MHz.

From the source files that generated these figures, patterns of uplink gain and downlink gain vs. angle from +Y axis (Figure 9-3) were input to the Telecom Forecaster Predictor (TFP) program. The resulting predictions were quite accurate (within +/- 1.5 dB) within 50° of boresight of either antenna, and somewhat less accurate (within +/- 3 dB) outside that range. Flight experience suggests that a significant source of error may be nulls of small angular extent that were not picked up in the original pattern measurements made every 4 degrees in azimuth and elevation. The residual (difference between signal level reported in spacecraft telemetry for the uplink or station monitor data for the downlink, and the corresponding predicted signal level) was usually positive. Also, the change in reported level as the spacecraft turned from one attitude to the next matched the predicted change with good accuracy.

9.2 High-Gain Antenna Gain Pattern

Figure 9-4 is the modeled gain pattern as a function of angle from HGA boresight, based on measured data out to 2.4° from boresight and extrapolated out to 3.5°.

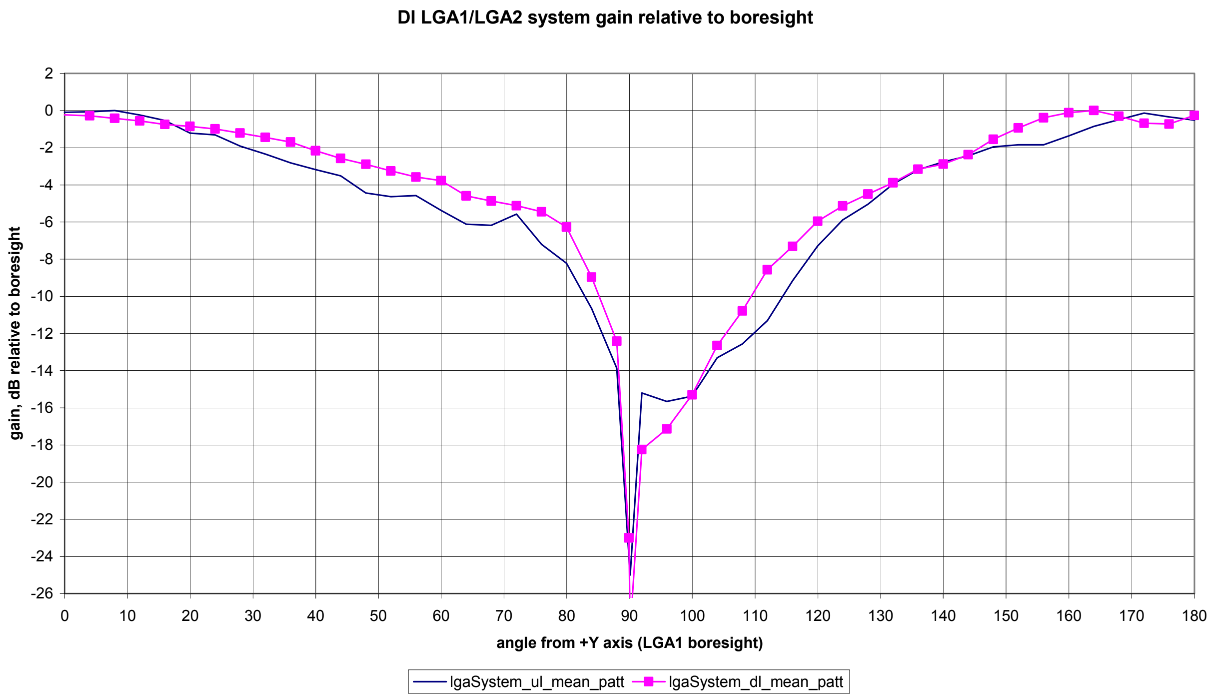

Figure 9-3. LGA system uplink and downlink patterns as modeled in TFP.

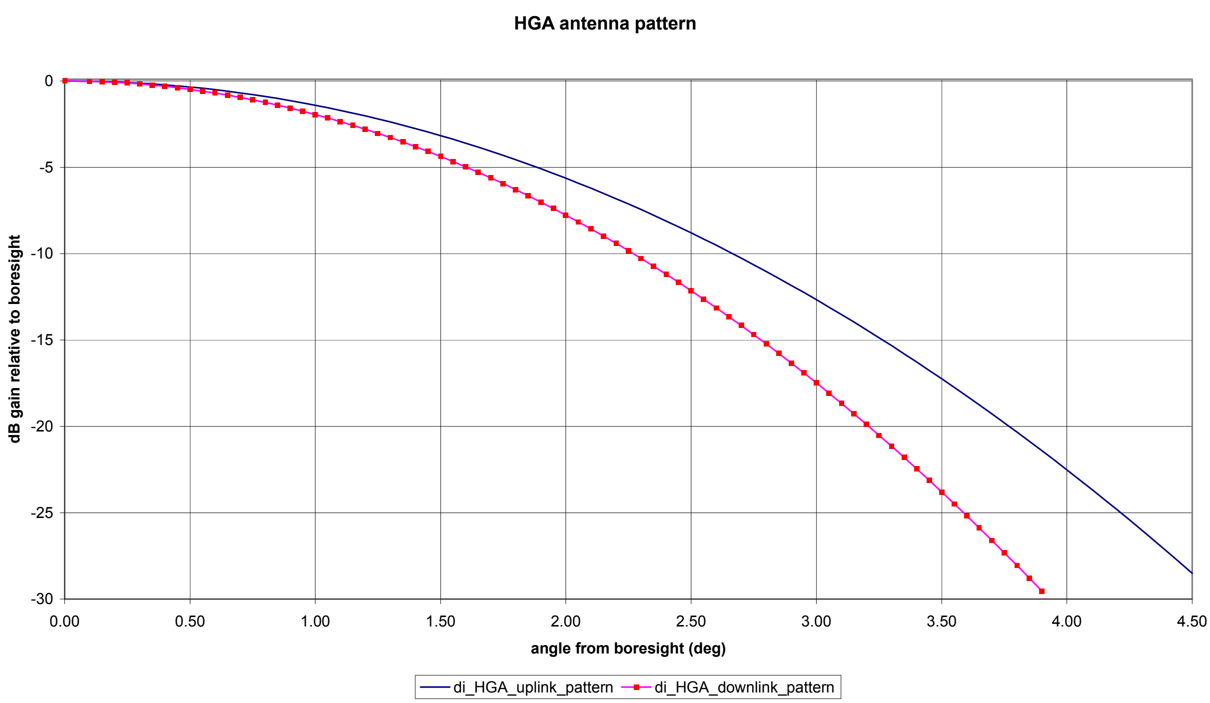

Figure 9-4. HGA uplink and downlink patterns as modeled in TFP.

The modeled pattern approximates the main lobe of the HGA (measured pattern in Figure 9-5).

Overall link performance with the HGA is affected by the pointing accuracy of the mechanical gimbal as well as the antenna pattern. In the worst case (which was not observed in flight), the antenna would be pointed to within +/-0.45° of the Earth. The pointing algorithm directs the antenna to the center of the Earth rather than to a particular tracking station. The difference between center-of-Earth and station pointing became negligible quickly, amounting to a maximum of 0.22° 5 days after launch and 0.09° 15 days after launch. The total HGA pointing error was modeled in TFP as 0.25°.

The modeled patterns in Figures 6-3 and 6-4 assume a parabolic beam shape:

(2 * pointing error / Beamwidth) 2 = Pointing loss / 3 dB

The 3-dB (half-power) beamwidth is specified to be greater than 2.75° for the uplink and greater than 2.36° for the downlink.

