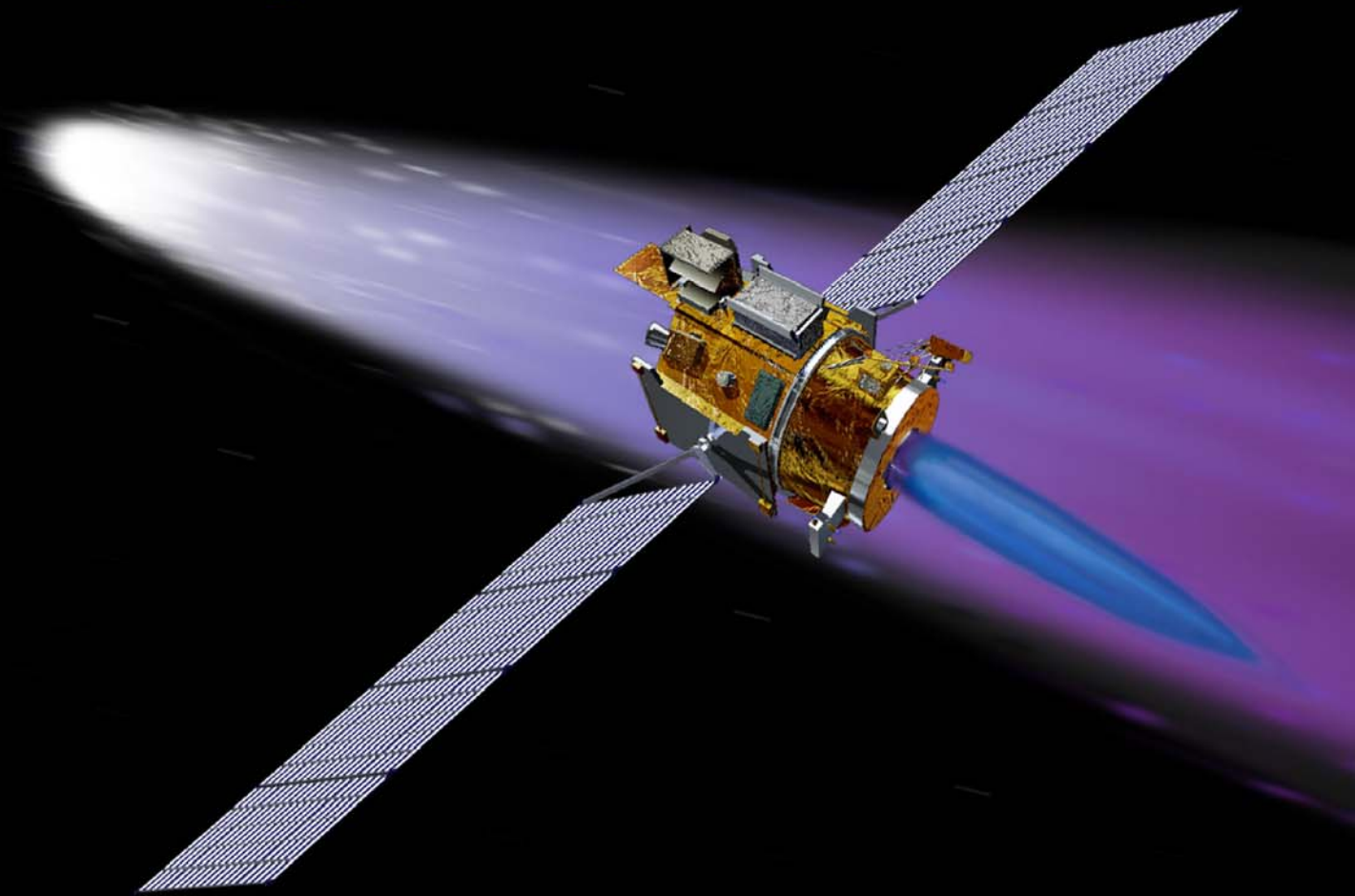


# *Deep Space 1*

## *Navigation: Extended Missions*



*Brian Kennedy, Shyam Bhaskaran,  
J. Edmund Riedel, and Mike Wang*

*September 2003*



# **DESCANSO**

**Deep Space Communications and Navigation Systems  
Center of Excellence**

## **Design and Performance Summary Series**



## **DESCANSO Design and Performance Summary Series**

### **Article 7**

# **Deep Space 1**

# **Navigation: Extended Missions**

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**September 2003**

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## 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 will describe the means by which JPL navigators determined and controlled the trajectory of the Deep Space 1 (DS1) spacecraft during the course of its extended missions.

It is worth noting that during most of the extended missions, DS1 was a dysfunctional spacecraft. This was due to the fact that the sole source of stellar reference used by the attitude control system (ACS) was the science camera. As such, this limited the attitudes that could be maintained by DS1 and constrained its operations leading up to and during the encounter with comet Borrelly. The impact of these constraints on navigation during the extended missions and their workarounds will be discussed in this article.

It is hoped that this article can be used as a source that documents the navigation challenges (and rewards) of DS1 and that future navigators can use it to gain insight into the implementation of new methods of guiding spacecraft towards scientifically rich encounters.

## Acknowledgements

The authors would like to thank many members of the NASA Community, whose efforts and inputs made the DS1 mission a very rewarding and successful experience: Tim McElrath, Don Han, and Marc Ryne for developing the DS1 radio navigation strategies during the primary mission; Marc Rayman, the DS1 Mission Manager, for having faith in the flight team to make the extended mission a success; Bob Werner, for developing ground tools that greatly simplified operations; Steve Collins, Tony Vanelli, Sam Sirlin, Sanjay Joshi, and Jim Alexander for their attitude control expertise; Jim Taylor, the DS1 Telecommunications Lead, for his inputs and for his tireless telecommunications support; the DS1 flight team, the DS1 flight controllers, and the personnel of the DSN facilities at Goldstone, Madrid, and Canberra.

# Section 1

## Deep Space 1

On October 24th, 1998, Deep Space 1 (DS1) became the first spacecraft launched under the New Millennium Program (NMP). The purpose of the NMP was to develop and certify new high-risk technologies for use in future low-cost science missions. DS1 served as an in-flight test bed for twelve new technologies. Navigation for this mission was performed using conventional radiometric navigation techniques, as well as an onboard Autonomous Optical Navigation System (AutoNav). The AutoNav system was one of the new technologies. Its effectiveness in navigating DS1 using autonomous optical navigation techniques is covered in [9]. Radiometric navigation of DS1 while under low-thrust is covered in [5] and [9].

### 1.1 Commencement of Extended Mission—September 19, 1999

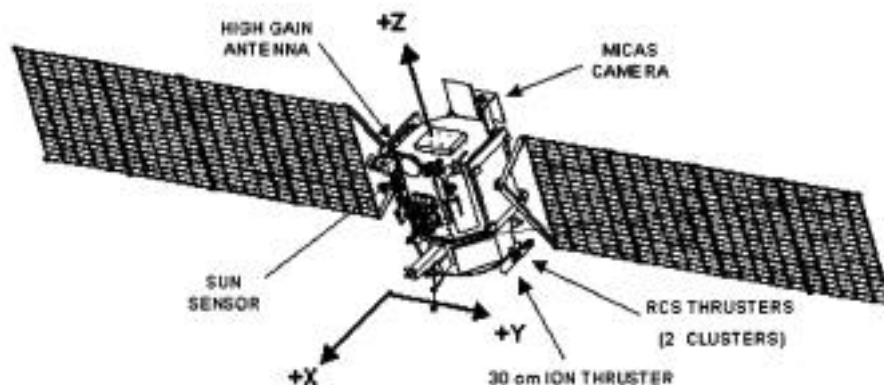
Following the successful completion of its primary mission in the summer of 1999, DS1 began an extended mission on September 18th, 1999. The goals of this mission were the collection of science data during flybys of comet Wilson-Harrington in January 2001 and comet Borrelly in September 2001. As a bonus, the mission would also further validate the effectiveness of the onboard AutoNav and its use of the Ion Propulsion System (IPS) [4] to maintain the spacecraft on course to its encounters.

These two technologies performed their tasks flawlessly during the first two months of the extended mission. Unfortunately, the spacecraft Stellar Reference Unit (SRU) failed on November 11, 1999. Without this, the flight team was required to leave the spacecraft in a Sun safehold configuration until a replacement plan could be enacted. While in this state, it became clear that DS1 could not encounter both comets Wilson-Harrington and Borrelly due to the loss of IPS thrusting schedule (or the so-called deterministic mission burns) after the star tracker failed. The DS1 science team met in January 2000 and decided that DS1 should bypass the encounter with Wilson-Harrington, and redesign the trajectory in order to maintain a planned encounter with comet Borrelly in September 2001.

Replacing the SRU and successfully making it to Borrelly required making use of three<sup>1</sup> of the original twelve technologies that were verified in the primary mission: the Miniature Integrated Camera Spectrometer (MICAS) camera, the imaging processing capabilities of the AutoNav and the Ion Propulsion System (IPS). This article will describe the roles played by the AutoNav image processing, Maneuver Planning, and Encounter Target Tracking software in the post-SRU extended mission. The roles played by the MICAS camera and the IPS will also be described. Figure 1-1 shows the flight configuration of the DS1 spacecraft and the key hardware components used for SRU replacement during the extended mission.

---

<sup>1</sup> The Solar Concentrator Array with Refractive Linear Element Technology (SCARLET) solar arrays, the Small Deep-Space Transponder (SDST), and the Plasma Experiment for Planetary Exploration (PEPE) were required as well. SCARLET was required to power the IPS, and PEPE was required to return charged-particle measurements from Borrelly. The role the SDST played in operations is described in [8].



**Fig. 1-1. The DS1 spacecraft.**

Following replacement of the SRU, a new low-thrust trajectory was developed. This trajectory required the use of near continuous IPS thrust in order to maintain spacecraft attitude using IPS thrust vector control (TVC) instead of the Reaction Control System (RCS) for attitude control. This reduced the usage of hydrazine (the fuel used by the RCS) from tens of grams per day to grams per day. This need to conserve hydrazine was the result of expending large quantities of hydrazine during the extended safehold and of maintaining the spacecraft in an Earth-pointed configuration for high-rate data passes without the use of the SRU. In the absence of an SRU, the flight team devised a complex technique that allowed them to maintain the spacecraft in an Earth-pointed attitude. This technique is described in [8] and [2].

The replacement of the SRU with the MICAS camera required changes to the attitude cruise navigation techniques and the flight software. Since scheduling optical navigation activities would increase the risk of losing celestial inertial reference, the optical Orbit Determination (OD) capabilities of the AutoNav could not be used during cruise, so radiometric OD would be required. Optical OD would still be used to support the approach phase of the encounter. The encounter with Borrelly required modifications to the tracking software that enabled it to estimate the errors within the inertial measurement unit (IMU) and to provide updated pointing to attitude control system (ACS) during the encounter.

Fortunately, the flight team was able to successfully operate the spacecraft in this degraded condition, and complete the planned flyby of comet Borrelly on September 22<sup>nd</sup>, 2001—exceeding the scientific objectives<sup>2</sup> of the encounter.

---

<sup>2</sup> In addition to returning comet spectroscopy and charged-particle measurements, the science team asked the flight team to return a 50-pixel image of the nucleus. An image of greater than 170 pixels was returned.

## 1.2 Commencement of the Hyper-Extended Mission—September 30, 2001

Following the successful completion of the extended mission, the DS1 mission was further extended with the intent of performing end-of-life testing on the IPS and exercising all other 8 hardware technologies onboard. The activities of this mission phase continued until December 18, 2001, after which time the DS1 spacecraft was decommissioned. Navigation activities during this phase included routine radiometric orbit determination, as well as analysis of IPS activities in order to help assess thruster performance under different operating regimes.

## 1.3 Timeline of the Extended Missions

09-18-99	End of primary mission, start of extended mission
11-11-99	Loss of SRU
02-00 - 05-00	Redesign, development, and testing of SRU replacement
06-00	Upload of new flight software and subsequent restoration of celestial inertial reference
06-00 - 05-01	Deterministic thrusting
07-16-00 - 07-19-00	Loss of star lock and recovery operations
10-03-00	one-way range data acquisition experiment
11-00	Ka-band experiments and solar conjunction
03-13-01	Upload of encounter flight software, subsequent loss of star lock following reboot, and recovery of star lock.
05-01 - 09-01	North–South thrusting
07-15-01 - 07-24-01	Loss of star lock and recovery operations
08-16-01 - 08-24-01	Loss of star lock and recovery operations
09-13-01	Loss of star lock and recovery operations
09-22-01	Borrelly encounter
09-30-01	Commencement of hyper-extended mission
09-01 - 12-01	IPS performance tests
12-18-01	Final communication with the spacecraft

## Section 2

### Operations without an SRU

Following the failure of the SRU in November 1999, normal spacecraft operations came to a halt. Maintaining a known attitude that would allow the spacecraft to continue thrusting on its mission trajectory was no longer possible, nor was it capable of accurately pointing its navigation/science camera during imaging opportunities such as optical navigation sessions or comet encounters.

