

RADIOMETRIC ORBIT DETERMINATION ACTIVITIES IN SUPPORT OF NAVIGATING DEEP SPACE 1 TO COMET BORRELLY

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Four months after its encounter with the asteroid Braille, Deep Space 1 lost the use of its only star tracker. After several months of planning, development and testing, new software was uploaded that allowed the spacecraft to restore celestial inertial reference and begin thrusting towards an encounter with comet Borrelly. The new mission plan would have to work within the constraints of the new software as well as minimize use of the dwindling supply of hydrazine, the fuel needed to maintain the spacecraft attitude.

In the spring and summer of 2001, as it approached comet Borrelly, the spacecraft lost its celestial reference several times. As the mission plan required nearly continuous low-thrust, the resulting attitude drifts caused the spacecraft to push itself off course. Difficulty in restoring attitude information had a further impact on the spacecraft trajectory. Modeling these attitude drifts before and during attitude recovery periods was necessary in order to determine the new orbit. This allowed for the timely redevelopment of upcoming mission burns that put the spacecraft back on course for its encounter with comet Borrelly.

INTRODUCTION

On October 24, 1998, Deep Space 1 (DS1) was 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 of great promise. By launching with so many untested features, DS1 embraced high-risk but held the potential of high rewards. Almost none of these technologies had a redundant back-up system on board the spacecraft. The failure of any of these technologies

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could have meant an early end to the main mission, and severely constrained successful validation of the others. In spite of the risks, in-flight validation of all twelve technologies was completed successfully, thus exceeding the success criteria.

Using these new technologies, DS1 followed an ambitious science plan that was to recover data from the flybys of three inner solar system bodies. This highly dynamic trajectory would not have been possible without the low-thrust provided by the Ion Propulsion System (IPS). The close flyby of asteroid Braille occurred near the end of the main mission. The DS1 extended mission started in September 1999, and planned for flybys of the comets Wilson-Harrington and Borrelly. These flybys were expected to acquire a wealth of infrared (IR) and visible light images using the Miniature Integrated Camera Spectrometer (MICAS). For the comet flybys, the Plasma Experiment for Planetary Exploration (PEPE) would recover charged particle data on the cometary coma and the IPS Diagnostic Sensors (IDS) had been reprogrammed to acquire field data.

Unfortunately, no high quality images were obtained at the Braille flyby. Subsequently, while en route to Wilson-Harrington, the Stellar Reference Unit (SRU) failed. The SRU is an 8x8 degrees Field of View (FOV) optical star camera, capable of providing absolute inertial reference to the Attitude Control Subsystem (ACS). Without it, the ACS became unable to determine and control DS1's inertial attitude. Implementing a solution would have required months of work. This did not allow enough time to resume thrusting towards Wilson-Harrington, so a direct trajectory to Borrelly was implemented. As no usable visible data was obtained from either Braille or Wilson-Harrington, comet Borrelly was the final opportunity for the DS1 team to prove the science gathering capabilities of DS1's technologies. It was also the last chance for the DS1 team to test the target tracking capabilities of the on board navigation system [1]. If they were successful, DS1 would produce the first detailed images ever taken of a comet nucleus.

With the spacecraft in "safe-hold" and the on board Autonomous Navigation (Autonav¹) system compromised due to the broken SRU, the mission team was challenged to first develop a new attitude control capability and then to develop a new navigation plan for reaching Comet Borrelly. The ACS solution is described fully in other papers [2][3]. The impacts of the ACS solution on the mission and the new radiometric navigation strategies will be detailed in this paper.

THE NEW ATTITUDE CONTROL SYSTEM

Given that DS1 launched with several unproven instruments and subsystems, it is surprising that the only complete hardware failure occurred in a flight-tested and -proven instrument. In November 1999, less than four months after the Braille flyby, the SRU failed completely. Without it, the ACS lost the only instrument capable of providing it with inertial attitude quaternions every 0.25 seconds [3]. This left the ACS with an Inertial Measurement Unit (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. When uncalibrated, the IMU might have an inertial drift of up to 3 degrees per hour [4]. The SSA could be used to keep an accurate fix on the direction to the Sun, but not the spacecraft

¹ Autonav was one of the original twelve new technologies. Its efficacy in navigating DS1 is documented in [7].

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. Fortunately, there was a solution.

Along with the IMU and the SSA, the MICAS camera and the Autonav system would play key roles in the replacement of the SRU and the successful completion of the extended mission. 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 ACS. Due to the small usable FOV of the MICAS camera (effectively .5x.75 degrees, as compared to the 8x8 degree FOV of the SRU [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 (+Z and +X, respectively, see figure 1.) 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.