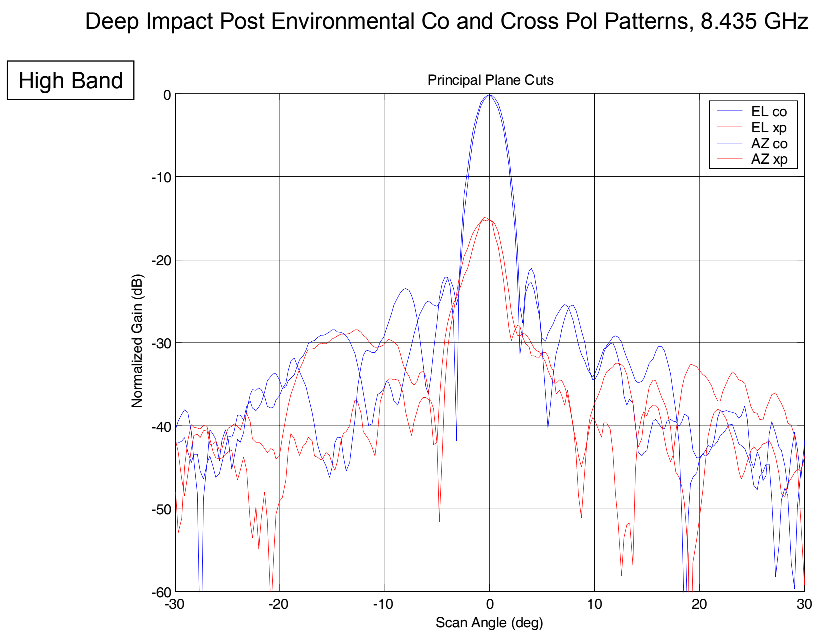

Figure 9-5. HGA measured downlink pattern (right circular polarization [RCP] and left circular polarization [LCP]).

9.3 Link Performance Prediction (Encounter)

DCTs produced by the TFP define the performance at a point in time. TFP has a database of link models for the flyby and a set of "common" models for the DSN stations available for all projects.

Tables 9-1 and 9-2 are uplink and downlink DCTs for the 70-m Goldstone station DSS-14 at 06:00 UTC on July 4, 2005, the nominal encounter time. The uplink from the station to the flyby was to LGA-1, and the downlink back to the DSN was from the HGA. The trajectory (SPK) and orientation (camera kernel [CK]) files are listed.

Table 9-1. Flyby LGA-1 uplink design control table.

```
Produced by DI V1.1 XML 07/06/2004
-------------------------------------------------------------------------------------------
Predict                     2005-185T06:00:00.000 UTC
Up/Down-Link                Two-Way
RF Band                     X/S:X/S
Spacecraft Configuration    Config A
Telecom Link                DSS14-LowGain1-DSS14
-------------------------------------------------------------------------------------------

COMMAND UP-LINK PARAMETER INPUTS
Cmd Data Rate               7.8125   bps
Cmd Mod Index               0.80     Radians
Cmd RngMod Index            0.0      Degrees
-------------------------------------------------------------------------------------------
Operations Mode             Calibration
Mission Phase               Flyby
DSN Site                    Gold-Gold
DSN Elevation               In View
Weather/CD                  90
Attitude Pointing           C-Kernels
-------------------------------------------------------------------------------------------

EXTERNAL DATA

SPICE Kernels (in load order)
  /msop/tfp/kernels/com/DSN_topo.frm
  /msop/tfp/kernels/com/de405s.bsp
  /msop/tfp/kernels/com/dsnstns.bsp
  /msop/tfp/kernels/com/dss-55.bsp
  /msop/tfp/kernels/com/dss-55_topo.frm
  /msop/tfp/kernels/com/earth_970804_200101_pred_B.bpc
  /msop/tfp/kernels/com/naif0007.tls
  /msop/tfp/kernels/com/pck00006.tpc
  /home/ditel/tfp_di/kernels/di/DIF_SCLKSCET.00011.tsc
  /home/ditel/tfp_di/kernels/di/di_sunsafe.tf
  /home/ditel/tfp_di/kernels/di/di_v03_soa.tf
  /home/ditel/tfp_di/kernels/di/dif_pred_Opnav_T1_DOY115_1.bc
  /home/ditel/tfp_di/kernels/di/launch_bet050112_101_20050102T205819_att.bc
  /home/ditel/tfp_di/kernels/di/naif0007.tls
  /home/ditel/tfp_di/kernels/di/spk_od001_keepInPath.bsp
  /home/ditel/tfp_di/kernels/di/spk_od017.bsp
  /home/ditel/tfp_di/kernels/di/commissioning_ck/DIF_SCLKSCET.00009.tsc
  /home/ditel/tfp_di/kernels/di/commissioning_ck/dif_pred_ADCSATTEST_1.bc
  /home/ditel/tfp_di/kernels/di/commissioning_ck/dif_pred_HRIStray_1_doy117.bc
  /home/ditel/tfp_di/kernels/di/commissioning_ck/dif_pred_MaySciCal_1.bc
  /home/ditel/tfp_di/kernels/di/commissioning_ck/dif_pred_Opnav_T1_1.bc
  /home/ditel/tfp_di/kernels/di/commissioning_ck/naif0007.tls
  /home/ditel/tfp_di/kernels/di/tcm3a/dif_pred_TCM3A.apgen_1.bc
  /home/ditel/tfp_di/kernels/di/tcm3a/older
  /home/ditel/tfp_di/kernels/di/tcm3a/spk_od017_flyby.bsp

Range                            (km)              1.3375e+08
Range                            (AU)              8.9406e-01
One-Way Light Time (OWLT) (hh:mm:ss)                 00:07:26
Station Elevation(s)            (deg)  [  24.19]
Theta: Hga,Lga1                 (deg)       NaN   60.83
Phi: Hga,Lga1                   (deg)       NaN  -68.67
```