Without the SRU, the ACS lost the only instrument capable of providing it with inertial attitude quaternions every 0.25 seconds. This left the ACS with an IMU (the solid-state gyro) and a coarse (0.5 degree) Sun Sensor Assembly (SSA). The IMU was effective at providing spacecraft rate information, which could be integrated to provide attitude, but it was too noisy and unstable to provide a reasonable attitude estimate for more than a few hours. The SSA could be used to keep an accurate fix on the direction to the Sun, but not the spacecraft rotation around that vector. Therefore, measurements from these systems alone would not enable the ACS to sustain a full 3-axis attitude estimate for more than a few hours, far too short to support lengthy IPS thrust arcs. A more detailed description of the SRU anomaly can be found in [2].

#### 2.1 SRU-Replacement Efforts

As the only other optical device onboard DS1, the MICAS camera would become the new de facto star camera. AutoNav would be used to process the MICAS images in order to extract the star locations needed by the ACS. Due to the small usable field of view (FOV) of the MICAS camera (effectively  $0.5 \times 0.75$  degrees, as compared to the  $8.8 \times 8.8$  degree FOV of the SRU [2,3] and magnitude limitations (6.0 or brighter) only a single star would be tracked at a given time. Another stellar reference would be needed and was readily available as measurements from the coarse SSA. Since the MICAS camera and the SSA were pointed along orthogonal spacecraft axes, their measurements would provide a strong relative geometry with which a new ACS could estimate and control the spacecraft attitude. The ACS would also be able to estimate the current biases and drifts within the IMU, which would have to be relied on to maintain correct inertial attitude during turns. With this in mind, a new attitude estimator and a new image-processing manager were written.

The AutoNav system contained substantial image processing capabilities. During the beginning of the extended mission, work was already underway to develop additional software that would be used during the upcoming comet encounter. This software, affectionately called “the Blobber,” was designed to search through a specified area of a MICAS image and return a list of any contiguous “blobs.” It was expected that these blobs would represent the nucleus of the comet, and that additional software could be used to rectify and extract appropriate targeting information for the nucleus tracking software (see Sections 8, 9, and 10.) In the context of star

identification, it served as a fast means of extracting the pixel and line locations of potential star candidates that needed to be passed along to the ACS.

## 2.2 The Role of the AutoNav Subsystem

In order to effectively use the AutoNav image processor for the SRU replacement, three new command and software interfaces were developed. The first one was between ground and the ACS, the second one was between the ACS and AutoNav, and the third one was between the ACS and AutoNav by way of the MICAS camera.

It was decided that the old method of configuring AutoNav software by adding new parameter files or expanding old ones would be cumbersome to use [9]. This was due to the expected high frequency of updates that would be needed in operations. Therefore an ACS storage facility, called a Parameter Settings (PSET) array, was made use of. Table 2-1 shows the entries in the PSET array used to store information for the main Navigation Software Element (the “Nav Task”). ACS PSET arrays are settable by a single ground command. An additional ground command was used to cause the ACS to transfer the array information to the main Nav Task. This ACS–Navigation interface required an additional queue interface to be added to the Nav Task.

**Table 2-1. Entries in image processing configuration array.**

Programmatic Label	Description
pix_start	Column at which the search software started looking for stars. This was typically set to pixel 10. Ignoring data that was too close to the edge of an image was preferred, since the optical distortion was quite prevalent (up to several pixels) near the edge of an image.
pix_end	Column at which the search software stopped looking for stars. This was typically set to line 1013 (out of 1023). See pix_start, above.
lin_start	Row at which the search software would start looking for stars in an image. This was typically set to line 300, which allowed the search software to ignore stray light artifacts that quite literally dominated the images at low Sun cone angles (50 to 90 degrees).
lin_end	Row at which the search software stopped looking for stars. This was typically set to line 1013 (out of 1023). See pix_start, above.
ceiling	Maximum pixel signal that would be considered valid star data. This was intended to be used to filter out saturated pixels that might be the result of cosmic ray strikes. This was set to 4000, out of a maximum signal of 4095. In practice, this sometimes resulted in valid signals from particular bright stars being thrown out by the star search software.
floor	Minimum pixel signal that would be considered for valid star data. This was the key to the performance of the star tracking software. This was set to be 40, which allowed the star search software to ignore the background noise that was prevalent in the images, even after background processing. This allowed valid, potential star signals to be sent to the ACS without flooding the ACS Star Identification software with false signals.
ceiling_noisy	This was the maximum value for the ceiling (see ceiling, above) used when background processing was not performed. In practice, this was set to 4000, but it was almost never used in flight.

floor_noisy	This was the minimum value for the floor (see floor, above) used when background processing was not performed. In practice, this was set to 100, but it was almost never used in flight.
blob_boundary_ext	Part of the statistical analysis that was performed to identify a star magnitude relied on a sampling of the background noise. This was used to compute the true signal coming from the star, minus the background interference. The boundary extension was the distance from a star “blob” around which a sample box was circumscribed. The average of pixel values that defined the edges of this box was used as the average background value.
verbosity	Setting (or clearing) this allowed the ground operators to turn on (or off) event reporting during star search processing. This was to allow diagnostic evaluation of the performance of the software when necessary.
acs_filter_width	This defined the maximum width of a star signal in the image, in pixels. In practice, this was set to be 200 pixels. It was intended that this be used to filter out large areas that might be stray light artifacts and not true stars. At low cone angles ( 45–50 degrees), large stray light artifacts would show up in the middle of the image. This filter was an attempt to prevent them from being mistaken as star signals.
acs_filter_height	This defined the maximum height of a star signal in the image, in pixels. In practice, this was set to be 100 pixels. See acs_filter_width, above.
fg_pic_bias	During picture background processing, a small bias was applied to the foreground image before the background image was subtracted. In flight, this was typically set to 10 DN.

During tracking operations, the ACS task would initiate an image by directly sending image exposure commands to the camera manager, with the request that the images be passed to AutoNav following the exposure. The extended image command interface developed for AutoNav’s use in the primary mission was used, since it allowed for user-defined data to be added to the header of the resulting image. This user-defined information was used to provide image handling, routing, and processing information to the AutoNav image processing software, as well as provide needed bookkeeping information to the ACS. The image processing software handled four image types: background images, solo images, and parts one and two of a pair of images.

When AutoNav received a background image, it was placed in a buffer for later application. The ACS routinely requested that background images be taken every half hour. This was intended to make sure that the background image was replaced often enough to track subtle changes in the stray light signature of the MICAS images [9].

Image pairs were shuttered back-to-back and sent to AutoNav for processing with the intent that persistent star data would show up in each image, but not transient signals from cosmic rays or other interference. This would allow the ACS to sort the “wheat from the chaff” and converge on a stable attitude solution. Solo images were requested once the ACS had decided that it was receiving a consistent, identifiable star signal. Most (over 99 percent) of the images taken for star tracking purposes were of the solo type.

Images could also be of a certain class: background A, background B, or no background. The image class type was used to control whether background processing would be applied to an image before processing. Although it was intended to use “background free” processing as a means of increasing throughput, in practice this was not necessary. Nearly all images used for



tracking underwent background processing to remove the static stray light signatures from the MICAS images. Table 2-2 shows the handling definitions and values used during the extended mission.

**Table 2-2. Image routing and handling definitions.**

Name	Value	Description
Image Type		
IMAGE_BKG	(0x8000)	Indicates that this picture is to be stored in the background image buffer for use in future background processing. This was used as a means of removing most of the noise from stray light artifacts. Images of this type would be of DIFF_CLASS_A or DIFF_CLASS_B (see Image Class, below).
IMAGE_SOLO	(0x8001)	This is the nominal image type.
IMAGE_PART1	(0x8002)	This is the first of two back-to-back images. These images are shuttered within two seconds of each other as way of letting the ACS star identification software discard spurious signatures that might be the result of cosmic ray interference. It also allows it to identify consistent star signatures, which it needs before declaring that it has locked onto a star.
IMAGE_PART2	(0x8003)	This is the second of two back-to-back images. See IMAGE_PART1, above.
Image Class		
DIFF_NOTHING	(0x8000)	Images of this class did not undergo background processing. In practice, pictures of this class were rarely shuttered.
DIFF_CLASS_A	(0x8001)	Images of this class were to undergo background processing using a background image that was of class "A." If the image in the background was not of type A, the ACS would be alerted, and a new background image would be shuttered.
DIFF_CLASS_B	(0x8002)	Undergo background processing with class "B". See DIFF_CLASS_A, above.

## 2.3 Operational Constraints

The key to effective use of the new software was the careful preselection of a known reference star, also known as a "lock star". With *a priori* knowledge of where the spacecraft should point the camera for Earth communications or for IPS burn arcs, suitable stars were chosen from a star catalog. These stars were dubbed "Earth stars" and "Thrustars," respectively. Over the course of the extended mission, it was noted that stars of magnitude 4.0 or brighter were ideal for use as reference stars. Stars of 5th or 6th magnitude could also be used, if they were a "red" spectral type, such as a class-M, since charged couple detectors (CCDs) tend to be more sensitive to red. The weak signal from stars less than 6th magnitude could not be relied on for tracking purposes, as the tracking software required consistent inputs to maintain a reliable lock. Due to these magnitude constraints, stars at suboptimal locations occasionally had to be used for inertial attitude reference, with a corresponding loss in thrusting effectiveness for Thrustars and a reduced communications bandwidth capability for Earth stars. Once a reference star was selected, its inertial right ascension and declination would be told to the new ACS, which could then use the reported star location within the frame of the image to finely tune its estimate of the attitude.

## 2.4 Bootstrapping

Since DS1 was now effectively equipped with a single-star tracker instead of a full-starfield tracker, getting the spacecraft into a known attitude became a proverbial “chicken or the egg” problem. Without a known inertial attitude, the spacecraft could not be commanded to point at a known reference star for tracking purposes. Consequently, unless the spacecraft was tracking a known reference star, it could not know or update the estimate of its inertial attitude. While not an impossible task, getting the spacecraft pointed in the right direction from zero knowledge required substantial ground interaction.

The crucial first steps were to determine the direction in which the spacecraft was pointing, update its knowledge of its inertial attitude, command it to point towards a known reference star, and activate the tracking software. Due to the fairly volatile nature of the IMU, this was expected to take at least several hours. There was considerable concern that in the event of a star tracking failure, the IMU might drive the spacecraft off attitude (and consequently off course if the IPS were thrusting) before the next tracking pass. It was thus expected that ground-directed attitude recovery efforts might become an operational norm. In practice, losses of inertial lock (LOL), occurred on several occasions with DS1. Further descriptions of LOLs and their impact on navigation are found in Section 4.4.

## Section 3

### Trajectory Profile

Before the flight testing and thrusting of the ion propulsion engine in June of 2000, the DS1 engineers had been designing and planning trajectories to comet Borrelly without a star tracker. There were many iterations of the solar electric propulsion (SEP) thrust profile between mission design team and navigation team required to plan and implement this trajectory.

#### 3.1 Wilson–Harrington

Before the loss of the SRU, the original encounter plan for the extended mission had itself been extended to include a flyby of the comet Wilson–Harrington in January 2001. However, reaching this target would have required thrusting to resume in January 2000. The aforementioned efforts to replace the SRU precluded this from happening. It was therefore decided early in the SRU replacement phase of the mission that a Borrelly-only trajectory would be needed.

#### 3.2 Hydrazine

Hydrazine is the propellant used by the Reaction Control System. The ACS makes use of the RCS to maintain the spacecraft attitude using the z-axis and x-axis facing thrusters (see Figure 1-1). However, during the period of time between the loss of the SRU and the restoration of attitude control (over half a year), a large amount of hydrazine was expended maintaining the spacecraft in its safing configuration and maneuvering the spacecraft during high gain antenna (HGA) communications with the Earth [8]. The remaining mass of hydrazine (approximately 9 kg of the original launch load of 32 kg) would have to be used very sparingly over the next 16 months. Fortunately for the mission, the ACS is able to control the x- and y-axis attitudes using thrust vector control whenever the IPS is running at a high enough throttle level. This would greatly reduce the duty cycle on the RCS and the usage of hydrazine. TVC is made possible by the thruster being mounted on two gimbals that allow up for +/- 5 degrees of slew in the x and y directions [3]. It was required that the IPS would be active for most of that time in order to stay in TVC mode. The limited amount of remaining hydrazine would have a large impact on trajectory design and maintenance as DS1 made its way towards Borrelly. To take advantage of TVC as a means of conserving hydrazine, a low-thrust trajectory was needed in which the IPS would be almost continuously active.

#### 3.3 Trajectory Design

With DS1, this initial trajectory was designed to maximize IPS ontime in order to make use of TVC. This trajectory called for ten months of deterministic thrusting, followed by a four and a half month ballistic arc before the encounter with Borrelly; this was done to maximize the

probability of a Borrelly flyby, allowing time for a possible mission recovery even in the event of an IPS failure. This trajectory plan called for thrusting to resume in early July 2000. The successful operation of the new SRU-replacement software allowed thrusting to resume in late June—one week earlier than expected.