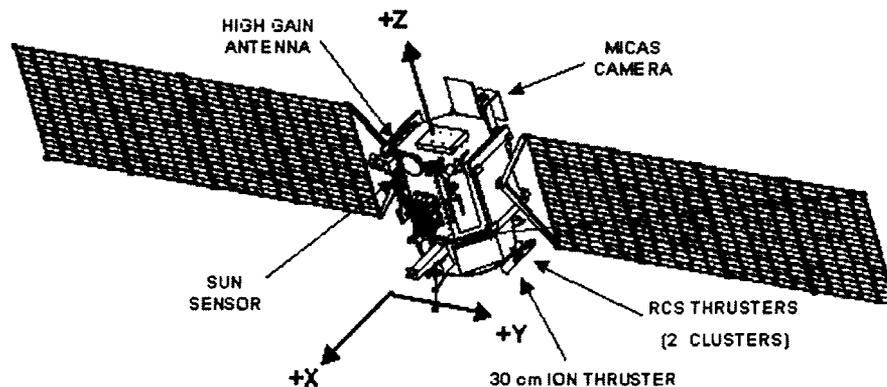


Figure 1: Deep Space 1 Configuration. The camera faces +Z, the ion thruster faces -Z, the SSA and HGA face +X and each RCS cluster contains 2 -Z, 1 +X and 1 -X thruster

With this solution in mind, a new attitude estimator and a new image-processing manager were written. This system, called “MURKY,” was built to be highly adjustable, anticipating the need to tune it in flight. Software development was complete by the end of April 2000. In June 2000, the new software was uploaded to the spacecraft and the flight team prepared for new flight operations.

Crucial first steps were to determine where 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. Also, it was unclear how robust the star tracking capability would be while a star was

being tracked. 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. The details of these issues and their impact on the navigation of DS1 will be described later.

The key to effective use of the new software was the careful pre-selection 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 “thrusters²”, 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 CCD detectors 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 sub optimal locations occasionally had to be used for inertial attitude reference, with a corresponding loss in thrusting effectiveness for thrusters 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.

NO HYDRAZINE, NO PROBLEM

About the time MURKY became operational, the DS1 team was faced with a new challenge: the realization that the remaining Hydrazine onboard was going to be barely sufficient to complete the mission. Hydrazine is the propellant used by the Reaction Control System (RCS). The RCS is used by the ACS to maintain the spacecraft attitude using Z-axis and X-axis facing thrusters [3][5] (see figure 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 [3]. The remaining mass of hydrazine (approximately 9³ kg of the original launch load of 32 kg [6]) 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 (TVC) whenever the IPS is running at a high enough throttle level⁴. 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. Typical low-thrust trajectories are designed to minimize fuel consumption [7] and will contain ballistic “coast” arcs that require the low thrust propulsion system to be inactive. With DS1, on the other hand, the initial trajectory

² This was shorthand for “thrust star”. They were also known as “burn stars”.

³ 2 kg was to be held in reserve for RCS TCMs at the Encounter, leaving only 7 for cruise operations.

⁴ At this throttle level, the IPS was putting out approximately 20 mN (milliNewtons) of thrust.

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 4.5 month ballistic arc before the encounter with Borrelly; this was done to maximize the probability of a Borrelly flyby, even in the event of an IPS failure. In order to achieve this ballistic arc, a burn profile alternating ecliptic north thrust attitudes with south attitudes was used, and adjustments were made to account for thrusting during telecommunications sessions.

THE NAV PLAN

Frequent orbit determination (OD) solutions would be needed to compensate for modeling errors in the predicted trajectory and to assess the performance of the IPS burns. Ideally, a solution that included tracking data up to the end of every Earth tracking pass (weekly or biweekly) would be delivered to the trajectory analyst. Because of the untimely demise of the SRU, the Autonav system could no longer be used to acquire asteroid and star image data for use in Optical OD [8]. Therefore, conventional radiometric OD would have to be performed by a member of the ground Navigation team. In order to determine DS1's orbit using only radio data, the original methods for modeling the spacecraft under low thrust [5] would need to be modified to deal with the changed conditions of the mission and an expected reduction in tracking data.