Added S/C Ant Pnt Offset (deg) 0

DSN Site Considered: DSS-14/DSS-14
At Time: 2005-185T06:00:00.000 UTC

Link Parameter	Unit	Design Value	Fav Tol	Adv Tol	Mean Value	Var
TRANSMITTER PARAMETERS						
1. Total Transmitter Power	dBm	73.01	0.00	-1.00	72.68	0.0556
2. Xmitter Waveguide Loss	dB	-0.45	0.02	-0.02	-0.45	0.0001
3. DSN Antenna Gain	dBi	72.85	0.20	-0.20	72.85	0.0067
4. Antenna Pointing Loss	dB	-0.10	0.10	-0.10	-0.10	0.0017
5. EIRP (1+2+3+4)	dBm	144.98	0.76	-0.76	144.98	0.0640
PATH PARAMETERS						
6. Space Loss	dB	-272.10	0.00	0.00	-272.10	0.0000
7. Atmospheric Attenuation	dB	-0.11	0.00	0.00	-0.11	0.0000
RECEIVER PARAMETERS						
8. Polarization Loss	dB	-0.05	0.00	-0.00	-0.05	0.0000
9. Degrees-off-boresight (DOFF) Loss	dB	-5.55	0.86	-0.87	-5.54	0.2489
10. S/C Antenna Gain (at boresight)	dBi	6.00	0.50	-0.50	6.00	0.0417
11. S/C Receive Pointing Loss	dB	0.00	0.00	-0.00	0.00	0.0000
12. Lumped Circuit Loss	dB	-6.20	0.50	-0.50	-6.20	0.0833
TOTAL POWER SUMMARY						
13. Tot Rcvd Pwr (5+6+7+8+9+10+11+12)	dBm	-133.02	-1.99	1.99	-133.02	0.4378
14. Noise Spectral Density	dBm/Hz	-171.72	-0.94	0.74	-171.79	0.1187
15. System Noise Temperature	K	487.26	-95.14	90.52	485.72	1436.5703
16. Received Pt/No (13-14)	dB-Hz	38.77	2.24	-2.24	38.77	0.5565
17. Required Pt/No	dB-Hz	26.18	-0.66	0.66	26.18	0.0484
18. Pt/No Margin (16-17)	dB	12.58	2.33	-2.33	12.58	0.6049
19. Pt/No Marg Sigma	dB	0.00	0.00	0.00	0.78	0.0000
20. Pt/No Margin-3Sigma (18-3*19)	dB	0.00	0.00	0.00	10.25	0.0000
CARRIER PERFORMANCE						
21. Recovered Pt/No (16+[AGC+BPF])	dB-Hz	38.77	2.24	-2.24	38.77	0.5565
22. Command Carrier Suppression	dB	-1.45	0.10	-0.10	-1.45	0.0017
23. Ranging Carrier Suppression	dB	0.00	0.00	0.00	0.00	0.0000
24. Carrier Power (AGC)	dBm	-134.47	-1.99	1.99	-134.47	0.4395
25. Received Pc/No (21+22+23)	dB-Hz	37.32	2.24	-2.24	37.32	0.5581
26. Carrier Loop Noise BW	dB-Hz	17.83	-0.20	0.15	17.81	0.0102
27. Carrier-Loop SNR (CNR) (25-26)	dB	19.51	2.26	-2.26	19.51	0.5684
28. Recommended CNR	dB	12.00	0.00	0.00	12.00	0.0000
29. Carrier Loop SNR Margin (27-28)	dB	7.51	2.26	-2.26	7.51	0.5684
CHANNEL PERFORMANCE						
30. Command Data Suppression	dB	-5.65	0.17	-0.18	-5.66	0.0051
31. Ranging Data Suppression	dB	0.00	0.00	0.00	0.00	0.0000
32. Received Pd/No (21+30+31)	dB-Hz	33.11	2.25	-2.25	33.11	0.5616
33. 3-Sigma Pd/No (32-3*sqrt(32var))	dB-Hz	30.86	0.00	0.00	30.86	0.0000
34. Data Rate (dB-Hz)	dB-Hz	8.93	0.00	0.00	8.93	0.0000
35. Available Eb/No (32-34)	dB	24.18	2.25	-2.25	24.18	0.5616
36. Implementation Loss	dB	1.50	-0.20	0.20	1.50	0.0133
37. Radio Loss	dB	0.50	-0.30	0.30	0.50	0.0300
38. Output Eb/No (35-36-37)	dB	22.18	2.33	-2.33	22.18	0.6049
39. Required Eb/No	dB	9.60	0.00	0.00	9.60	0.0000
40. Eb/No Margin (38-39)	dB	12.58	2.33	-2.33	12.58	0.6049
41. Eb/No Marg Sigma	dB	0.00	0.00	0.00	0.78	0.0000
42. Eb/No Margin-3Sigma (40-3*41)	dB	0.00	0.00	0.00	10.25	0.0000
43. BER (from 38)	none	5e-18				

Table 9-2. Flyby HGA downlink design control table.

```
Produced by DI V1.1 XML 07/06/2004
-----------------------------------------------------------------------------------------------
Predict                     2005-185T06:00:00000 UTC
Up/Down-Link                Two-Way
RF Band                     X/S:X/S
Diplex Mode                 N/A
LNA Selection               LNA-1
Spacecraft Configuration    Config A
Telecom Link                DSS14-HighGain-DSS14
-----------------------------------------------------------------------------------------------

TELEMETRY DOWN-LINK PARAMETER INPUTS
Encoding                    Reed Solomon (255,223) concatenated with C.E. (7,1/2)
Carrier Tracking            Residual
Oscillator                  2 Way VCO
Sub-Carrier Mode            Squarewave
PLL Bandwidth               30.00    Hz
Tlm Usage                   Engineering (ENG) - Real Time
Tlm Data Rate/Mod Index     200000   bps/ 72.00    Degrees
Tlm Rng/DOR Mod Index       0.00     Rads/ Off      Radians
-----------------------------------------------------------------------------------------------
Operations Mode             Calibration
Mission Phase               Flyby
DSN Site                    Gold-Gold
DSN Elevation               In View
Weather/CD                  90
Attitude Pointing           EarthPointed
-----------------------------------------------------------------------------------------------

EXTERNAL DATA

SPICE Kernels (in load order)
  /msop/tfp/kernels/com/DSN_topo.frm
  /msop/tfp/kernels/com/de405s.bsp
  /msop/tfp/kernels/com/dsnstns.bsp
  /msop/tfp/kernels/com/dss-55.bsp
  /msop/tfp/kernels/com/dss-55_topo.frm
  /msop/tfp/kernels/com/earth_970804_200101_pred_B.bpc
  /msop/tfp/kernels/com/naif0007.tls
  /msop/tfp/kernels/com/pck00006.tpc
  /home/ditel/tfp_di/kernels/di/DIF_SCLKSCET.00011.tsc
  /home/ditel/tfp_di/kernels/di/di_sunsafe.tf
  /home/ditel/tfp_di/kernels/di/di_v03_soa.tf
  /home/ditel/tfp_di/kernels/di/dif_pred_Opnav_T1_DOY115_1.bc
  /home/ditel/tfp_di/kernels/di/launch_bet050112_101_20050102T205819_att.bc
  /home/ditel/tfp_di/kernels/di/naif0007.tls
  /home/ditel/tfp_di/kernels/di/spk_od001_keepInPath.bsp
  /home/ditel/tfp_di/kernels/di/spk_od017.bsp
  /home/ditel/tfp_di/kernels/di/commissioning_ck/DIF_SCLKSCET.00009.tsc
  /home/ditel/tfp_di/kernels/di/commissioning_ck/dif_pred_ADCSATTEST_1.bc
  /home/ditel/tfp_di/kernels/di/commissioning_ck/dif_pred_HRIStray_1_doy117.bc
  /home/ditel/tfp_di/kernels/di/commissioning_ck/dif_pred_MaySciCal_1.bc
  /home/ditel/tfp_di/kernels/di/commissioning_ck/dif_pred_Opnav_T1_1.bc
  /home/ditel/tfp_di/kernels/di/commissioning_ck/naif0007.tls
  /home/ditel/tfp_di/kernels/di/tcm3a/dif_pred_TCM3A.apgen_1.bc
  /home/ditel/tfp_di/kernels/di/tcm3a/older
  /home/ditel/tfp_di/kernels/di/tcm3a/spk_od017_flyby.bsp
Range                            (km)              1.3373e+08
Range                            (AU)              8.9396e-01
DL One-Way Light Time     (hh:mm:ss)                 00:07:26
Station Elevation(s)            (deg) [  24.19]
Theta: Hga,Lga1,Lga2            (deg)     0.25   90.25   90.25
Phi: Hga,Lga1,Lga2              (deg)   111.79  -90.00   90.00
Added S/C Ant Pnt Offset        (deg)                     0.25

-----------------------------------------------------------------------------------------------
DSN Site Considered:        DSS-14/DSS-14
At Time:                    2005-185T06:00:00.000 UTC
-----------------------------------------------------------------------------------------------
```

Link Parameter	Unit	Design Value	Fav Tol	Adv Tol	Mean Value	Var
TRANSMITTER PARAMETERS						
1. S/C Transmitter Power	dBm	42.70	0.50	-0.50	42.70	0.0417
2. S/C Xmit Circuit Loss	dB	-3.76	0.50	-0.50	-3.76	0.0833
3. S/C Antenna Gain	dBi	35.60	0.50	-0.50	35.60	0.0417
4. Degrees-off-boresight (DOFF) Loss	dB	-0.22	0.22	-0.22	-0.22	0.0154