The processes of designing and planning a trajectory to encounter comet Borrelly are described as follows:

- 1) A computer program named SEP Trajectory Optimization Program (SEPTOP) was used to design the DS1 trajectory at JPL. This program performs a constrained optimization of the propellant (xenon gas) consumption, target encounter time, and the deterministic IPS thrust direction and duration as a function of time. The constraints include adjustments to the use of hydrazine, forced coasting (no IPS thrusting), forced thrusting in specific directions (such as stars), and cone angle constraints (i.e., restrictions to the thrust direction with respect to the Sun-spacecraft line) so that the radiators and the sensitive instruments will not be pointed close to the Sun, etc.

The results of the SEPTOP outputs were used as starting conditions to the Navigation Trajectory (NAVTRAJ) program described in the next step. It is worth pointing out that NAVTRAJ was an integral part of AutoNav during the primary mission.

- 2) A numerical integrated trajectory program, NAVTRAJ, and high precision dynamic models were used to retarget the trajectory based on the results of the optimal SEPTOP trajectory, which is also called the nominal trajectory. It is important to note that the NAVTRAJ program and the SEPTOP program have the same spacecraft power and propulsion models. NAVTRAJ has ability to make changes in the direction and duration of each thrust segment, as defined in the IPS thrust profile (see below for details). It is assumed that the changes in the NAVTRAJ trajectory and the IPS thrust profile are relatively small in comparison with the results from SEPTOP. If there are significant changes, then it will be required to redesign a new SEPTOP trajectory for input to NAVTRAJ. This process is iterated until a converged NAVTRAJ trajectory is obtained. Most of the NAVTRAJ input files are generated by the SEP Thrust Profile program (SEPPROF) which reads the SEPTOP outputs and then generates files for input to NAVTRAJ. The NAVTRAJ input files are described as follows:

- a) Maneuver File: This file defines the IPS thrust profile. The thrust profile is divided into a sequence of planning cycles containing either IPS thrusting or coasting. In each IPS plan, a duty cycle value is used to specify the ratio of engine “on” vs. “off” time, where “off” is primarily for telecommunications and autonomous navigation operations. Before the loss of the star tracker, the nominal duration of each planning cycle was 7 days and a duty cycle of 92% was used for the DS1 mission operations. Some planning cycles are shorter due to the operational constraints such as trajectory correction maneuvers (TCMs), close encounter events, etc. The thrust profile may contain several IPS segments (or thrust arcs). Each individual IPS segment is defined as a combination of

consecutive IPS plans where the IPS is thrusting continuously except the imposed duty cycle. During the comet Borrelly operations, the design of duty cycle and IPS plans was driven by the DSN (Deep Space Network) tracking schedule.

- b) **OD File:** This file includes the starting spacecraft epoch state and covariance for each planning cycle. It can be generated by either SEPPROF or another utility called the ODFILE program. In general, if the epoch state in the OD file is the same as SEPTOP, NAVTRAJ is used to generate flight products (including a trajectory) for upload on the spacecraft. If the OD file contains the current OD solution which is different from SEPTOP, NAVTRAJ is used either to generate a new set of flight products if the deviations from the nominal trajectory are small, or to show that a redesign of a new SEPTOP trajectory is needed if the deviations from the nominal trajectory are significantly large.
  - c) **Xenon Mass File:** This file contains the estimated available xenon mass as a function of time according to the nominal IPS thrust profile.
  - d) **Hydrazine Mass File:** This file contains the estimated hydrazine mass as a function of time based on the predicted ACS activities.
  - e) **Control File:** This file contains the target conditions, gravitation and solar pressure models, spacecraft dry mass, and spacecraft power model. The spacecraft power model is derived directly from the SEPTOP outputs. At a given time, the total spacecraft mass is defined as the sum of spacecraft dry mass, xenon mass, and hydrazine mass.
  - f) **Spacecraft Propulsion System File:** This file contains a table of the IPS thrust and xenon mass flow rate as a function of power. NAVTRAJ uses this file directly. However, SEPTOP uses the weighted least-squares fits to the table using 4th order polynomials which produced good approximation for a given power range.
- 3) A MATLAB utility called THRUSTAR was used to select a set of sufficiently bright stars for use either as the thrust directions for IPS thrusting or Earth-pointed directions for telecommunications. The processes of selecting stars was very complicated and required an iterative procedure to obtain a trajectory (usually not optimal) to arrive at the desired B-plane target conditions. In general, the selection of a “thruststar” is based on the star brightness and color, its angular distance from the Sun, and its location near the optimal thrust directions as derived from SEPTOP. Occasionally, if a “thruststar” could not be obtained near the optimal thrust direction, then the thrust direction was vectorized to select several thrust stars to achieve the desired thrust direction. When a desired trajectory was obtained, the locations (right ascensions and declinations) of stars were then implemented in the maneuver file to replace the IPS profile generated by NAVTRAJ. Due to the Sun cone angle constraints, a single thrust star was usually locked on by the camera to maintain the spacecraft’s attitude for a period of a couple of weeks. Therefore, each individual IPS thrust segment may require several thrust stars. As a result, this trajectory is not

an optimal one. However, it is the best available trajectory which is designed to arrive at the comet Borrelly.

- 4) The initial selection of a set of thrust stars was based on the optimal thrust directions derived from SEPTOP. The locations of the thrust stars were then implemented in the input maneuver file. A MATLAB utility program IPSTARGET was used to target the trajectory to arrive at the desired B-plane. IPSTARGET first calls a subset of the NAVTRAJ "C" program to compute nominal B-plane coordinates at encounter and then perturbs the trajectory to compute the B-plane partial derivatives with respect to duration of thrusting on each star in order to retarget the trajectory at the desired B-plane by adjusting that duration. Similar to NAVTRAJ, IPSTARGET has a capability to make changes in the direction and duration of each thrust segment as defined in the maneuver file. Also note that IPSTARGET uses the exact same input files as those of NAVTRAJ. The strategy used for IPSTARGET was to change the direction and duration for the first few thrust stars (usually one or two) at the beginning of the thrust profile or the thrust segments of interest and hold the rest of thrust stars as fixed IPS TCMs. After the desired thrust directions were computed, THRUSTAR was used again to select new thrust stars as described in the step (3). This process was iterated until the best available trajectory was obtained. If a large deviation from the nominal trajectory occurred as a result of a new OD solution, then the processes in steps (3) and (4) were used to redesign a new trajectory instead of going back to SEPTOP. Note that most of the DS1 Borrelly trajectory designs used the THRUSTAR/IPSTARGET interfaces instead of the SEPTOP/NAVTRAJ interfaces.

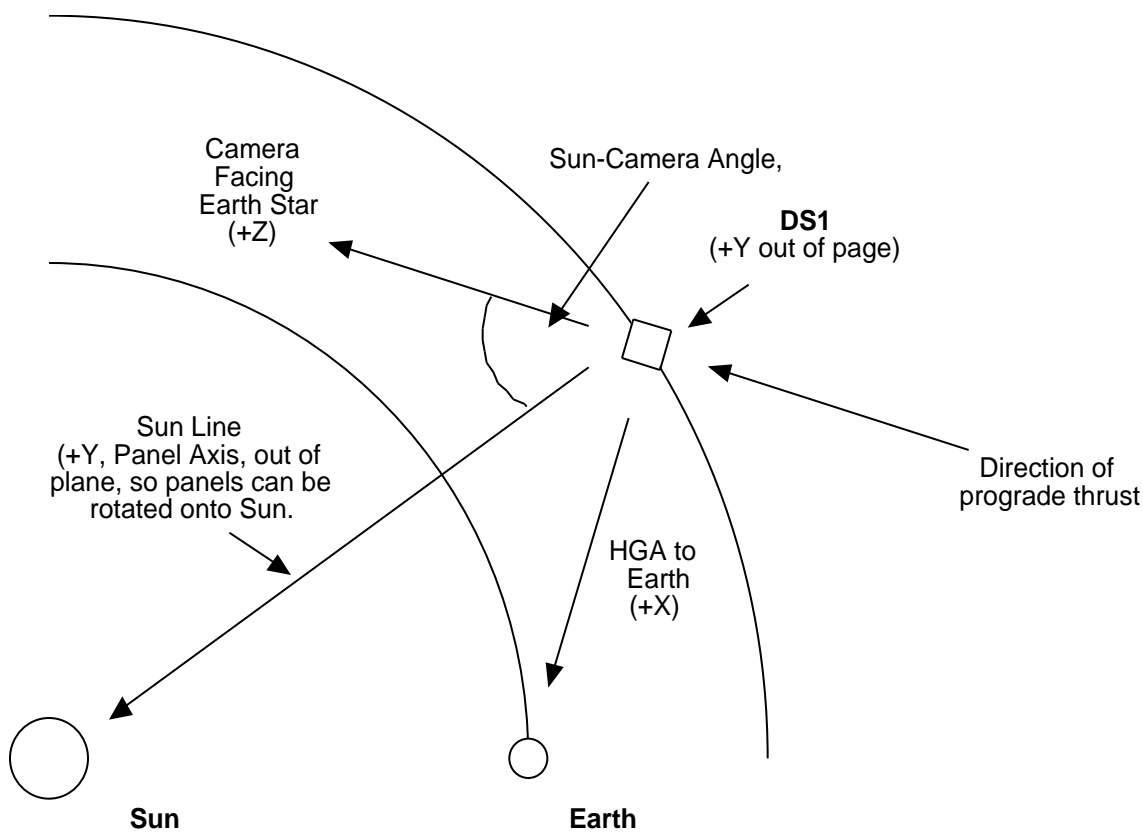
### 3.4 Implementation in Operations

The thrust profile design methods described above took into account the need for IPS thrusting during Earth passes. These thrustings were constrained to attitudes that allowed the fixed-boresight HGA to point at the Earth during times when a DSN antenna was scheduled to track DS1 and downlink data at a high rate. During these Earth passes (typically eight hours long), the IPS throttle level was set to a low level (approximately 22.4 mN), which still allowed sufficient control authority for ACS to control attitude using TVC. Although this low throttle level minimized the impact on the DS1 trajectory, it still needed to be modeled in order to provide a targeted burn profile.

Following the creation of a nominal thrust profile, the flight sequencing team would integrate the orientations and thrust levels into the backbone sequence. Typically, a backbone sequence is a single, absolutely-timed sequence that runs on the spacecraft for several weeks. This sequence controls a majority of the routine spacecraft operations, including (but by no means limited to) telecommunications configuration, operational spacecraft reorientation, star tracking software management, and IPS thrust-level management.

Telecommunications configuration is based on the scheduled DSN antenna and the expected off-Earth angle of the HGA boresight. Typically, if the HGA boresight was pointed within 1 or 2 degrees of Earth, it allowed use of the highest supportable data rate at that distance. Pointing 3 or 4 degrees from Earth meant that the supportable data rate would be one or two rates lower than the maximum rate.

Figure 3-1 shows a heliocentric view of the Sun, Earth, and spacecraft configuration while in Earth point. During Earth communications, solar panel pointing requirements constrained the spacecraft to be either prograde or retrograde thrusting within the plane of the ecliptic. This resulted in a limited set of stars that could be tracked. If the nearest tracking star was suboptimally located and required substantial off-pointing of the HGA (as described above), it would result in a decreased supportable data rate.



**Fig. 3-1. Earth-point geometry (viewed from heliocentric north).**

The sequencing of an attitude transition was fairly straightforward. First, the tracking software would be commanded to stop tracking. Next, the IPS would be turned off, and the spacecraft would be commanded to turn to a new attitude. Since the biases and drifts of the IMU were well calibrated by the previous time spent locked to a reference star, these turns were executed using the IMU as the means of attitude propagation. Without exception, these turns completed with the spacecraft in the desired inertial attitude. Once at this new attitude, the tracking software would be told the magnitude and inertial location (right ascension and declination) of the star that it would expect to see when it started tracking. It would also be told what exposure duration to use for camera commanding. It would then be told to start commanding the camera, at which point it would start receiving star signals from the camera by way of the AutoNav image processor. Shortly afterwards, the IPS was commanded to repressurize the plena and start thrusting. Finally, the ACS would be commanded to start controlling the spacecraft attitude using TVC. The timing of all of these commands was set to allow for a nominal time to pass before progressing to the next command. In other words, the

turn was expected to be complete before the star tracking software was enabled, the IPS wasn't turned on until the plena had repressurized, and the ACS wasn't put into TVC mode until the IPS reached a steady state.

### 3.4.1 Deterministic Thrusting

For 10 months following the replacement of the SRU, the spacecraft was expected to be thrusting deterministically towards an encounter with Borrelly. Table 3-1 shows a two-month segment of the burn profile followed by DS1 during this period of deterministic thrusting. Typically, odd-numbered arcs in this table represent week-long thrust arcs, while even-numbered arcs represent short (6- to 10-hour) burns, during which time the spacecraft was aligned to point the HGA at the Earth.