Nav Models

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

For IPS thrust arcs, thrust computations queried from telemetry were fed directly into the thrust model. Since the camera boresight was aligned closely along the same spacecraft axis as the IPS thrusting vector, the inertial location of the star could be used as the thrust direction. In order to account for slightly off-axis pointing of the camera, gimbaling of the thrust vector for TVC and the changing location of the star in the camera FOV, small corrections to the pointing would be estimated⁵.

The RCS activity induced by deadbanding and spacecraft turns would have a different character in the extended mission, as compared to before the SRU failure. With the near continuous use of TVC, there would not be as much unbalanced RCS deadband activity to model [5][9]. Also, without an active Autonav system on board, there would no longer be turn-intensive optical navigation activities to model [8][9]. Previously, modeling these activities made significant use of an onboard record of spacecraft RCS (and IPS) activity, known as the non-grav history file⁶ [10]. For the extended mission, the non-grav file was used in the placement and rough sizing 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 while trying to acquire (or re-acquire) its reference star. Many mosaic events occurred in the "blind," (i.e. not during telecommunications sessions) and were consequently hard

⁵ In theory, being able to get an *a priori* estimate for any star offset from the +Z axis would have been useful for predicts

⁶ Originally used by the Autonav system to assist in onboard orbit determination [8].

to estimate, using radiometric data. While the turn pulses themselves were small, they did have a large aggregate effect if several images were shuttered before MURKY locked onto the star. Unfortunately, when the spacecraft had lost attitude lock for lengthy periods, the inertial directions of the RCS activity recorded on the non-grav file were untrustworthy. This would need to be taken into account by using simple, loosely constrained impulsive models for turn activities, and those models estimated in the OD filter.

Nav Data

The data types used for DS1's radio navigation were conventional ranging and 2-way Doppler measurements⁷. The relatively infrequent tracking passes to acquire these data occurred once or twice every week, in the form of a so-called Earth pass or a midweek pass. During an Earth pass, the ground communicated with the spacecraft through the spacecraft HGA while the spacecraft was at an Earth-pointing attitude. During a midweek pass, the spacecraft would be at a nominal trajectory burn attitude, and communication was only possible through one of the Low Gain Antennae (LGA).

In an effort to conserve hydrazine, Earth passes were scheduled two or three times per month. Normally, it was only during Earth passes that ranging data was acquired. In an effort to make the most of this ranging opportunity, these passes were scheduled so they spanned the handover between the Goldstone and Canberra complexes of the Deep Space Network (DSN). This allowed for acquisition of near-simultaneous North and South ranging data⁸, which provides powerful cross-range angular position determination [5]. As mentioned previously, Earth stars were not always optimally positioned to allow the fixed HGA to point directly at the Earth. This could restrict the available bandwidth, and resulted in the sacrifice of 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 in the earlier phases of the mission, long modulation times were needed to prevent out-of-modulo range measurements from being taken in the event of missed thrust, or of mistrusting [5].

During a midweek pass, 2-3 hours of doppler data would be acquired. Although only a limited amount of doppler was received, it provided strong visibility into the health-status of the IPS. Due to the use of smaller DSN antennae and the fairly weak LGA, telemetry was rarely available, even at low bit rates. With the absence of telemetry during these tracks, the doppler signature was one of two means of providing an indication of the health of the spacecraft and its trajectory. With one exception, ranging data was not available during mid-week tracks. Many experiments with low-modulated ranging to attain data were attempted, but these produced mixed results.

Nav Filter Changes

The reduction in tracking data and model fidelity resulting from the SRU failure required a change to the filtering strategy. Initially, the nominal pre-SRU Radio Nav filter configuration (Ref. 4, Table 1) was used for post-SRU OD. For the first few months using the new models, the solutions were very well behaved. After that, the OD began to exhibit strange behaviors,

⁷ Thermal oscillations in the onboard transmitter prevented 1-way doppler from being useful for Navigation.

⁸ It was also convenient for the flight team, since these handovers tended to occur during prime shift.

including slow convergence, large stochastic ranges and multiple-sigma corrections to thrust magnitude and pointing (several mN and several degrees, respectively). After considerable evaluation and discussion it was determined that the filter was trying to extract too much information from the very limited amount of data, so a simplified filter 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. With these changes in effect, a stable OD was achieved that was fairly easy to maintain under normal circumstances.

LOST ATTITUDE LOCK, AND ITS EFFECT ON NAVIGATION

Early in the post-SRU-loss recovery operations, while “normal” operations procedures were evolving, methods for coping with information loss associated with loss of inertial lock events had to be developed. Periods of miss-directed thrusting (“miss-thrusting”) would occur whenever the new ACS star tracking software would lose its inertial reference star. These periods of attitude uncertainty were referred to as Losses of Lock (LOLs).