5. S/C Transmit Pointing Loss	dB	-0.00	0.00	-0.00	0.00	0.0000
6. EIRP (1+2+3+4+5)	dBm	74.32	1.28	-1.28	74.32	0.1821
PATH PARAMETERS						
7. Space Loss	dB	-273.49	0.00	0.00	-273.49	0.0000
8. Atmospheric Attenuation	dB	-0.11	0.00	0.00	-0.11	0.0000
RECEIVER PARAMETERS						
9. DSN Antenna Gain	dBi	74.02	0.10	-0.10	74.02	0.0017
10. DSN Antenna Pnt Loss	dB	-0.10	0.10	-0.10	-0.10	0.0033
11. Polarization Loss	dB	-0.08	0.10	-0.10	-0.08	0.0033
TOTAL POWER SUMMARY						
12. Tot Rcvd Pwr (6+7+8+9+10+11)	dBm	-125.44	-1.31	1.31	-125.44	0.1904
13. SNT at Zenith	K	15.10	-0.30	0.30	15.10	0.0150
14. SNT due to Elevation	K	1.41	0.00	0.00	1.41	0.0000
15. SNT due to Atmosphere	K	7.08	0.00	0.00	7.08	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	23.59	-0.30	0.30	23.59	0.0100
19. Noise Spectral Density	dBm/Hz	-184.87	-0.06	0.05	-184.87	0.0003
20. Received Pt/No (12-19)	dB-Hz	59.43	1.31	-1.31	59.43	0.1908
21. Required Pt/No	dB-Hz	56.06	-0.15	0.15	56.06	0.0025
22. Pt/No Margin (20-21)	dB	3.37	1.32	-1.32	3.37	0.1933
23. Pt/No Marg Sigma	dB	0.00	0.00	0.00	0.44	0.0000
24. Pt/No Margin-2Sigma (22-2*23)	dB	0.00	0.00	0.00	2.49	0.0000
CARRIER PERFORMANCE						
25. Recovered Pt/No (20+[AGC+BPF])	dB-Hz	59.43	1.31	-1.31	59.43	0.1908
26. Telemetry Carrier Suppression	dB	-10.20	1.09	-1.26	-10.26	0.2302
27. Ranging Carrier Suppression	dB	0.00	0.00	0.00	0.00	0.0000
28. DOR Carrier Suppression	dB	0.00	-0.00	-0.01	-0.00	0.0000
29. Carrier Power (AGC) (12+26+27+28)	dBm	-135.70	-1.95	1.95	-135.70	0.4207
30. Received Pc/No (25+26+27+28)	dB-Hz	49.17	1.95	-1.95	49.17	0.4210
31. Carrier Loop Noise BW	dB-Hz	14.77	0.00	0.00	14.77	0.0000
32. Carrier Loop SNR (CNR) (30-31)	dB	34.40	1.95	-1.95	34.40	0.4210
33. Recommended CNR	dB	10.00	0.00	0.00	10.00	0.0000
34. Carrier Loop SNR Margin (32-33)	dB	24.40	1.95	-1.95	24.40	0.4210
TELEMETRY PERFORMANCE						
35. Telemetry Data Suppression	dB	-0.44	0.11	-0.13	-0.44	0.0025
36. Ranging Data Suppression	dB	0.00	0.00	0.00	0.00	0.0000
37. DOR Data Suppression	dB	0.00	-0.00	-0.01	-0.00	0.0000
38. Received Pd/No (25+35+36+37)	dB-Hz	58.99	1.32	-1.32	58.99	0.1933
39. 2-Sigma Pd/No (38-2*sqrt(38var))	dB-Hz	58.11	0.00	0.00	58.11	0.0000
40. Data Rate	dB-Hz	53.01	0.00	0.00	53.01	0.0000
41. Available Eb/No (38-40)	dB	5.98	1.32	-1.32	5.98	0.1933
42. Subcarrier Demod Loss	dB	0.00	0.00	0.00	0.00	0.0000
43. Symbol Sync Loss	dB	0.00	0.00	0.00	0.00	0.0000
44. Radio Loss	dB	0.30	0.00	0.00	0.30	0.0000
45. Output Eb/No (41-42-43-44)	dB	5.68	1.32	-1.32	5.68	0.1933
46. Required Eb/No	dB	2.31	0.00	0.00	2.31	0.0000
47. Eb/No Margin (45-46)	dB	3.37	1.32	-1.32	3.37	0.1933
48. Eb/No Marg Sigma	dB	0.00	0.00	0.00	0.44	0.0000
49. Eb/No Margin-2Sigma (47-2*48)	dB	0.00	0.00	0.00	2.49	0.0000
50. BER of Conv Decoder (from 45)	none	3.5872e-09				

At encounter, the X-band downlink was received by DSS-43 at Canberra as well as by DSS-14 and a four-station array of 34-m stations at Goldstone. The DSS-14 performance at encounter is defined by the downlink DCT in Table 9-2. The predicted performance of the four-station array is shown in Figure 9-6. Nominal encounter (06:00 UTC SCET or 06:08 UTC ERT) appears at 8 hours on the figure's timescale.

In the bottom half of the figure, the threshold for each possible flyby rate appears as a horizontal line. The Pt/No threshold for 200 kbps with (7,1/2) coding is 56.06 dB-Hz, which is defined in the Table 3-1 mi_look table. The predictions of the worst-case (mean minus 3-sigma) Pt/No for each station and the array are the curves on the figure. At 8 hours, the four-station array was predicted to support 200 kbps with 1.8 dB of margin.

For comparison with the reported performance, note the predicted mean value of 5.98 dB for bit SNR in line 41. For (7,1/2) coding, the predicted symbol SNR is 3.01 dB lower, or 2.97 dB.