**Table 3-1. A thrust profile used during deterministic thrusting.**

Arc	Start Time	Duration (days)	Right Ascension	Declination	Thrust Level (mN)
1	01-DEC-2000 02:00:00.0000	4.503	17.148	-10.182	0.022410
2	05-DEC-2000 15:10:00.0000	0.399	339.300	-8.940	0.022410
3	06-DEC-2000 01:10:00.0000	6.524	17.148	-10.182	0.022410
4	12-DEC-2000 15:20:00.0000	0.221	344.410	-6.890	0.022410
5	12-DEC-2000 21:10:00.0000	9.697	12.171	7.585	0.022410
6	22-DEC-2000 16:15:00.0000	0.268	349.500	-4.770	0.022410
7	22-DEC-2000 23:05:00.0000	10.620	12.171	7.585	0.022410
8	02-JAN-2001 15:15:00.0000	0.371	359.640	-0.410	0.022410
9	03-JAN-2001 00:35:00.0000	7.532	22.871	15.346	0.030525
10	10-JAN-2001 15:10:00.0000	0.210	4.720	1.800	0.030525
11	10-JAN-2001 20:55:00.0000	5.696	22.871	15.346	0.031126
12	16-JAN-2001 15:00:00.0000	0.395	9.650	4.400	0.031126
13	17-JAN-2001 01:50:00.0000	7.470	38.969	5.593	0.031126
14	24-JAN-2001 14:55:00.0000	0.213	14.810	6.580	0.031126
15	24-JAN-2001 20:45:00.0000	5.696	38.969	5.593	0.031126
16	30-JAN-2001 14:50:00.0000	0.444	20.040	8.710	0.031126
17	31-JAN-2001 03:00:00.0000	6.597	33.250	8.847	0.031126
18	06-FEB-2001 18:55:00.0000	0.204	25.330	10.770	0.031126
19	07-FEB-2001 00:30:00.0000	9.488	33.250	8.847	0.031727

### 3.4.2 North-South Thrusting

In order to achieve a nearly ballistic trajectory during the last four months of the cruise phase, a burn profile alternating approximately ecliptic north thrust attitudes with approximately south attitudes was used. Adjustments to the nominal north-south burn directions were made to account for thrusting during telecommunications sessions and for deviations from exactly north-south attitudes. Table 3-2 shows a list of north-south attitudes in the months before the encounter. Arcs 1, 3, 5, and 8 in this table show examples of alternating, self-canceling north-south arcs, while arcs 2, 4, and 9 show stars used to allow alignment of the HGA on Earth. It was important to keep the trajectory of a nearly ballistic form to guard against the possibility of loss of IPS thrust.



**Table 3-2. North–south thrust attitudes used to maintain a converged “ballistic” trajectory.**

Arc	Start Time	Duration (Days)	Right Ascension	Declination	Thrust Level (mN)
1	24-MAY-2001 00:45:00.0000	5.442	276.496	65.563	0.022410
2	29-MAY-2001 12:00:00.0000	0.510	121.941	21.582	0.022410
3	30-MAY-2001 02:00:00.0000	6.468	92.812	–65.589	0.022410
4	05-JUN-2001 14:00:00.0000	0.419	128.177	20.441	0.022410
5	06-JUN-2001 01:30:00.0000	13.639	276.496	65.563	0.024213
6	19-JUN-2001 18:30:00.0000	6.634	138.808	14.942	0.024213
7	26-JUN-2001 10:30:00.0000	7.566	328.325	–13.552	0.022410
8	04-JUL-2001 01:00:00.0000	6.364	92.812	–65.589	0.029924
9	10-JUL-2001 10:30:00.0000	0.346	151.976	9.997	0.022410
10	10-JUL-2001 20:00:00.0000	4.975	263.748	61.875	0.022410
11	15-JUL-2001 20:00:00.0000	8.893	273.475	64.397	0.025114
12	24-JUL-2001 18:30:00.0000	0.401	166.254	7.336	0.022410
13	25-JUL-2001 5:30:00.0000	5.514	92.812	–65.589	0.029924
14	30-JUL-2001 8:30:00.0000	0.365	166.254	7.336	0.022410
15	31-JUL-2001 04:30:00.0000	14.137	92.812	–65.589	0.025415
16	14-AUG-2001 09:30:00.0000	0.528	177.674	1.765	0.022410
17	15-AUG-2001 00:00:00.0000	6.529	276.496	65.5630	0.022410

### 3.4.3 Cone Angle Constraints

Due to stray light problems with the camera [3], spacecraft orientations during which the camera boresight was within 45 degrees of the Sun were not allowed, as a flight rule. Theoretically, this constraint prevented certain thrust attitudes from being realized, requiring “vectorization” of a desired thrust arc. In practice, this was not needed during cruise, nor during the Ion Propulsion System and Reaction Control System TCMs. However, the possibility of having to do so was realized and plans to vectorize TCMs at encounter were developed.

## Section 4

### Navigation of a Low-Thrust Mission with Radio OD

In order to effectively determine DS1's orbit using only radio data, the original methods laid out for navigating the spacecraft under low thrust had to be modified to match the changed conditions under which the spacecraft was to be operated. Due to a reduction in the frequency of high-rate and low-rate tracking passes, there was a decreased availability of range and Doppler data during the extended mission. Also, the original methods for modeling the spacecraft IPS and RCS activity had to be modified to account for data that might no longer be correct. As it turned out, this reduction in tracking data and model fidelity required a change to the OD filtering strategy.

#### 4.1 Data Types

As with all missions, radiometric data (Doppler and range) for DS1 was acquired during tracking passes using the various antennas at the DSN complexes at Goldstone, Canberra, and Madrid. Delta differential one-way range (DDOR) data acquisition was not planned during the cruise phase of the extended mission. Its use in the approach phase of the mission is discussed in Section 9.

##### 4.1.1 Earth Passes

During a high-rate DSN pass, the ground communicated with the spacecraft through the spacecraft HGA, with the spacecraft at an Earth-pointing attitude. There were only three Earth passes scheduled per month, on average. This was necessitated primarily by a need to limit attitude transitions. DSN passes typically require a transition before the beginning of a track in order to align the HGA with the Earth and a transition back to a nominal burn attitude following the track. Turning the spacecraft was expensive from a hydrazine standpoint and was considered potentially risky from an attitude knowledge standpoint, given the nature of the tracking software. On the plus side, because of their stronger signal levels, DSN passes were typically the only time at which ranging measurements to the spacecraft could be taken. Whenever possible, these passes were scheduled so that they spanned the handover between the Goldstone and Canberra complexes. This allowed for near-simultaneous north and south ranging data to be taken. As was discovered during OD validation in the primary mission, estimating geocentric declination in low-thrust trajectories benefits from the strong geometry provided by north and south range data.

As mentioned in Section 3.4, Earth stars were not always optimal with respect to HGA pointing. This often constrained bandwidth and sacrificed ranging data in favor of downloading the weekly backlog of telemetry. If bandwidth was limited during a north track, operational efforts were made to obtain range data at the end of the track to provide a stronger geometric correlation with the south range data. As was the case in the earlier phases of the mission, long-

range modulation times were needed to prevent out-of-modulo range measurements in the event of missed thrust, or mistrusting. This reduced the amount of range data received.

#### 4.1.2 Midweek Passes

During a low-rate communication session, also called a “mid-week pass,” the ground communicates with the spacecraft through one of the low-gain antennas (LGAs) while the spacecraft was at a burn attitude. Due to the use of smaller DSN antennas and the fairly weak LGA, telemetry was rarely available, even at low bit-rates. During these passes, only a limited amount of Doppler (2–3 hours) was received, but it provided very strong visibility into the burn activity. This was very valuable for the OD and stood in stark contrast to the poor thrusting visibility during the Earth passes. With the absence of telemetry during these tracks, the Doppler signal provided rapid assessment of the health of the spacecraft and its trajectory. With one exception, ranging data was not available during mid-week tracks. Many different ranging configurations were attempted in an effort to attain range measurements, but these met with mixed results.

## 4.2 Modeling

The primary spacecraft non-gravitational perturbation models needed to navigate DS1 were Solar Radiation Pressure (SRP), IPS thrusting, and RCS activity caused by turns and deadbanding. The SRP model was unchanged from that used in the primary mission. The original methods for modeling the spacecraft IPS thrust arcs and RCS activity were slightly modified from those used in the primary mission [5].

### 4.2.1 RCS Activity

The modeling of the RCS activity induced by deadbanding and turns was somewhat simplified in the extended mission. Since no optical navigation (opnav) activities were performed, the non-gravitational force (nongrav) file was no longer needed to estimate their effects on the trajectory. It is also worth noting that the occasional loss of attitude lock made the inertial measurements of the RCS activity untrustworthy. Therefore, a modeling scheme that relied on them was not used. However, the nongrav file was still of some use, as it assisted in the placement of impulsive burns that could be used to model the effects of turns by the spacecraft. It was especially useful with respect to modeling the impulse placed on the spacecraft when DS1 was mosaicking. Mosaicking is a set autonomous spacecraft turns that DS1 underwent whenever it was trying to acquire (or reacquire) its lock star. Since the mosaic turns are so small, the overall effect of the spacecraft is somewhat akin to a mini-RCS TCM.<sup>3</sup> Also, since many mosaic events occurred outside of a DSN track, a simplified, loose model had to be used to estimate their impact. While the turn pulses themselves were small enough, they did have a large aggregate effect that needed to be taken into account.

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<sup>3</sup> Since the z-facing RCS thrusters are used to control attitude, the effect of a mosaic activity (nine attitude changes of approximately half a degree) could amount to several cm/s of delta-V in the +z direction of the spacecraft.

## 4.2.2 IPS Activity

For IPS activity, a simplified thrusting model made use of the thrust history recorded in telemetry, and assumed that attitude was tied directly to the thruster direction. Due to thrusting uncertainties and approximate location of the star in the camera, the true burn attitude was uncertain, so a simplified “use star direction to define as burn attitude” strategy was used.

## 4.3 Filtering

Initially, the nominal pre-SRU-loss radio navigation OD strategy was used for post-SRU-loss OD. For the first few months using the new models, the solutions were very well behaved. However, subsequently, the OD began to degrade exhibiting slow convergence, large stochastic ranges and multiple-sigma corrections to thrust magnitude and pointing (several mN and several degrees, respectively). It was determined that the filter was trying to extract too much information from the very limited amount of data available, so a simplified filter strategy was used with fewer variables and tighter sigmas (1 mN and 1 degree). Highly constrained stochastic accelerations were used to help smooth the resulting trajectory and to account for some of the uncertainty induced by the TVC activity and thrust measurements.

## 4.4 OD Impact During Loss and Recovery of Attitude

Following loss of inertial lock (LOL), inertial reference would need to be quickly restored. If inertial reference was not quickly restored, the errors of the IMU would slowly cause the spacecraft attitude to drift. Since DS1 was thrusting most of the time, this drift would cause an ever-increasing divergence away from the expected trajectory. Following attitude recovery operations, determining the new position and velocity of the spacecraft was of prime importance, since the future thrust profile would have to be quickly corrected to keep the spacecraft on course for Borrelly. Once characterized, any velocity errors could be accounted for by modifying future burn arcs. If a long time passed before velocity errors could be quantified, an uncomfortably large position error could build up. For example, if the spacecraft was miss-pointed by 20 degrees for five days at full thrust, a velocity error of 8 meters per second would accrue in a direction normal to the thrust vector. After this time, the position error would be 2000 km and would continue to increase by 5000 km per week. As the spacecraft neared Borrelly, quick evaluation of the LOL effects on DS1’s orbit became important as the planned trajectory was to be modified in a timely fashion. See Table 4-1 for list of attitude loss events.

**Table 4-1 Attitude losses, time ranges, and causes.**

Start	End	Cause
06/12/00	06/12/00	Initial attitude recovery.
07/16/00T20:00	07/19/00T01:00	Solar interference with star observations.
03/13/01T16:00	03/16/01T2000	Planned reboot following flight software upload.
07/15/01T20:00	07/24/01T1800	Unknown, possible lock acquisition failure.
08/16/01T12:00	08/24/01T1100	Solar interference with star observations.
09/13/01T17:00	09/14/01T0100	Inability to acquire initial lock.