If inertial reference was not quickly restored, the bias and drifts of the IMU would 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. By 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 would become important if the planned trajectory was to be modified in a timely fashion. Table 1 contains a list of all attitude recovery times before the encounter with Comet Borrelly.

**Table 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 FSW 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.

The following sections will describe each of the six LOL events, its cause, the flight team’s response, the Nav team’s response, and the effect the LOL had on the planned spacecraft trajectory. The prior, well understood Navigation models would have to account for gross

uncertainties in the pointing of the previously fixed thrust vectors. At first, these thrust miss-pointings were for the greatest part unknown, but techniques to discern them would evolve as each LOL was dealt with.

Loss of Lock 1

This was the initial attempt to restore the spacecraft attitude control after the loss of the SRU. After rebooting the spacecraft with the new star tracking software, the flight team decided to let the spacecraft autonomously search for a star using a “walking mosaic” of successive images. In the surprisingly short period of several hours the spacecraft reported successful lock. Long exposure images (of several seconds) containing this star were downloaded for examination, and the Nav Team successfully identified the new star based on its relative location to dim stars seen in the same images. The knowledge of spacecraft-Sun angle and a rough estimate of the HGA pointing based on the signal strength at the DSN helped narrow the list of potential stars from thousands to dozens [6]. Once the spacecraft was made aware of the true location of the newly found star, celestial inertial reference was considered officially restored after seven months of flying without a SRU.

The spacecraft flawlessly maintained attitude knowledge, allowing the flight team to gain experience with (and confidence in) the new software. Over the nine days following restoration of inertial reference, with the spacecraft under RCS control and the ion engine turned off, the NAV team was able to establish a reasonable OD without having to model the effects of the substantial number of small turns made during the initial star search activity. The flight team restarted the ion engine, continued testing and on June 28 put DS1 back on course to Comet Borrelly.

Loss of Lock 2

Less than one month later, however, at the start of a routine Earth tracking pass, telemetry indicated that the tracking software had lost its star. Fortunately, the HGA signal strength reported by the DSN indicated that the spacecraft was not grossly miss-pointed, and therefore the IMU hadn't drifted too far. By studying the signal strength of the HGA and sending small corrective turns to the spacecraft, high-rate communication was maintained [3]. The flight team elected to re-use the active mosaicking search method to locate a star and lock onto it. Identification of the star and rectification of the spacecraft's attitude knowledge would follow. After a few hours of turning and imaging, the spacecraft successfully locked onto a star. However, identification of this star took a few hours, much longer than expected. This was caused by the characteristic of CCD cameras in which they register more signal from red stars. In practice, this meant that a 3rd magnitude blue star might register the same signal as a 5th magnitude red star. Consequently, this greatly increased the number of stars that would have to be checked before the identity of the current lock star could be discovered. The star in question turned out to be a dim red star.

Once the spacecraft attitude was corrected, a simple attempt to model the misdirected thrusting of the ion engine was undertaken. Before the start of the tracking pass, the spacecraft attitude had been drifting for two days. The ending attitude of this drift was determined by applying the approximate attitude error at the start of the tracking pass. For these two days, the engine was assumed to be burning along the average of the starting and ending attitudes. To model the large amount of RCS activity during the walking mosaic, a small 1mN finite burn was applied over the search duration. The resulting OD using this model showed that at the end of the tracking pass,

the spacecraft had a position and velocity discrepancy of approximately 1 m/s and 100 km from the nominal trajectory. These differences were not large enough to merit a redesign of the trajectory.

After examining telemetry for clues as to what happened, it was discovered that the onboard image processing software started processing dozens of spurious star signals just before the time of lost lock. These “fake stars” were likely caused by high-energy particles from a coronal mass ejection which had erupted in the direction of DS1. Since the camera susceptibility to cosmic rays was well known, a mechanism for using pairs of images to separate constant star signal from transient cosmic ray signal was built into MURKY and used during star acquisition and re-acquisition [3]. However, since the software was written to only accept a small number of stars per image, the sheer number of false signals prevented the true star signal from being registered.

It is worth pointing out that it was hypothetically possible to configure the spacecraft to autonomously turn off the engine upon any loss of lock. This would have made orbit determination easier for the Nav team, but this benefit was not worth the risk of lost thrust and additional hydrazine usage by being placed into RCS mode. Even if the spacecraft were to be miss-pointed by several degrees, it would still achieve 90% of its required thrusting in the right direction. In the case of this LOL event, two days of missed thrusting would have meant having to recover 10 m/s of thrust instead of 1 m/s, and the additional expenditure of 40-60 grams of hydrazine.