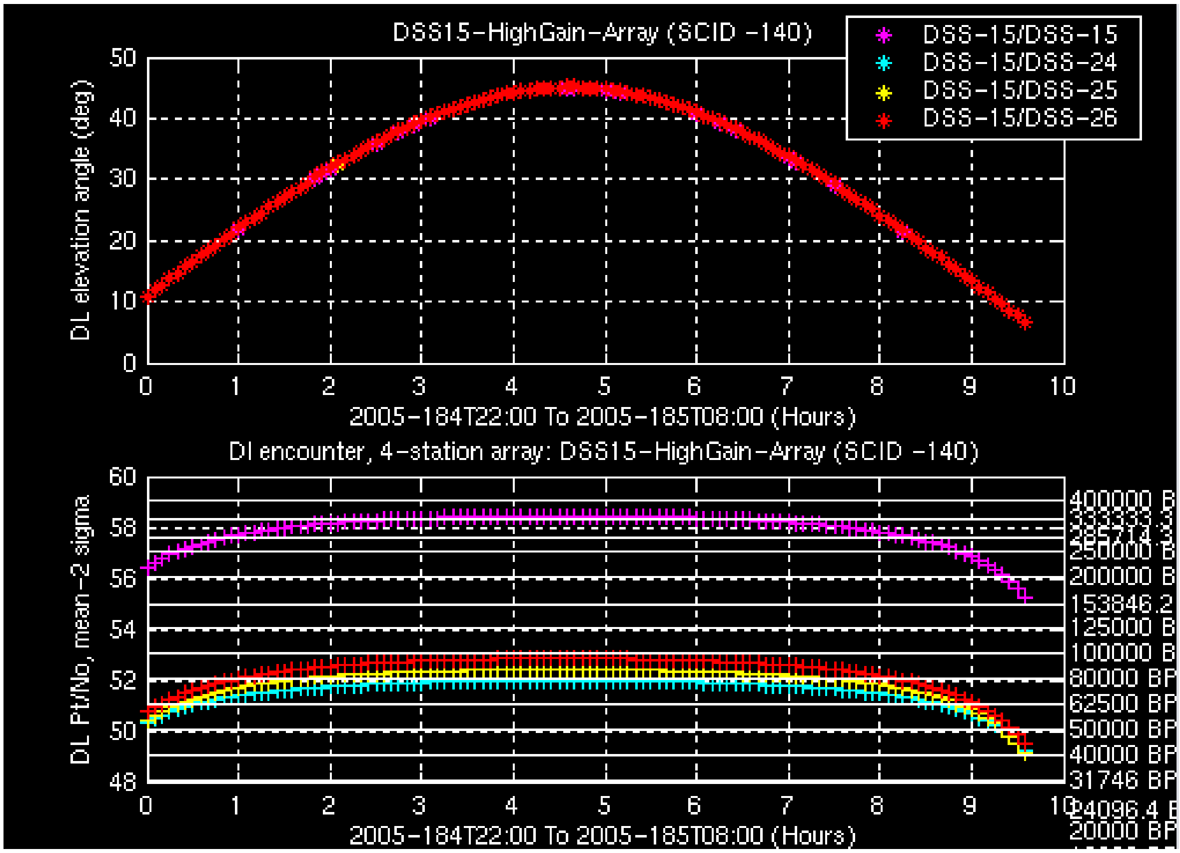

Figure 9-6. Four-station-array predictions on encounter day: elevation (top), downlink Pt/No (bottom).

9.4 Link Performance Comparison with Prediction (Encounter)

Figure 9-7 shows the 200-kbps SSNR from the four-station array for times corresponding to the prediction in Figure 9-6. At 06:00, the predicted SSNR is 2.97 dB. The reported value averaged about 3.4 dB, which is good agreement and good performance.

The detailed differences between the shapes of Figure 9-7 and Figure 9-6 show the differences between a real track and the modeled one that is predicted. Real tracks often have "glitches," short downward or upward spikes relative to the longer average. The prediction is for a single downlink mode, a single flyby antenna, and the full array. In the time before 00:00 UTC, the plot shows the step increases in SSNR as stations are added to the array. The glitch before 02:00 is caused by a station receiver out-of-lock resulting from the sequenced downlink mode of the flyby changing from coherent to noncoherent. The glitches at 06:30 and after are caused by receiver out-of-locks resulting from going back to the coherent mode, and then the flyby downlink being sequenced from the HGA to the LGA for the first look-back sequence.

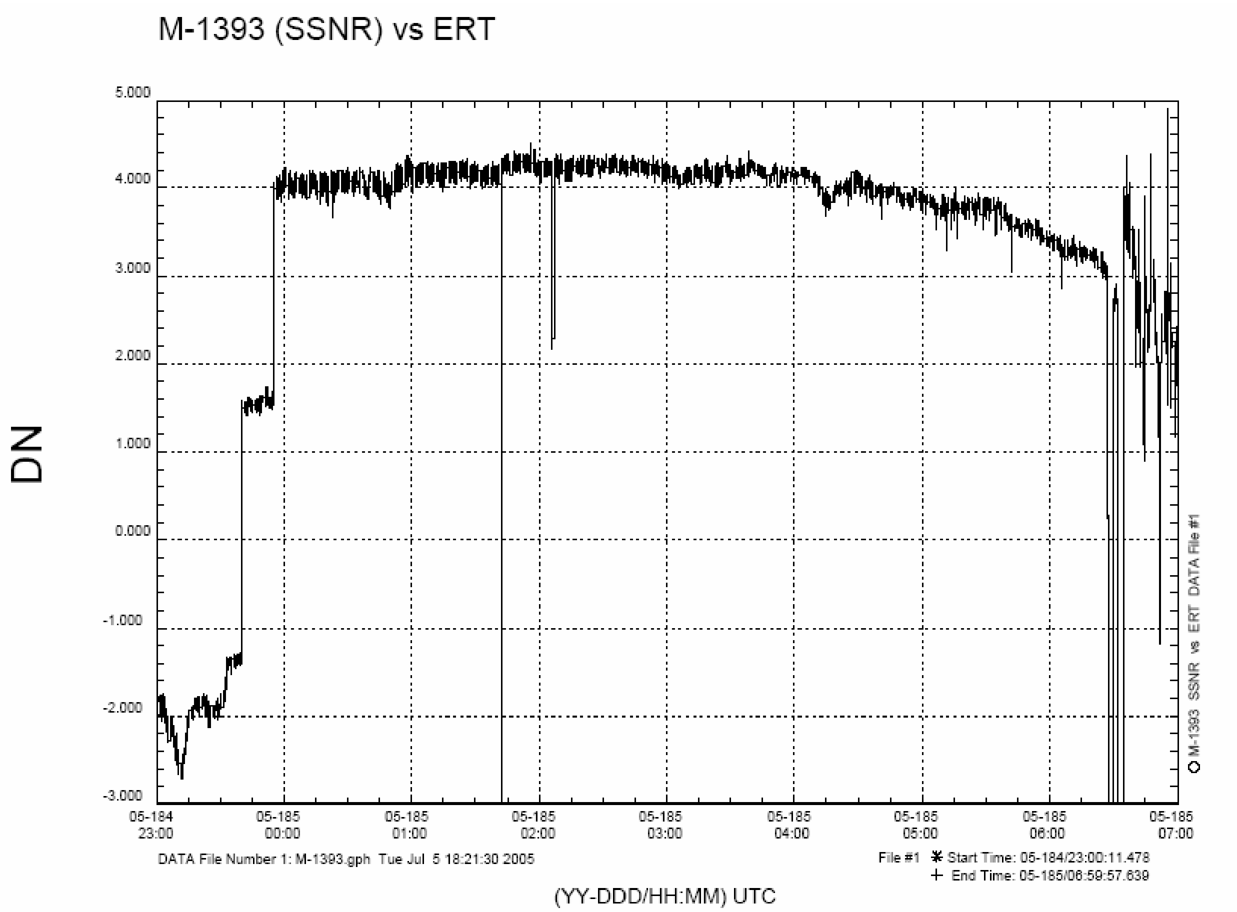

Figure 9-7. Four-station-array reported SSNR (composite output of all stations).

Section 10

Telecom Lessons Learned

DI was a successful mission. In the telecom area, much was well conceived, designed, tested, and flown. We would want to use these as models for the future. Even so, there were some problems that made it difficult to predict and assess telecom performance during flight, required peaks in telecom staffing, required the stations to operate in nonstandard modes, made telecom planning time-consuming, or resulted in lost data. Lessons drawn from these experiences could smooth the operation of telecom subsystems for projects that still have time to incorporate them.

These lessons learned are grouped by major mission phases: development; assembly, test, and launch operations (ATLO); and flight. The DSN is an integral part of any project's telecom operations, so this section includes both DI and DSN lessons learned.

10.1 What Could Serve as a Model for the Future

10.1.1 All Hardware

None of the telecom components were of new design. The X-band components had all flown on previous missions and some in fact were residual hardware left over from these projects. The S-band transceiver was a commercial product. The hardware components caused no real problems in flight. Their characteristics and performance, well tested during ATLO, allowed for efficient operations during flight.

Lesson: For many missions, simple-to-operate and reliable telecom equipment can result in telecom being regarded as a cost-effective "utility" for the spacecraft.

10.1.2 DSN

Coordination meetings, organized by the NOPE, with project system and telecom people in attendance, before launch and before encounter prevented some problems.

Lesson: These meetings should be made standard practice for missions in the future.

10.1.3 Ops

During ATLO, provisions were made for people to call in remotely to meetings while doing work. Such multitasking was particularly effective for "subsystems" such as telecom, which may have sporadic or short-duration but critical inputs to make in meetings.