#### 4.4.1 A Case Study: LOL 5 in Late August 2001

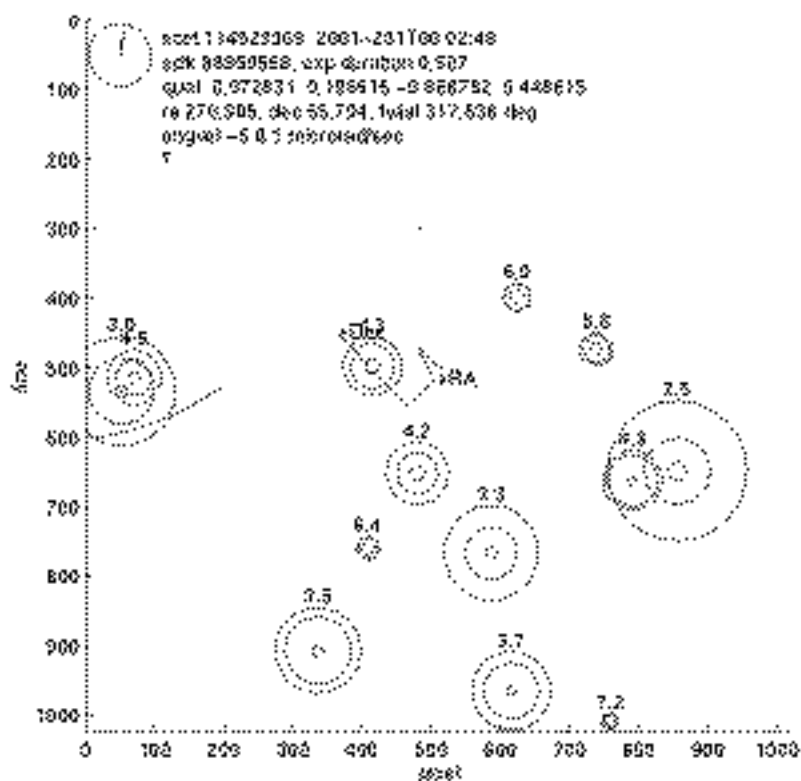
Less than two months from the encounter with Borrelly, solar interference (radiation-induced effects on the camera electronics) caused the camera to be flooded with false signals. These false signals caused the ACS software to drift away from its planned reference star as it chased the myriad false stars.

The resulting drift lasted two days, after which the spacecraft fortuitously found a new star to track. Recovery efforts began 5 days after the initial LOL, at the start of what should have been a routine Earth tracking pass.

At this point in the spacecraft's orbit, aligning the HGA with the Earth while the spacecraft thrusting was in a prograde direction required pointing the camera little more than fifty degrees from the Sun (see Figure 3-1). At this attitude, scattered light problems that troubled the camera since the start of the mission [3] were dominating the 3.5-second exposure images that were taken. This made the onboard centroid processing almost unusable, since the high number of false signals would overwhelm any star signatures. (At this phase in the mission, centroid data packets were used to provide picture previews of images taken during recovery activities.) This would increase the possibility of downlinking an image that contained an identifiable star field by only selecting images that were known to contain stars of sufficiently bright magnitude to make identification likely.

The low Sun cone angle of the camera made attitude recovery operations very difficult, so it was decided to rotate the spacecraft a full 180 degrees from a prograde to a retrograde attitude. This somewhat risky maneuver would have two benefits. By flipping, the two and a half days of roughly prograde thrust could be mostly canceled out by retrograde thrust. Also, the Sun would no longer be able to interfere with camera images, allowing for deeper exposures to be taken. In order to take full advantage of this, the centroid sequences were enhanced to take 10-second exposures and to also run in a continuous loop. Following the flip, one large HGA corrective turn was performed just before the end of the current tracking pass. At the start of the first of two more borrowed passes, the new sequences were uploaded and activated. The new centroid packets contained vivid signatures of dim stars (down to 8th magnitude) and provided enough indication of relative motion that a reasonable estimate of IMU drift could be derived. The deep images selected for downlinking proved immediately useful. Less than five hours into the pass, the spacecraft attitude was determined and corrected. The subsequent attempt to turn to and lock onto a suitable reference star was quite successful. Using the second of the two

borrowed passes, the flight team was able to prepare the spacecraft for its first observation of comet Borrelly, which was scheduled to occur less than twelve hours later.



**Fig. 4-1. A recreated picture of one of the centroid data packets taken before recovery activities in LOL 5. It shows the 2.5 magnitude reference star that was locked onto. A 4.2 magnitude “companion” star is also visible, along with 11 false star signals caused by solar activity.**

Modeling all of this activity sufficiently to allow for a useful OD solution was difficult. Of key importance was identification of the star that the spacecraft had locked onto for the two and half days before the sequenced turn to Earthpoint. Fortunately, the navigation team successfully identified this star based on knowledge of its hypothetical location and the presence of a small “companion” star which showed up periodically in the centroid data (See Figure 4-1). A simple model, consisting of five days of thrust on the now known star, three days of approximate prograde thrusting, and two days of retrograde thrusting was developed. This enabled an immediate assessment of the effects on the trajectory. During the recovery period, the attitudes of several burn arcs and turn-delta-Vs were estimated. Hypothetical spacecraft rates were approximated by looking at the observed change in locations of stars that appeared in centroid data. Figure 4-2 shows images from which a drift rate of .3 degrees per hour can be determined. These images show three stars in the camera FOV, with magnitudes of approximately 4.5, 7, and 9. Other signals are stray light artifacts or cosmic rays.

After a couple of days, a reasonable OD estimate was produced, and this enabled fine-tuning of the pointing and thrusting for the upcoming north burn arc. The preliminary OD showed that after the end of the recovery efforts, the spacecraft had a position and velocity discrepancy of 5600 km and 20.5 m/s from the nominal trajectory. After three weeks of post-recovery data, an overlap of this fit with an OD comprised entirely of post-recovery modeling showed an agreement of 300 km and 0.7 m/s. The resulting B-plane shift was 18,787 km in B•R, 27,568 km in B•T and 1,158 seconds in time of flyby (TOF).

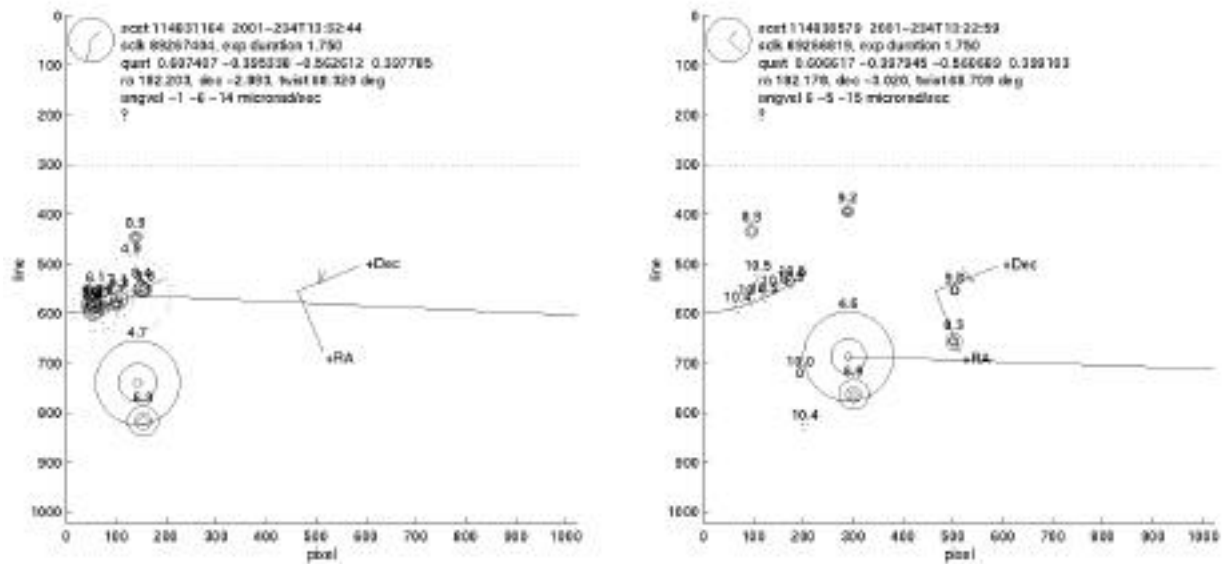


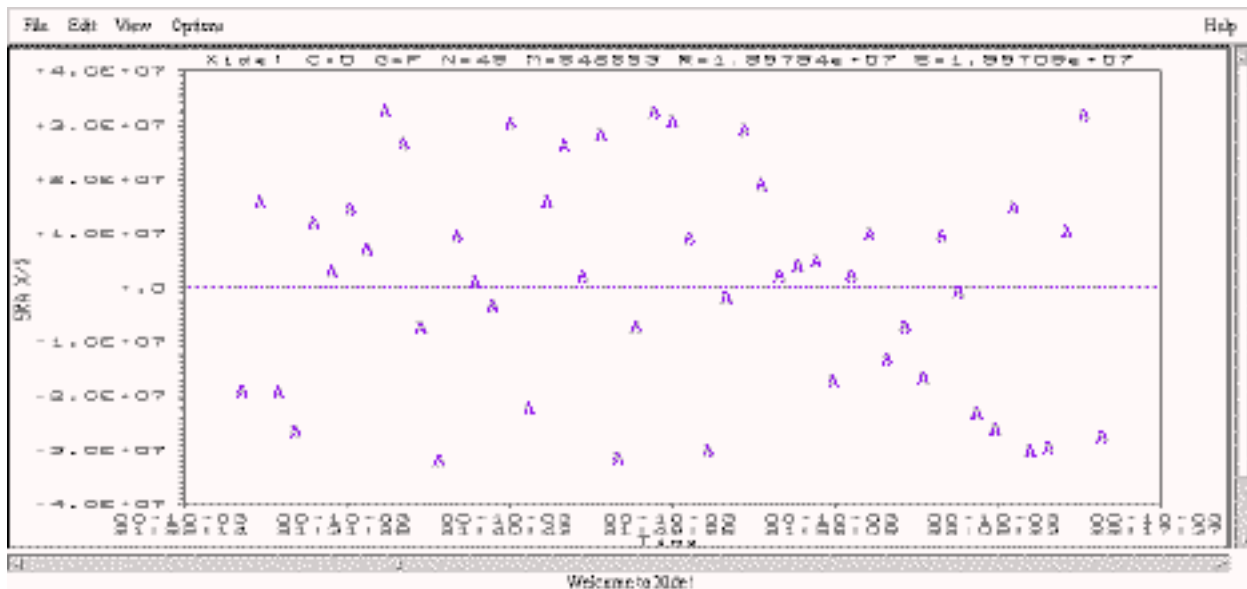
Fig. 4-2. Centroid images taken 10 minutes apart.

## Section 5

### Experiments with One-Way Non-Coherent Ranging

On October 3, 2000, an experiment to acquire one-way non-coherent ranging was attempted with DS1 using deep space station (DSS) 14. This experiment was to provide a proof of concept that one-way ranging was a feasible method of acquiring navigational data. This was done in support of the (then upcoming) Contour mission which made use of a transceiver instead of a transponder [7] for Earth communications. The key operational difference between these two devices is that a transceiver does not have a coherent two-way downlink mode. In order to ensure that non-coherent one-way ranging would be a viable navigational aid, DS1 was asked to perform ranging tests with the DS1 transponder operated in non-coherent, one-way mode.

Due to reasons that bear further exploration, this experiment met with limited success. None of the range data acquired was useful for navigation or analysis. Figure 5-1 shows a plot of the residuals for all of the range data received during this test. The data includes non-coherent one-way range data followed by two-way coherent range data. The noise ranges of these data show a range of  $\pm 30000000$  range units. This is seven orders of magnitude larger than expected.



**Fig. 5-1. Range residuals during one-way range test, in range units (RU).**

It is believed that there were a few problems that may have contributed to the poor test results:

- The relatively short cycle times of each data point;
- The uncertainty in the knowledge of the spacecraft trajectory needed to create the proper ramped uplink;
- The uncertainty in knowing the sky reference frequency (TFREQ);

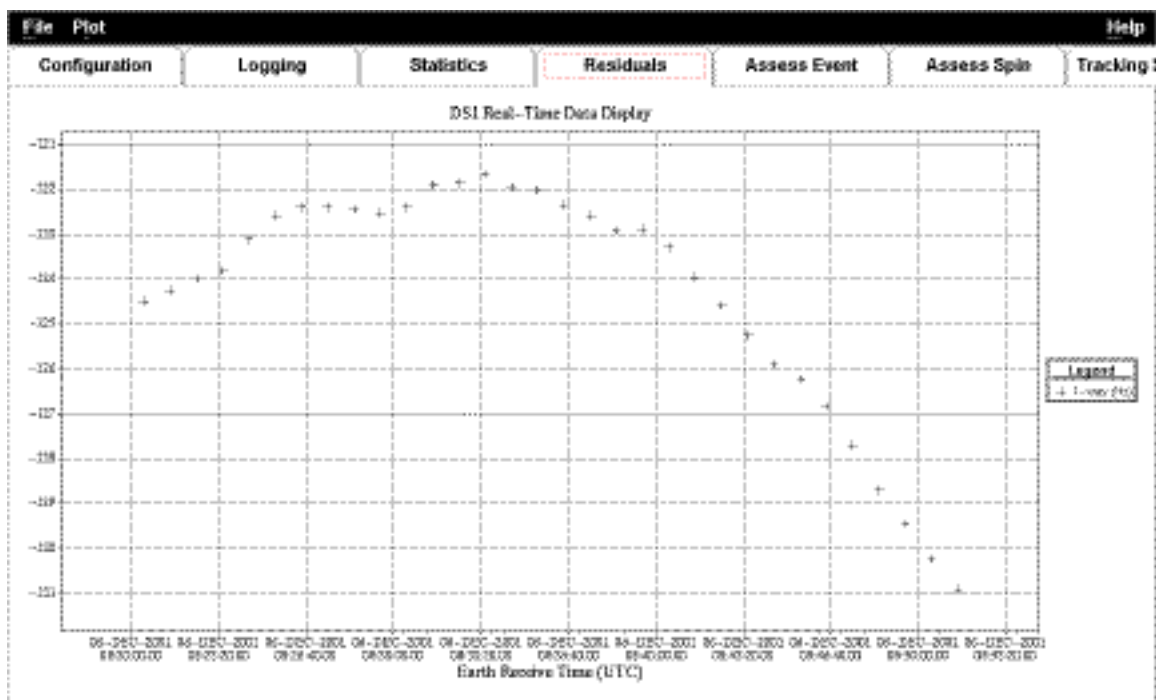


- A possibly incorrect round-trip light time (RTLTL) setting of the SRA hardware at the groundstation.