After July 2000, the spacecraft tracking software behaved flawlessly for twelve months. This allowed the Nav team to iron out the nominal OD methods as described in the above section on Navigation.

Loss of Lock 3

With the expectation of a planned reboot and attitude recovery that would follow the March 2001 upload of new flight software⁹, the flight team set out to refine their recovery strategies. It was decided that using hydrazine to perform active star searches was unnecessarily wasteful, and a passive search approach was used. This passive method amounted to getting the spacecraft to Earthpoint [3], disabling the tracking software and allowing the spacecraft to drift in the direction of the IMU biases. When necessary, turns would be commanded to maintain Earthpoint. Images would then be commanded and downloaded to the ground as often as possible within the bandwidth supportable by the HGA. Most importantly, it was also decided to leave the ion engine running to support TVC mode. This would help conserve hydrazine as well as take advantage of another feature of TVC: reduced image-motion. While under TVC mode, spacecraft inertial rates are exquisitely small when compared to the rates in RCS mode. These rates amount to microradians per second in TVC instead of tens of microradians per second in RCS. In practice, this prevented the signal from dim stars from being smeared across several pixels and falling below signal threshold. Arbitrarily pointed, long (several-second) exposures could now be taken with the high expectation of their containing a uniquely identifiable star field. Unfortunately, this would add more complexity to the OD modeling, as the non-gravitational activity during a

⁹ This software load contained new target tracking software that would be used during the encounter with Borrelly. It was designed to estimate the biases and drifts of the IMU based on approach imaging, and update the ACS pointing information accordingly [1].

recovery would now include several small finite burns along unknown vectors, and several turns using the RCS.

On March 13, the reboot occurred as planned. Attitude recovery, however, did not go as well as was expected. It took intense ground interaction, spanning three days and several tracking passes, before the spacecraft was pointed in the right direction¹⁰. During these passes, ten pictures were downlinked to the ground and several spacecraft turns were commanded in (occasionally futile) attempts to re-align the HGA with the Earth¹¹. Overnight, the spacecraft drifted by tens of degrees while the engine was running in order to conserve hydrazine. Attempts to estimate the IMU biases based on the decay of the HGA signal strength and the turn requirements were unsuccessful. It was not until March 16 that enough star fields were successfully identified to allow a reasonable estimate of the IMU biases to be made. Following updates to these estimates and to the attitude, a nearby candidate reference star was locked onto¹².

Modeling all of this activity proved difficult, and consequently there was no successful OD during this recovery period. At best, any approximation of the post-recovery position and velocity would be inaccurate by several hundred kilometers and several meters per second. Limited time, personnel and the lack of a good model of IMU drift precluded setting up a Monte Carlo test case that could have provided an appropriate post-recovery state with a legitimate, modest statistical uncertainty. A nominal spacecraft state with a very large uncertainty was used to start a new OD arc with data from the week following the recovery. The resulting converged solution was less than optimal for assessing needed changes to the upcoming burn profile, as it showed implausibly large state errors and corrections to the model. Even so, it was used to provide needed antenna pointing predictions to the DSN¹³. When three weeks had passed since the recovery, enough data existed to perform a reliable OD. This showed that after the recovery, the spacecraft had acquired a 5800 km position error and an 11.5 m/s velocity error from the nominal trajectory. The resulting B-plane shift¹⁴ [1] was -30,249 km in B•R, 29,044 km in B•T and -5,649 seconds in Time Of Flight¹⁵ (TOF). Accounting for this required large changes to nominally planned trajectory.

The large differences between the post-recovery one-week arc and the post-recovery three-week arc illustrate the inherent difficulty in estimating the position and velocity of a spacecraft operating under constant low thrust using short data arcs [5]. It served as an example the need to model the spacecraft drift profile as well as possible during future losses of lock. This would be especially true when the mission timeline would not allow a leisurely three week period in which to accumulate enough tracking data to perform a normal OD.

¹⁰ In hindsight, the difficulty in acquiring a star was likely caused by a zeroing out of the IMU biases as a result of rebooting. In theory, resetting these biases to the pre-reboot values would have provided better control of the spacecraft drift than leaving them at zero.

¹¹ One turn in particular involved a large turn that would sweep the HGA across the Earth in the hopes of using the signal increase as a means of determining attitude and restoring HGA communication.