Lesson: This is a good practice to be continued since flight operations will remain cost-constrained in the future.

DI benefited from an absolutely top-notch, well-integrated Ball Aerospace and JPL flight team. The telecom team had both Ball and JPL members. The project and flight team management to achieve the coordinated ops was transparent at the subsystem level.

Lesson: This is a good model for flight operations of future projects, a middle course between in-house JPL flight operations and contracted flight operations such as with Mars Odyssey.

The project used simple, high-margin telecom modes when possible. Selecting two or three uplink rates from the nine available and three or four downlink rates from the 27 available, using the HGA whenever possible, and not being excessively greedy for downlink rate at encounter were part of this. The simple modes resulted in less telecom analysis and prediction effort than would otherwise be required; and the usually generous planned-in margin most often resulted in data return even when unmodeled problems (such as DSN equipment degradation) occurred. The operating crosslink had a single commandable mode (“on”).

Lesson: Design the normal modes for your spacecraft and mission for simplicity and high margin. It pays off during flight ops.

10.2 What Could Be Improved

10.2.1 LGA Testing

Pattern tests on the model every 4 degrees were not fine-grained enough to reveal the location and depth of all nulls lurking in a given region. Despite prelaunch plans to the contrary, DI followed the practice of other flight projects in repeatedly putting the Earth in poorly modeled portions of the LGA system pattern to achieve communications during mission-required orientations for science calibrations, TCMs, and encounter activities.

Lesson: Push for high-fidelity LGA pattern measurements, including the effects of the spacecraft and instruments in the antenna’s field of view (FOV).

10.2.2 HGA

The planned “autotrack” HGA operating mode had a defined total pointing error of about 0.25°. The prelaunch measured pattern available to the flight team extended to 2.5°, but a gimbal problem forced us to use the HGA out to 3.5°. Early in cruise, this software problem temporarily required an operating mode in which the gimbal was not commanded to move but rather the entire spacecraft was oriented to point the HGA within a few degrees of the Earth. Periodic “maneuvers” moved the HGA in inertial space to lead the Earth, and the Earth would gradually move closer to boresight, and then the HGA would lag the Earth until the next orientation maneuver. Lack of detailed pattern data beyond 2.5° from boresight limited how seldom these maneuvers could be done.

Lesson: Even for an HGA that is planned to be operated within 1 dB of boresight, the pattern should be measured broadly. The data will be needed sometime during flight.

10.2.3 SDST

"Clear carrier" condition prevented us from going away from (7,1/2) coding. The DI SDSTs were two from the "group buy" that also provided SDSTs to MER, Dawn, and others. During MER's ATLO, these SDSTs were found to have a firmware error that would occasionally cause loss of the telemetry subcarrier and telemetry symbols from the modulated downlink. The telemetry could be restored only by rebooting the SDST. On DI, this was called "clear carrier." Its cause (commanding the SDST to change its encoding mode) was known from MER testing and analysis but too late to fix in DI. "Clear carrier" occurred during DI ATLO as well, resulting in a flight rule to minimize the number of encoding mode changes. "Clear carrier" did not occur during flight, but the flight rule led to leaving telemetry modulation on the downlink during delta-DOR. Because it was hard to change a standard script governing station operation during a pass, this confused the DSN as to whether they should lock to the telemetry.

Lesson: A project faced with a comparable situation needs to ensure that workaround modes are effectively communicated to those, such as DSN personnel, who are affected by them.

10.2.4 S-Band Crosslink

Neither S-band receiver sent automatic gain control (AGC) or SNR data to the corresponding C&DH, so no telemetered estimate of link margin was available from either the flyby or the impactor. Such measurements could have helped validate the crosslink performance during ATLO. Lack of signal-level data made performance during the 24 hours leading up to impact entirely dependent on generous link margins and the correct and thorough link predictions made two years before launch. Telecom personnel used to AGC in the SDST felt like drivers accustomed to reading an oil pressure gauge being forced to rely on an "idiot light."

Lesson: Use a relay radio more like Electra, first deployed in the Mars Reconnaissance Orbiter (MRO). Electra is typically configured to output a signal-level profile at the end of a relay pass. However, the relay link signal level telemetry should be continuous in real time for a mission like DI that relays its science in real time.

10.2.5 TWTA

The engineering telemetry was unduly sensitive to temperature, and several important channels were not converted to engineering units. The TWTA baseplate was near 40°C shortly after launch, but this had decreased to 10°C in July after the instruments were turned off post-encounter. The temperature change produced an apparent decrease in TWTA output RF power of about 0.2 dB. It was not possible to determine if the actual TWTA output remained constant or had begun to degrade. DI TWTAs are residual Cassini hardware. Not having helix current, input current, and cathode current channels converted to amperes on DI made it difficult to compare DI TWTA operation with that on Cassini (which did convert the channels to amperes).

Lesson: Better TWTA engineering telemetry would allow for a better in-flight assessment of performance. This is significant if the project's power amplifier actually is producing questionable performance in flight, or for longer missions.

Helix current produced "outliers" that led to a lot of work (ISA Z85877, [13]), as detailed in Section 8. It was suspected but not determined with certainty that the outliers were mostly the result of noise in the telemetry system. Outliers, which occurred only once every several thousand samples, were not seen during DI ATLO. The Cassini X-band TWTA does not produce outliers.

Lesson: Scrutinize subsystem telemetry more completely during ATLO, or make it easy to query ATLO data during flight. (Given the priority of things, telecom did not have time during flight to research an ATLO data query process.)

10.2.6 C&DH

Flyby file data was not "randomized," resulting in corrupted image frames (ISA Z85490). The corrupted image frame problem is described in Section 7. Use of a randomizer on the X-band link was considered during development but not implemented because of cost. (The S-band data from the impactor on the crosslink was randomized.) Fortunately, both the flyby SDST design and the DSN receiver operations modes allowed for workarounds. The ground receiver workaround was calculated to alleviate the problem sufficiently (by a factor of 50!) but not eliminate it entirely. The SDST could have been operated in either of two modes that would have eliminated the problem. However, the project did not want to introduce untested modes during flight, so chose the ground receiver approach. This resulted in a placing a significant burden in operational complexity on the project ACE and the DSN stations.

Lesson: "Test as you will fly." The data corruption problem was not detected during ATLO because flight-like data was not used for the telemetry modes that turned out to have problems. Only engineering telemetry files, not uncompressed science image files, were used for the 100-kbps and 200-kbps compatibility tests.

Lesson: DI is not the first project, nor probably the last, to see unexpected data problems for the first time in flight. The ATLO schedule should provide for testing comprehensive sets of the modes the SDST is capable of being commanded to, even those not planned to be used. Testing the modes on the ground would provide the project confidence to use them in flight if found necessary.

There was no engineering telemetry from subsystem elements depending on the 1553 bus when spacecraft control unit B (SCU-B) was in control. This resulted in most SDST and TWTA engineering telemetry from SCU-B being invalid. Only downlink rate, telemetry frame length, and symbol clock information was available. Telecom was "blind" to performance during these times, except for the inference from the in-lock state of telemetry at the station and the AGC and SNR in-station monitor data.

Lesson: Each subsystem on a project should define a set of "heartbeat" telemetry status and performance channels (perhaps a dozen). These channels should be made available at some rate in all downlink modes, including fault-protection modes.