At the geocentric distance to the spacecraft (2+ AU), the cycle time of 639 seconds between ranging points was sufficient to produce usable ranging data for routine DS1 navigation. Had DS1 had a larger HGA, shorter cycle times might have been supportable. For the purposes of this experiment, there was an interest in producing as many data points as possible, and a shorter cycle time of 64 seconds was chosen. The resulting decrease in data quality in favor of data quantity might have been much greater than expected.

While operating in non-coherent mode, the auxiliary oscillator on board DS1 showed initial transient trends of 7Hz/min. These settled down into an acceptable trend of 1 Hz/min after the auxiliary oscillator reached a level of thermal stability. This trend is seen dramatically in the Doppler residuals (see Figure 5-2). It was assumed for the purposes of this test that a trend of 1 Hz/min would be acceptable.

Uncertainties in the DS1 trajectory could have contributed to this trend enough to violate this assumption. Also, there are biases in the auxiliary oscillator signal and the Doppler residuals that were expected to require real-time calculation of new ramped uplink tables in order to have the uplinked signal arrive at the spacecraft at an unchanging frequency. Creating these uplinked tables properly required *a priori* knowledge of the DS1 trajectory.



**Fig. 5-2. Typical trend in one-way Doppler residuals.**

At the time of this experiment, the navigation filtering strategy was undergoing needed changes to improve spacecraft OD in the face of a reduced radiometric data schedule. This

resulted in predicted orbit errors that might have contributed to the failure to acquire valid one-way range points. In hindsight, shortening the duration of the test in order to devote time to updating the OD solution and predicts based on recent data might have been desirable.

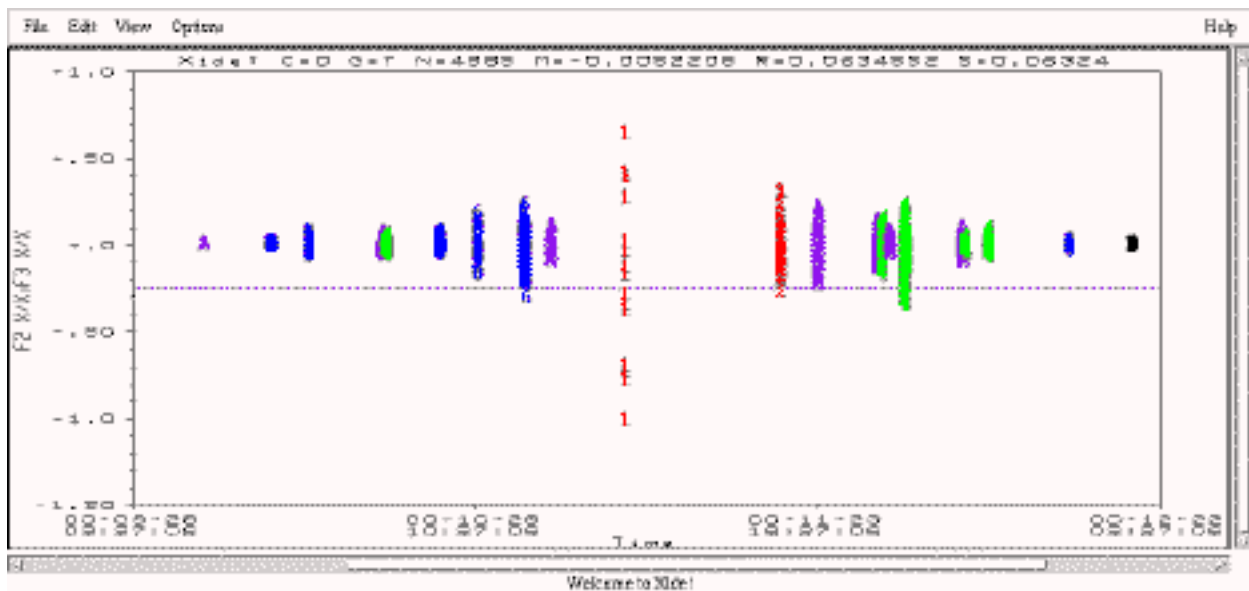
On two occasions (DR#G06768 and DR#G06683), the station SRA was configured with an incorrect RTLTL. On both of these occasions, the range data received showed a signature similar to that received on October 3. The resulting scattered range measurements on these occasions were also effectively unusable for navigation. It is possible that the RTLTL configuration for the one-way test was based on an invalid mission reference trajectory. For missions with a dynamic trajectory, such as DS1, preliminary reference trajectories can often be several light-seconds in error from “as flown” trajectories. On the day in question, the RTLTL was 2327 seconds, and the prepass configuration for this test specified a RTLTL of 2324 seconds.

Further information on the one-way coherent ranging technique can be found in [6] and [7].

## Section 6

### Solar Conjunction

On November 12, 2000, DS1 reached superior solar conjunction. Around this time, communication with the spacecraft was subjected to large amounts of solar interference. The spacecraft spent nearly an entire month (October 30 until November 27) locked to the same star, with the engine running at low throttle. The star was oriented such that the spacecraft HGA would be Earth-pointed during most of the month. This left the spacecraft in an operationally stable configuration. Limited communication with the Earth would be possible (and expected), but no critical commanding would be required during conjunction.



**Fig. 6-1. Doppler residuals during solar conjunction.**

The effects of DS1's passage through solar conjunction on the Doppler data can be seen in Figure 6-1. The noise signatures visible during tracking passes just before and after conjunction show a great deal of interference. Nominally, Doppler tracking data can be weighted to .1 mm/sec (5.6 mHz) for navigation purposes. During conjunction, the large noise signatures in the Doppler data required de-weighting of certain passes by one, two, or possibly more orders of magnitude. Table 6-1 shows the Doppler weighting used for tracking passes before and after conjunction. Tracking data received on November 14 was not used.

**Table 6-1. Doppler weights used during conjunction, by pass.**

Date	Weight (mm/s)
10/12	1
10/18	1
10/23	1
10/26	3
10/30	5
11/01	2
11/07	15
11/14	80 (not used)
11/20	5
11/23	1
11/28	2
12/01	1

Although the quality of the Doppler data was highly degraded, modeling of the nongravitational forces during conjunction was simplified. During this time, the spacecraft was left in a single, fixed attitude for just over four weeks. No attitude changes or RCS deadband activity needed to be modeled, allowing for clean fits and good estimation of range biases.

## Section 7

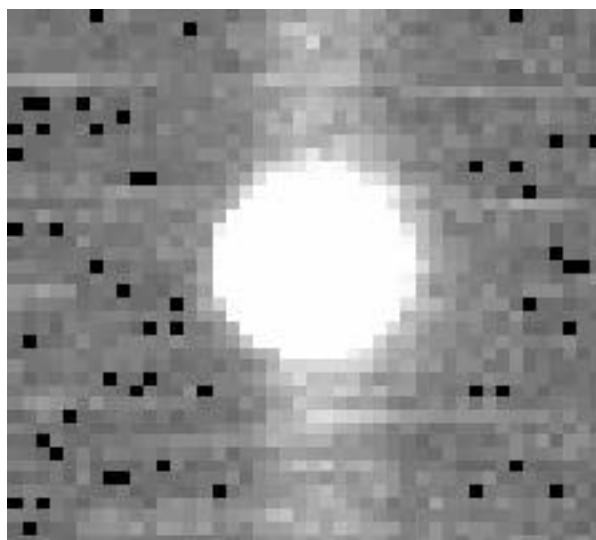
### Encounter Rehearsals

In the months leading up to the comet encounter, the flight team prepared and executed activities for the spacecraft that would test the expected performance of the spacecraft during the encounter. On May 1, 2001, an extended observation of the planet Jupiter was performed. On May 8, 2001, the first of two full encounter rehearsals was performed. On June 28, 2001, the second of two rehearsals was performed. These activities were designed to test the effectiveness of the newly uploaded comet tracking software, the performance of the attitude control system, and performance of the command and data handling system.

#### 7.1 Jupiter Watch

The intent of the Jupiter Watch activity was to test the estimation performance of the new nucleus tracking software and to exercise the interfaces between that software and the ACS. With the loss of the SRU and the requirement to keep the camera boresight pointed at the tracking target, the IMU was the primary instrument used by the ACS to determine spacecraft attitude. Since the camera was not used to provide inertial pointing information to the ACS, the IMU drifts were not estimated, and the determined attitude of the spacecraft drifted accordingly. This drift was reflected in the attitude quaternion applied to every tracking image used by the tracking software. It was the task of the nucleus tracking software to estimate the biases and drifts within the IMU, as well as the relative comet-spacecraft state. Once estimated, this information was used by the tracking system to provide pointing updates to the ACS during the encounter.

The planet Jupiter was chosen as a target because it is large enough to be observed by the camera as an extended body and bright enough to resolve consistently at short exposure durations. At a distance of 5.49 AU, the disk of Jupiter produced a 13-pixel image in the camera (each pixel of the  $1024 \times 1024$ -pixel CCD is approximately 13 microradians across). Figure 7-1 shows an edited portion of one of the images taken during this activity. The artifacts visible above and below the image of Jupiter are the result of signal bleeding, which is a common characteristic of CCDs when bright objects are being imaged. A suitable minimum brightness cutoff was chosen for this activity to allow the tracking software to ignore the signal bleed and background noise when processing the pictures for Jupiter's signal.



**Fig. 7-1. The planet Jupiter.**

This test was quite successful. The tracking software performed as expected, processing dozens of Jupiter images over the course of two hours. The pointing updates provided to the ACS allowed it to keep the camera boresight pointed at Jupiter for the duration of the activity. Over the two hours of this test, the uncalibrated drifts in the IMU allowed the estimate of the spacecraft attitude to drift by more than half a camera field of view. Had the tracking software not been estimating the IMU errors, it would have failed to provide the required absolute pointing corrections to keep Jupiter within the camera field of view for the entire activity. The performance of the tracking software during the encounter itself is covered in Sections 8 and 9.

## 7.2 Rehearsal 1 and Rehearsal 2

In early May, 2001 and late June, 2001, the spacecraft was prepared for two comet encounter rehearsals. This preparation included the upload of several sequences that would command the spacecraft instruments during the encounter, as well as the uploading of parameter and ephemeris files needed by the nucleus tracking software.

These rehearsals caused the spacecraft to go through the same turn rates that it would undergo during the encounter itself. Because of this, a body such as Jupiter would not provide a suitable target, due to the slowly changing relative pointing vector. In order to spoof the spacecraft into thinking that it was about to fly past a target, an ephemeris was constructed to represent a simulated target, and the tracking software was configured to track it.

An onboard image simulator was responsible for intercepting any images that were sent to the tracking software from the camera. Once intercepted, the simulation software determined where the hypothetical target should appear in the image based on the target ephemeris, the estimated spacecraft location and the estimated attitude of the spacecraft at the time the image was shuttered. The simulation software then rendered a suitably shaded and sized image of the target into the picture of (mostly) empty space. The doctored image was then passed to the nucleus tracking software.

Since the simulation software based the placement of the spoof target image on the estimated spacecraft attitude, the tracking software was not able to estimate drifts in the IMU. In order to more accurately assess the behavior of the IMU during the tracking turn, the ephemeris of the false target was given careful consideration. It was constructed in such a way that the timing and direction of several camera exposures would result in the capture of several bright stars. Post-rehearsal evaluation of the location of these stars in the image frames allowed the flight team to assess the performance of the IMU during the rehearsal.

These rehearsals occurred on May 8 and June 28. The results were mixed, but enlightening. The spacecraft ACS was able to command the spacecraft through the nominal pointing profile without any problems, and the command and data handling system was able to keep up with the flow of science data requested from the instruments. A separate problem in each of the rehearsals resulted in the loss of some of the stellar location data that was to have been used to analyze the drifting in the IMU during rehearsal. However, enough insight into the performance of the spacecraft had been gained to have confidence in achieving a successful encounter. The lessons learned from the rehearsals (and the Jupiter observation) were folded into the encounter plan, and further testing continued on the flight system testbeds.

## Section 8

# Approach Phase and Encounter Using Optical and Radio OD

### 8.1 Comet Nucleus Tracking during the Encounter

A closed-loop onboard tracking system was used to find and maintain lock on the comet nucleus during the flyby. This software was an extension of the original AutoNav software, with an important enhancement: it was able to provide pointing updates to the ACS that took IMU drift and bias into account. Since the MICAS camera would be used primarily to observe the comet during the encounter, maintaining attitude using a reference star would not be possible.

### 8.2 Comet Ephemeris Development

Due to the relatively large non-gravitational forces that act on comets (e.g., outgassing), predicting an accurate ephemeris for even short periods into the future can be quite difficult. Thus, even though ground telescopic observations going back several decades were available for Borrelly, an intensive campaign was undertaken to improve its ephemeris for the DS1 flyby [1]. After its recovery in the sky during its current apparition in May 2001, over 200 observations were obtained from telescopes located at Loomberah, Australia, the United States Naval Observatory in Flagstaff, Arizona, and the Table Mountain and Palomar observatories located in southern California. The observations were processed by members of the Solar System Dynamics (SSD) group at the Jet Propulsion Laboratory (JPL) and delivered to the DS1 navigation team. In all, three deliveries were made; the first using just the ground observations and the last two using a combination of spacecraft and ground observations. More details of the comet ephemeris development can be found in [1].

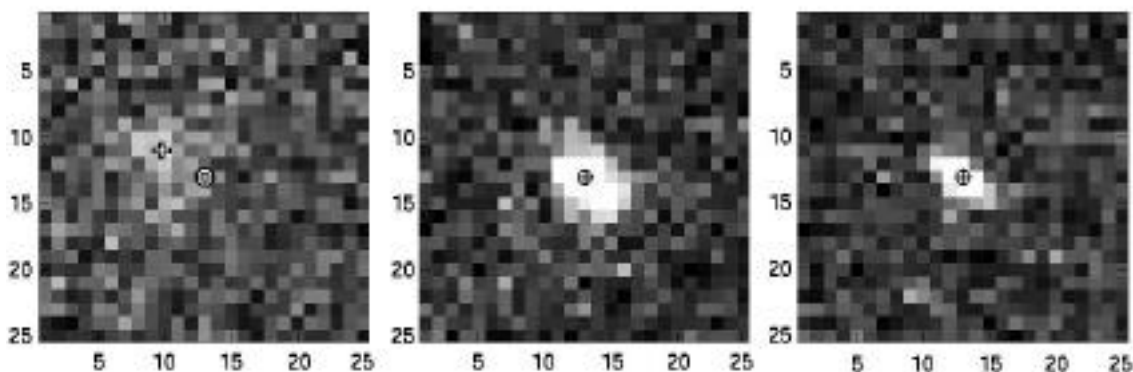
### 8.3 File Upload Strategy

As during the primary mission, the comet tracking software made use of files for configuration and setting initial conditions. Files containing the latest estimates of the spacecraft and comet trajectories were uploaded to the spacecraft before the encounter. This allowed the ephemeris server to provide the ACS with an appropriate *a priori* pointing direction. The parameters that characterized the expected response of the camera to the nucleus, coma, and stray light (background noise) were also uploaded. This was to allow the tracking software a high likelihood of successfully identifying the nucleus in the images.



## 8.4 Radio OD Delivery Accuracy

Even though the OD after LOL 5 looked stable, there was still some concern about errors that had been unaccounted for. The upcoming observations of Borrelly were expected to resolve some of this uncertainty. The observations taken in early September showed a 1000–1500 km difference between the predicted and observed locations of the comet. Figure 8-1 shows the results from the observation of Borrelly on September 10. The latest radiometric OD solution was used for the initial prediction of the comet within the camera FOV. At that distance to the comet (22 million km), each 13-microradian pixel spanned 282 km. This placed the predicted location of the comet nucleus within 1100 km of where the images showed it to be. Over the first four observations, the position error between observed and predicted comet location was consistent, implying that no significant velocity errors remained from modeling LOL 5 (See Section 4.4.1). The position error was the source of much consternation and was not fully understood until later in the approach phase.



**Fig. 8-1.** Left frame: Observed (+) vs. predicted (o) location of Borrelly using co-added images. Middle and Right frames: Registration performed on two stars seen in co-added images.

## 8.5 Borrelly Approach Using Radio OD

Determining the heliocentric orbital out-of-plane errors as well as establishing the validity of the OD was accomplished with two DDOR observations taken on September 14 and September 15, one week before the encounter. The resulting OD showed close agreement (20–30km) to the previous OD. As well as validating the out-of-plane results of the radiometric OD, they also provided a higher certainty on the predicted time of flight (TOF):  $\pm 3.3$  seconds with DDOR, and  $\pm 14$  seconds without. After one more week of radiometric data, these TOF uncertainties changed to  $\pm 3.5$  seconds with DDOR, and  $\pm 4.7$  seconds without.

## 8.6 Ephemeris Rectification

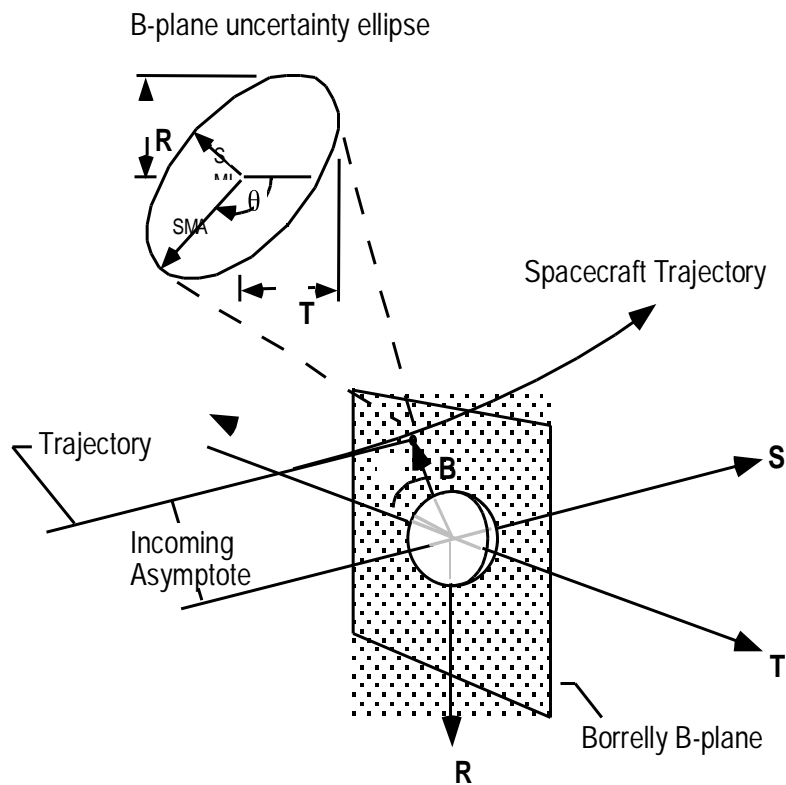
Once the DDOR campaign showed that the radio OD was not a major source of error, efforts shifted to determining why the ground-based comet ephemeris did not agree with the spacecraft observations. Eventually, it was found that if the center-of-brightness computed from the ground observations used the brightest pixel, rather than the standard Gaussian fit to the

brightness profile, the results agreed considerably better with the spacecraft. Furthermore, observations taken at Palomar Observatory and processed using the bright pixel method, were now in fairly good agreement with the spacecraft. Nevertheless, discrepancies still existed which were eventually attributed to the lack of an accurate model for outgassing used in the comet orbit estimates. Recently it was found that an acceleration model which had jets at the assumed comet pole, and varying with the angle between the pole and the Sun, resulted in the ability to fit longer data arcs from the ground when combined with spacecraft data [1].

## Section 9

### The Borrelly Encounter and the TCM Strategy

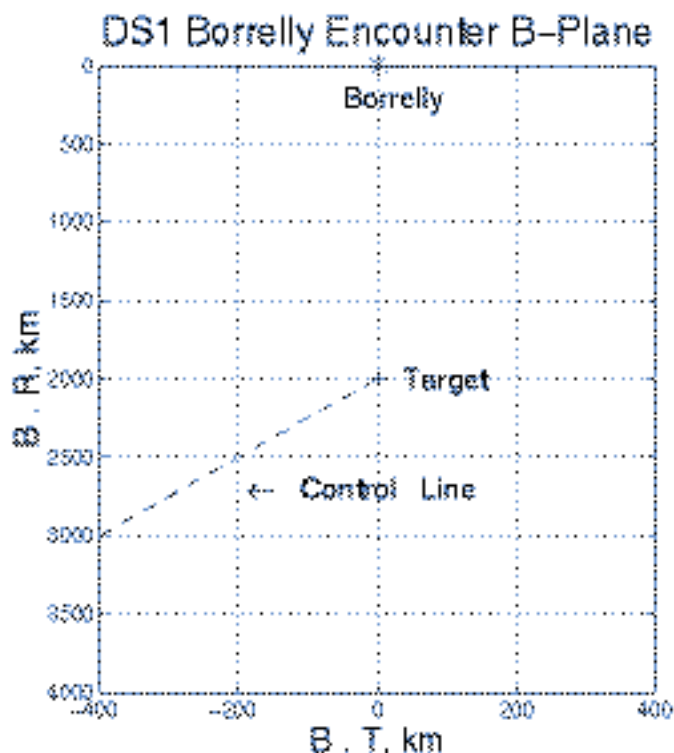
Targeting computations and analysis was performed in the B-plane coordinate system. The B-plane is a plane passing through the center of the target body and perpendicular to the incoming asymptote,  $S$ , of the hyperbolic flyby trajectory. Coordinates in the plane are given in the  $R$  and  $T$  directions, with  $T$  being parallel to the Earth mean ecliptic plane of 2000. The angle  $\theta$  determines the rotation of the semi-major axis of the error ellipse in the B-plane relative to the  $T$ -axis and is measured positive right-handed about the  $S$ -axis (see Figure 9-1).



**Fig. 9-1. Targeting in the B-plane coordinate system.**

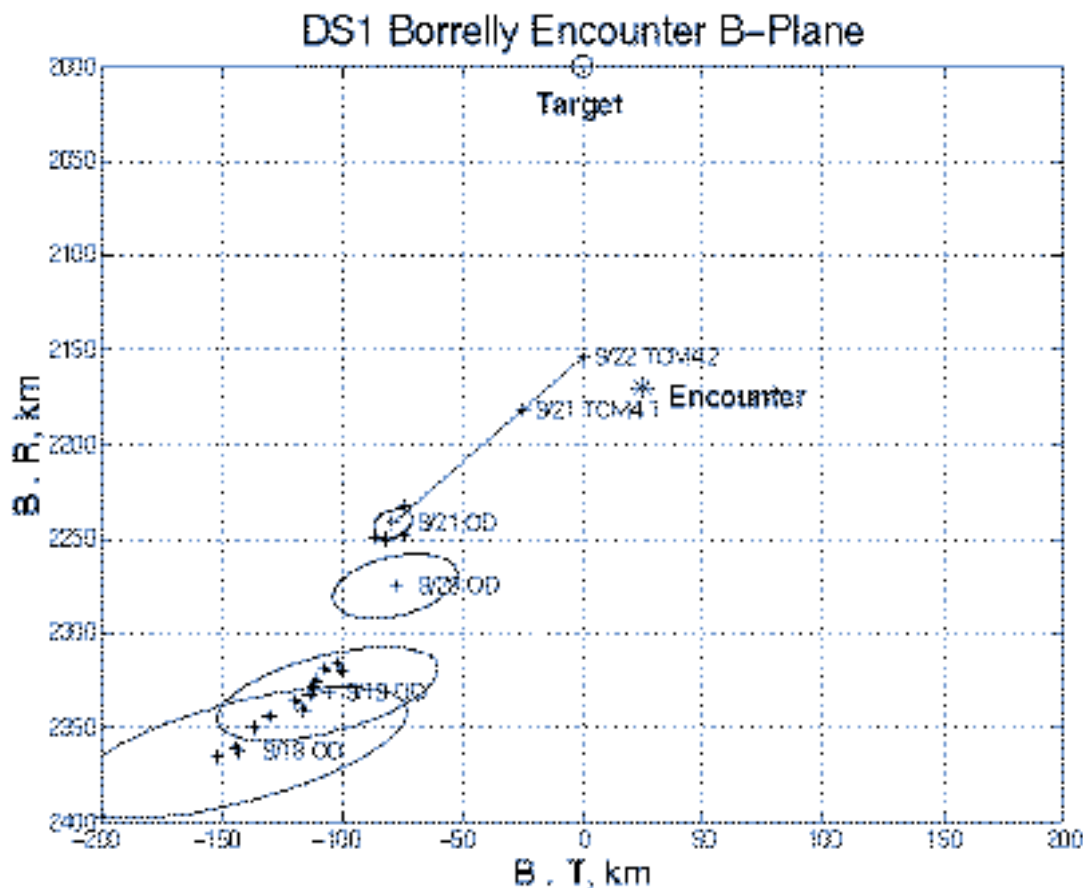
The first of several IPS TCMs occurred on September 11, 2001. This TCM, 1.1, refined the B-plane targeting to place it near an area of the B-plane known affectionately to the navigation team as the “Magic Control Line.” This line intersected the  $B \cdot T$  axis at approximately 2000 km  $B \cdot R$ . Its slope was defined as the direction in which the B-plane position was controllable by thrusting while the HGA was aligned with the Earth (see Figure 9-2). Once there, the final targeting of the Borrelly flyby point was controlled solely by Earth-pointed IPS TCMs. This meant that no RCS TCMs were needed for the encounter and little or no offpointing from Earth was required. Although there was a reserve of 2 kg of hydrazine for RCS TCMs, not having to use this provided much additional mission assurance, given the severe fuel shortage,

especially when the large uncertainty in the remaining hydrazine was considered. Control of the B-plane was exercised in such a way as to arrive at Borrelly with  $B \cdot T$  as close to 0 as possible. This was desired, as the encounter sequence was designed assuming that Sun-relative geometry. Control of the final values of  $B \cdot R$  and TOF were not as critical because the AutoNav system would adjust TOF, although some knowledge of TOF was still necessary for mission success. It was also desirable to approach 0  $B \cdot T$  from the negative side, as the approach from this side could be controlled by throttling up during Earth telecommunications passes. There was limited ability to throttle down (the IPS has a minimum operable power) to achieve a relative backward motion along the control line, and completely shutting down the engine would have consumed vital hydrazine. If for any reason the spacecraft-comet B-plane shifted into positive  $B \cdot T$ , corrective TCMs would have required that the spacecraft be reoriented into a prograde attitude. This would have been a difficult, fuel-consumptive, and dangerous maneuver.