10.2.7 ATLO

In addition to a typically busy and time-compressed ATLO schedule, the project's approved DSN compatibility test plan for the DSN compatibility test trailer at Ball Aerospace and the later verification test plan for the test station at KSC (named MIL-71) both required around-the-clock staffing to test the planned telecom modes and data rates. DI gained the services of the single experienced JPL SDST telecom test engineer, who efficiently planned a set of tests to confirm critical data modes and uncover problems. This engineer also ensured that the collection of conversion data (data numbers [DN] to engineering units [EU] of dBm) for the SDST received signal-level measurements. He generated telemetry look-up tables of DN to EU for the wideband AGC and carrier-lock accumulator (CLA). Accurate dBm values proved essential on one occasion in flight when a station had the uplink polarization set in error (with no station indication to verify this). The correctly converted CLA enabled telecom to confirm the supportable command rate to be used to get a time-critical command in.

Lesson (project): Testing plans must also consider the kind of input data required (science data files for science data modes) and the kinds of data to be collected (sufficient DN-to-EU conversion data over ranges of temperature), particularly for channels that are nonlinear or a strong function of temperature. Compressed test schedules may require operators with previous experience on similar tests or subsystem elements. Test staffing should allow for the training of new operators to reduce dependence on a single experienced individual.

Lesson (DSN): Provide instrumentation to indicate unambiguously all configuration elements at the station, including the states of the microwave elements.

DI did not fund a Telecom Operations Handbook. During flight, therefore, telecom relied heavily on the SERs written during development by the Ball Aerospace telecom lead. Good as the SERs were, they were not written specifically for flight ops. Having over 20 of them to cover X-band and S-band meant that the search for specific information was tedious and too often dependent on the Ball engineer who wrote most of the SERs finding the information.

Lesson: The MER telecom ops handbooks for X-band and UHF are models that future projects should follow.

The flight team was required to review many ATLO test results in too short a time before launch. It was determined by the project quite late that launch approval was contingent on each subsystem having reviewed the test bench (or flight spacecraft) data for each of approximately 30 tests. While reviewing this data was a learning experience for the subsystem analysts on the flight team, they also had critical development work and training tests to complete before launch. If the need for test data by the flight team had been identified to subsystems earlier, it would have eased the time crunch.

Lesson: Staffing levels and schedules need to be consistent with the tasks imposed. Because of the learning curve, large tasks imposed late often can't be resolved simply by throwing more people at them.

10.2.8 DSN

On acquisition day, there was initially a problem locking to and flowing 10-bps safe-mode data. DSN personnel have presented their assessment of these problems [14] for possible lessons learned for the MRO launch in August 2005. Three causes were identified: (1) Personnel at the initial acquisition Complex unilaterally deviated from the agreed-to "Project/DSN Plan"; (2) they missed the (on-Net) safe-mode announcement; and (3) the ground data system wasn't configured as had been tested in operational readiness tests. The fixes were twofold: (1) Ensure that the entire DSN ops team understands that any changes in plans must be discussed with and approved by the NOPE; and (2) ensure that the NOPE requests positive confirmation of all mission-critical announcements from each Complex.

Lesson: In a complex operation, mistakes will be made despite training. Reduce these through coordination and planning meetings and conferences. Test the planned and contingency configurations to be used. Provide information to those involved in future similar activities, as was done in July 2005 by the DSN for the benefit of the MRO launch.

There were problems on separation/encounter day with 70-m station hardware and operations. The DSN also assessed a series of problems that occurred with the 70-m stations during the days leading up to encounter and on the day of encounter. As summarized from [14], the problems resulted in the loss of 98 minutes of telemetry out of 14,400 minutes planned. The loss was far smaller than specified in the project-DSN agreement, but any data lost during critical events is of concern. Of the 98 minutes, 95 were due to problems with the subreflector at the 70-m station at Madrid. In addition, transmitter arcing at the 70-m station at Goldstone occurred over several passes, resulting in the project using a scheduled 34-m backup station for the uplink. The 34-m uplink didn't result in quantifiable telemetry loss, but combined with the project's planned use of the LGA for the uplink, it degraded ranging performance. It also put an additional burden on the ACE and project telecom. Inappropriate use of ranging modulation led to a brief period of corrupted telemetry data, and a subsequent decision not to do further ranging caused a miscue between the project and the DSN as to station receiver configuration.

Lesson: Schedule as much backup station support as possible in critical periods. Late in the game, DI scheduled extensive 34-m backup support for the week leading up to encounter. Consider the side effects of using the backup support to avoid problems with configurations that were planned for the primary support. Prioritize the remaining capability, determine constraints, and cancel lower-priority activities (such as ranging) that could interfere with or degrade higher-priority activities (such as DI's optical navigation images).

Phase glitches on the uplink may cause inversions of the received ranging signal, causing ranging bias, when the station receiver is in the suppressed carrier mode. (This was a side effect of the project's decision to use this mode to work around the corrupted image frame problem.) It was determined that DSS-55, a 34-m station at Madrid, did not have a "mod kit" installed to prevent turning on or turning off uplink command modulation from producing phase glitches. Also, the transmitter arcing at DSS-14, the 70-m station at Goldstone (previous paragraph) is believed to be the source of uplink phase glitches that caused several ranging phase inversions totaling the degradation of 381 minutes of ranging and the loss of 455 minutes more. These ranging losses did not affect the ultimate outcome of the navigation to the comet.

Lesson: The DSN's receiver cognizant engineer developed the suppressed carrier mode fix for DI, and also identified the causes of the ranging bias. Enable the spread of this kind of expert knowledge as far as possible. Be on top of station configuration (the lack of the "mod kit"). Schedule (more?) preventive maintenance before critical periods to minimize the possible hardware failures. (The DSS-14 transmitter is still subject to arcing at full 20-kW power output, with the specific cause not resolved as of mid-July 2005.)

Ranging integration times were insufficient to account for changes in RTLT over the duration of a pass. Ranging acquisitions are normally started at the beginning of a pass, using the then-current RTLT. If the actual RTLT by the end of the pass has changed by a large fraction of the integration time, the correlation of received and transmitted ranging signals is degraded. By encounter, DI's RTLT was changing by 5 seconds over the duration of a typical-length pass. The remedy, as defined by the DSN's ranging expert and discussed in Section 7, was to increase integration times beyond the values required by signal level (Pr/No).

Lesson: Document the ranging expert's information in the standard project/DSN interface document [9].

Less than one month after launch, DI experienced data latency—delays of up to 2–3 hours in receiving telemetry data downlinked at 200 kbps. The DSN found that this occurred when other spacecraft (for example, Cluster) were also downlinking at high rates to the same sites. To reduce this problem, the DI NOPE modified a parameter in a Reliable Network Server (RNS) configuration tables to give DI a higher priority, but at the risk of losing more frames in real time. With this modification, the data is not lost permanently. It is on the station original data record (ODR), but it takes a special request to recall it.

10.2.9 Ops

There was insufficient flight team staff in some subsystem areas. Over the year before launch, and during flight, the team size kept growing, but seemed always to lag behind the amount of work. In March 2004, telecom was staffed at a 0.25-person level, beginning work on supporting the mission plan development and the validation of the telecom prediction tool and its data base. Over the next several months, this increased first to 0.5, then to 0.75 as additional work was anticipated to support risk reviews, flight-rule development, and test-bench validation. Prior to launch, with command and telemetry data base work, writing of procedures and contingency plans, and participating in launch training tests, the level grew to 1.0 with additional as-needed support from a second person for long training tests. (The Ball telecom person was supporting ATLO at the Cape.) By encounter, telecom was at a level of 2.0+, with four people involved, so that around-the-clock support could be possible during the last 36 hours before encounter.

Lesson: Use a task outline, like the *Develop Operations Tools for and Operate the Telecom Subsystem* procedure in *JPL Rules!* [15] to negotiate with the project at all stages to balance the tasks required against the staff provided.