**Fig. 9-2. DS1 at Borrelly encounter B-plane.**

The second TCM, 1.3, was scheduled for September 14. Due to the response required by LOL 6, the TCM was cancelled. Originally, the spacecraft was intended to be placed on the magic control line by this TCM, but this was effectively accomplished by reorienting the spacecraft onto a previous Earth star. Following this cancelled TCM, the IPS was shutdown as previously scheduled. This allowed the spacecraft B-plane position to shift day by day, due to unmodeled RCS activity. TCM 2.1 occurred on September 17, at Earth-point orientation. This corrected the targeting to take into account the new updates to the Borrelly ephemeris.



**Fig. 9-3. Final DS1 at Borrelly encounter B-plane.**

Following TCM 2.1, the spacecraft B-plane target moved closer to the desired aim point (Figure 9-3 shows the final encounter B-plane). The shifts in the B-plane location from September 18 to September 21 are based on daily OD solutions using optical data and multiple radiometric strategies (long arc, short arc, with and without DDOR, etc.). These shifts were caused by non-gravitational impulses from RCS activity. These shifts were expected to occur, and are evident as the B-plane intersection moves “up and to the right, along the magic control line” (see Figure 9-3). On September 21 and 22, the last two TCMs, 4.1 and 4.2, were designed and executed to line up DS1 for its encounter with Borrelly. Both TCMs occurred at Earth-point orientation. Following their successful execution, it was the task of the nucleus-tracking component of AutoNav to autonomously command the pointing of the spacecraft and the execution of the close-in science sequences. A detailed description of the performance of this software can be found in [1].

On September 22, at 22:30:36 ET, DS1 flew past Borrelly at 2171.2 km in B·T, 31.2 km in B·R. This was six seconds earlier than predicted. The highest resolution image of the nucleus was obtained approximately two minutes before closest approach and can be seen in Figure 9-4.



**Fig. 9-4. The comet Borrelly.**

## Section 10

### Commencement of Hyper-Extended Mission

Following the successful encounter with comet Borrelly and the subsequent conclusion of the extended mission, Deep Space 1 began its hyper-extended mission in late September, 2001. The main thrust of this mission was to study the performance and behavior of the Ion Propulsion System, which had far exceeded all expectations by operating in deep space for over a year and a half. Enough xenon remained onboard to put the IPS through a few months of rigorous testing, at which time it was put into new voltage and mass-flow configurations. Some of these modes were potentially hazardous to the health of the engine and would not have been performed during any previous mission phases.

#### 10.1 Navigation Analysis of IPS Acceptance Test

During this phase of the mission, the primary role of navigation was to provide routine OD support for tracking prediction purposes and to assist in any unplanned spacecraft anomalies. The navigation team also served in analyzing the engine performance during certain tests. One of these tests was a rerun of the IPS Acceptance Tests (IATs) that were originally run during the DS1 primary mission. Of primary interest was determining if there was any degradation in thruster performance over the three-year span since the original IAT. The results of the later IAT are shown in Figure 10-1 and Table 10-1. An in-depth analysis of these results and how they compare with the expected results is covered in [10].

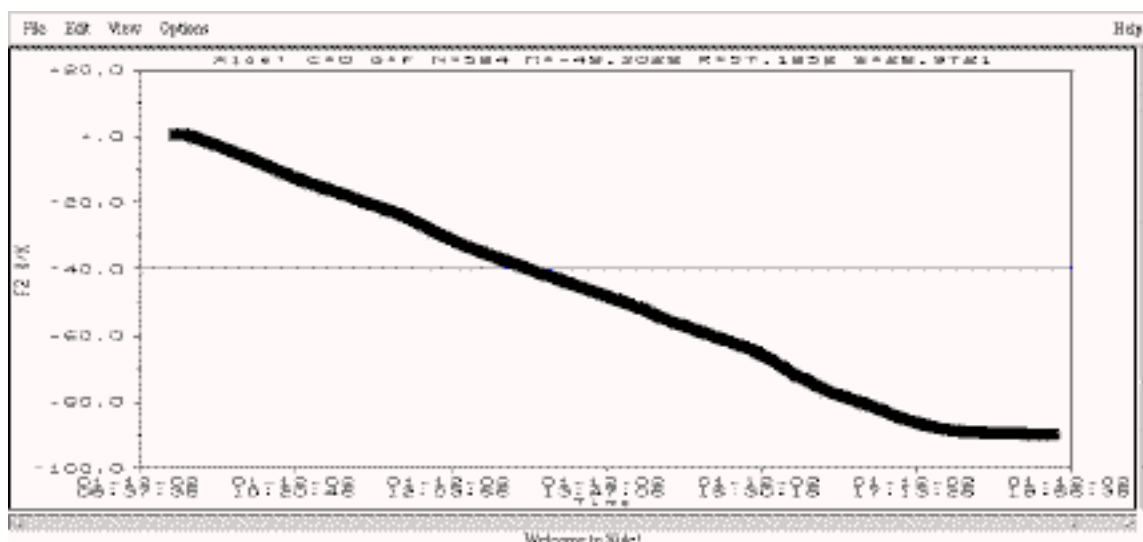


Fig. 10-1. Doppler signature observed during IAT3.

**Table 10-1. Doppler-based thrust measurements.**

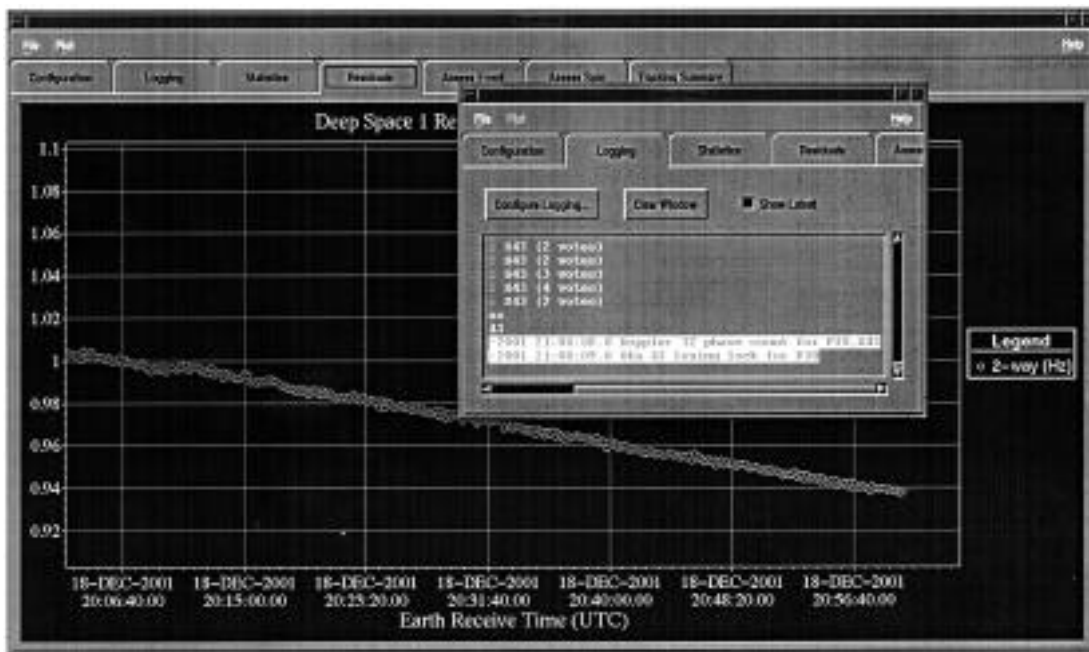
Time Range	Expected (mN)	Measured (mN)
09:02:00 - 09:15:00	20.6	20.57
09:16:00 - 09:45:00	24.5	23.90
09:46:00 - 10:15:00	27.4	26.66
10:15:01 - 10:30:00	20.6	20.53
10:31:00 - 10:40:00	19.0	19.24
10:41:00 - 10:50:00	22.1	21.72
10:51:00 - 11:00:00	22.8	22.26
11:01:00 - 11:10:00	23.5	20.44
11:11:00 - 11:15:00	20.6	20.61
11:20:00 - 11:45:00	32.0	30.17
11:46:00 - 11:55:00	29.7	28.84
11:55:15 - 12:05:00	27.3	26.61
12:05:15 - 12:15:00	24.5	23.99
12:15:10 - 12:25:00	22.5	22.14
12:37:00 - 12:46:00	24.5	24.12
12:55:00 - 14:05:00	21.0	21.22
14:06:00 - 14:15:00	32.4	32.10
14:30:00 - 15:15:00	22.0	21.23
15:16:00 - 15:30:00	30.4	31.15
15:31:00 - 15:45:00	40.6	40.76
15:46:00 - 15:50:00	22.0	21.29
15:51:00 - 16:05:00	32.0	32.43



# Section 11

## Decommissioning

On December 19, 2001, the DS1 spacecraft was decommissioned. The last received real-time navigation data can be seen in Figure 11-1, which shows Doppler residuals received during a tracking pass with DSS 43. The spacecraft was left in a Sun safhold configuration. The fault-response sequences were modified in order to prevent the spacecraft from turning on any transmitters. The IPS remained shut down, having been turned off on December 18 following the completion of the IPS end-of-life tests.



**Fig. 11-1. The last real-time Doppler data received from DS1, by way of DSS 43, on December 18, 2001.**

In early March of 2002, the flight team was reconvened in an attempt to restore communications to the spacecraft during opposition. At that time, the safhold configuration allowed the fixed boresight of the HGA to point to within a few degrees of the Earth, which would have allowed further Ka band experiments to be conducted. Unfortunately, attempts to contact the spacecraft proved unsuccessful. Based on the expected rate of hydrazine consumption and the limited amount remaining (< 1 kg), it was expected that the spacecraft had already run out of hydrazine and was no longer in a powered state. Several strategies were tried, including nominal pointing offsets to account for navigation uncertainty and using multiple antennas in order to make the search more efficient.

New navigation solutions were also computed using different nongrav strategies to account for additional uncertainties in the last known state of the spacecraft. Efforts to regain contact ceased on March 14.

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## Abbreviations and Acronyms

ACS	attitude control subsystem
AU	astronomical unit
AutoNav	Autonomous Optical Navigation System
CCD	charged couple detector
DDOR	Delta differential one-way range
DESCANSO	Deep Space Communications and Navigation Systems Center of Excellence
DS1	Deep Space 1
DSN	Deep Space Network
DSS	Deep Space Station
FOV	field of view
FSW	flight software
HGA	high gain antenna
IAT	IPS Acceptance Test
IMU	inertial measurement unit
IPS	Ion Propulsion System
JPL	Jet Propulsion Laboratory
Ka-band	deep-space frequency band: 31.9 to 32.1 GHz (down)
LGA	low-gain antenna
LOL	loss of inertial lock
MICAS	Miniature Integrated Camera Spectrometer
MPL	Mars Polar Lander
NASA	National Aeronautics and Space Administration
Nav	navigation
Nav Task	navigation software element
NAVTRAJ	Navigation Trajectory (computer program)
NMP	New Millennium Program
nongrav	non-gravitational
OD	orbit determination
opnav	optical navigation
PEPE	Plasma Experiment for Planetary Exploration
PSET	parameter of settings
RCS	Reaction Control System
RTL	round-trip light time
SCARLET	Solar Concentrator Array with Refractive Linear Element Technology
SDST	small deep-space transponder
SEP	solar electric propulsion
SEPPROF	SEP Thrust Profile
SEPTOP	SEP Trajectory Optimization Program
SRA	sequential ranging assembly
SRP	Solar Radiation Pressure

SRU	Stellar Reference Unit
SSA	Sun Sensor Assembly
SSD	Solar Systems Dynamics
TCM	trajectory correction maneuver
TFREQ	sky reference frequency
TOF	time of flight
TVC	thrust vector control