The process for reviewing test-bench data (the file of commands issued to the spacecraft (log.html) vs the time plots of telecom telemetry from the Whale server) was cumbersome. Moreover, the data was not in an easy-to-assimilate form, making the prelaunch test-data review that much more difficult.

> Plots. At the beginning, only full-page *.pdf plots for each individual channel were available. Time scales were in ERT, but spacecraft commanding was done in SCET. As a workaround, the attitude determination and control subsystem (ADCS) provided a MATLAB plot capability named Messaging Architecture for Networked and Threaded Applications (MANTA), to show, in up to six stacked plots per page, both the chosen subsystem *configuration* state changes vs. SCET and the chosen performance telemetry. For most test-bench data, telecom *performance* data is static, and hence useless by itself.

Logs. Additionally, time-ordered listings of the commands issued to the subsystem and fault-protection responses were made available as log.html files. Different activity leads "hid" the log.html files in different locations within a large directory structure or sometimes neglected to provide these files at all. As a workaround, the project funded a person to work several weeks to produce the MANTA plots and the log.html for telecom and several other subsystems.

Lesson: Standardize on the data products to be provided to each subsystem so that the analysts can spend their time reviewing data rather than searching for it. Announce the availability of data, including directory locations. An example of both lessons is the "daily Whale data" files that were reliably produced and announced by e-mail starting a month after launch.

DI lacked standardized tools to review sequence products (only had the Unix operating system's function global/regular expression/print [grep] for most). The project required each subsystem to review and produce a checklist for each sequence of commands to be uplinked. The review products provided to telecom were two file types, named *.pef and *.dkf. The PEF is the predicted events file, and the DKF is the DSN keywords file. The *.dkf was not a problem to review, though it was a problem not unique to DI to produce a consistently correct one without some editing. The *.pef is a text file that can be several hundred pages long. The only tool commonly made available for the *.pef is the Unix function "grep." By trial and error, telecom developed a set of text strings for grep that cut a *.pef down to 3–60 pages, depending on the sequence's complexity. Unfortunately, the simple grep produces only the first line of a command element. Recovering additional critical lines required pulling them manually out of the full *.pef. On the positive side, the announcement of *.pef availability, directory location, and review meeting time in the big-font e-mails (BFEs) made review more efficient than it had been.

Lesson: Provide a standard review tool or output for all subsystems, ideally a file like a grep output (with search strings specified by the user) but with extended capabilities such as the ability to produce all lines of a command element.

DI was operated from two separate mission support areas (MSAs) at JPL. DI real-time online operations were done in one small MSA at JPL and another at Ball Aerospace until the separation and encounter events. Separation/encounter was done in another MSA in a different building at JPL, to accommodate the whole flight team and to showcase our big event in a camera-friendly environment. To configure the encounter MSA, the project incurred the cost of installing/adapting a complete set of workstations, ports for outside-the-firewall computers, and voice net equipment. Though the encounter MSA was larger than the launch/cruise one, some functions (X-band telecom, ACE, ground data system, sequence) were in a separate room from the other functions (including S-band telecom, the flight director, and the mission manager).

Lesson: At the project level, plan what is required to operate the spacecraft. Plan, and replan as necessary, to meet institutional requirements and constraints. Consider the cost (to the institution if not the project) of reconfigurations.

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Abbreviations and Acronyms

ACE	real-time mission controller (call sign)
ADCS	attitude determination and control subsystem
AGC	automatic gain control
AMMOS	Advanced Multi-Mission Operations System
ATLO	assembly, test, and launch operations
AU	astronomical unit
BB	baseband
BER	bit error rate
BFE	big-font e-mail
BLF	best-lock frequency
BOT	begin-of-track
BP	baseplate
BWG	beam waveguide (antenna)
C&DH	command and data handling
CCD	charge-coupled device
CCSDS	Consultative Committee on Space Data Systems
CCT	Central Communications Terminal
CDU	Command Detector Unit
CFDP	CCSDS File Delivery Protocol
CK	camera kernel
CLA	carrier-lock accumulator
CNR	carrier-loop signal-to-noise ratio
CPU	central processing unit
CTB	command and telemetry board
dB	decibel
dB-Hz	decibel-hertz
dBi	dB isotropic
dBic	dBi circular
dBm	dB milliwatt
DCT	design control table
delta-F	change in frequency
delta-V	change in velocity
DESCANSO	Deep Space Communications and Navigation Systems Center of Excellence

DI	Deep Impact
DKF	DSN keywords file
DN	data number
DOFF	degrees off boresight
DOR	differential one-way ranging
DOY	day of year
DSCC	Deep Space Communications Complex
DSMS	Deep Space Mission System
DSN	Deep Space Network
DSS	Deep Space Station
DTF	DSCC Test Facility
EIRP	effective isotropic radiated power
ENG	engineering
EOT	end-of-track
EPC	electronic power converter
ERT	Earth received time
EU	engineering unit
FCT	Flight Control Team
FOV	field of view
GDS	Ground Data System
grep	g/re/p for global/regular expression/print
GSE	ground-support equipment
GTP	Generalized Telecom Predictor
HEF	high–efficiency (antenna)
HGA	high-gain antenna
HRI	High-Resolution Instrument
I&T	integration and test
IR	infrared
ISA	Incident/Surprise/Anomaly
IST	integrated system test
ITS	Impactor Targeting Sensor
JPL	Jet Propulsion Laboratory
kbps	kilobits per second
KSC	Kennedy Space Center
ksps	kilosymbols per second
LCP	left circular polarization

LGA	low-gain antenna
LSB	least significant bit
MANTA	Messaging Architecture for Networked and Threaded Applications
MER	Mars Exploration Rover
MGA	medium-gain antenna
MIL-71	military (station) 71 at Kennedy Space Center
MMO	Mission Management Office
MRI	Medium-Resolution Instrument
MRO	Mars Reconnaissance Orbiter
MSA	mission support area
MSB	most significant bit
NASA	National Aeronautics and Space Administration
NEAR	Near-Earth Asteroid Rendezvous
NIC	Network Interface Card
NO_OP	no operation command
NOCC	Network Operations Control Center
NOP	Network Operations Plan
NOPE	Network Operations Project Engineer
OCXO	oven-controlled crystal oscillator
ODR	original data record
ORT	operational readiness test
P/L	payload
Pc/No	ratio of carrier power to noise spectral density
PDU	power distribution unit
PEF	predicted events file
POR	power-on-reset
Pr/No	ratio of ranging power to noise spectral density
Pt/No	ratio of total power to noise spectral density
QPSK	quadrature phase-shift-keyed
RCP	right circular polarization
RCV	receive, receiver
RF	radio frequency
RFF	radio frequency flyby
RNS	Reliable Network Server
RT	rate
RTLT	round-trip light time

S/C	spacecraft
S/N	serial number
SAT	select at test
SCET	spacecraft event time
SCU	spacecraft control unit
SDST	small deep-space transponder
SER	System Engineering Report
SNR	signal-to-noise ratio
SNT	system noise temperature
SPE	static phase error
SPICE	Spacecraft, Planet, Instrument, C-Matrix Events
SPK	SPICE kernel
SSNR	symbol signal-to-noise ratio
TBD	to be determined
TCM	trajectory-correction maneuver
TFP	Telecom Forecaster Predictor
TFREQ	transmit frequency
TLM	telemetry
TNT	2 4 6-trinitrotoluene
TWTA	traveling-wave tube amplifier
USN	Universal Space Network
UTC	Universal Time Coordinated
VCO	voltage-controlled oscillator
VLBI	very-long-baseline interferometry
WG	waveguide
Whale	DI’s data query, plot, and log archive system
WTS	waveguide transfer switch
XBT	X-band transponder
XDOR	X-band DOR
Xmit	transmit, transmitter
Xmtr	transmitter