¹² It would turn out that it had locked onto a star that was a full two degrees away from our desired star [5]. This oversight was quickly noted and corrected.

¹³ The errors in this trajectory made themselves apparent as a 50 milliradian pointing error two weeks later. Later, more reliable OD confirmed a 100,000 km out-of-plane position error in the trajectory.

¹⁴ Up until encounter, trajectories are targeted to hit the B-plane at 0km in B•R, 2000 km in B•T and 0 second shifts in TOF.

¹⁵ At an expected flyby velocity of 16 km/s, this would amount to a position error of 90,000 km.

Loss of Lock 4

In July 2001, just over two months before the encounter, the spacecraft again lost hold on its reference star. At this time, the burn profile was divided into weekly burn arcs that alternated between ecliptic north pointing and ecliptic south. This tacking of the spacecraft was used to keep the spacecraft on a ballistic trajectory, while still allowing for the use of the ion engine to maintain attitude in TVC mode. Since some fine-tuning of the trajectory was still required, the spacecraft was commanded via the backbone sequence to change stars midway through one of its two-week burn arcs. DS1 failed to lock onto its new star, and it started to drift on July 16. This was the first time that the new ACS software failed to successfully transition from one known star to another.

The flight team became aware of the problem during a midweek pass on July 18. Fortunately, it turned out that several hours after the spacecraft failed to lock onto its star, its still active tracking software locked onto a different star that had drifted into the camera FOV. Since the spacecraft was in a locked state, it was decided that it would be best to leave it at its current attitude. To help determine the current attitude for future reference, a long exposure image of the current star was commanded for later downlink when at Earthpoint. Over the next five days, the spacecraft maintained its mostly toward-Borrelly thrusting and turned to its sequenced Earthpoint attitude with only an approximate seven degree error in declination. That error did not cause a large enough antenna pointing error to significantly limit bandwidth during recovery operations.

Modeling of the drift during the tracking pass was aided by the attitude identification of multiple downlinked images and onboard-processed star center-location “centroid” data. Modeling of thrusting of the previous week proved to be a little more difficult. It turned out the fourth magnitude star (as measured by the camera response) was really a 7th magnitude star of class-M. It evaded identification until July 31. Before it was identified, a hypothetical location for the star was determined by backing out the effects of the Earthpoint turn from the best approximation of the attitude at the start of the tracking pass. This was used as the burn attitude for the eight days in which it was locked to the star. The 14 hours during which the spacecraft drifted was modeled as a slow, constant turn from the direction of the planned burn star to the direction of the mystery star. The resulting OD using this model showed that at the end of the tracking pass, the spacecraft had a position and velocity discrepancy of 6800 km and 7 m/s from the nominal trajectory. Later OD based on the true attitude of the mystery star refined this discrepancy to 3500 km and 8 m/s. The resulting B-plane shift was -38,109 km in B•R, -49,064 km in B•T and 416 seconds in TOF. This perturbation required breaking the upcoming two week burn arc into two one-week burn arcs in order to get back on track to Borrelly. These new burn arcs were offset from the original burn arc by several degrees, and were at a much higher throttle level.

Loss of Lock 5

The need to perform a fifth attitude recovery was foreshadowed by an odd doppler signature observed during a midweek pass on August 16th. The configuration of the pass was carrier-only through the spacecraft LGA. Without telemetry, spacecraft health was determined by an assessment of the doppler data and a nominal subcarrier offset of +/- 35 kHz¹⁶. The doppler showed a small residual with a very large trend (See figure 2). Normally, a large trend in the

¹⁶ Had the spacecraft been unable to see any consistent star information, this subcarrier offset would have been changed to +/- 20 kHz.

doppler would indicate an incorrect predicted thrust level or thrust attitude. However, days of mismodeled thrust would also be accompanied by a large residual value. This apparently sudden change in the doppler deflection could have been caused by an autonomous IPS throttle down to conserve power, or a loss of lock. Since the subcarrier was still nominally offset, a loss of lock was ruled out and the upcoming tracking pass with the 70-meter antenna at Goldstone was expected to be business as usual. It would turn out that the cause of this LOL was solar flare interference. This time, it had so deluged the camera with false signals that the tracking software was convinced it had never lost lock, and never changed the subcarrier to an alarm offset. Fortunately, after only two days of drifting it stumbled onto a star that was bright enough to shine consistently through the noise of the false signals (See figure 3.)

On August 21, the flight team again found themselves starting recovery operations when telemetry showed that the spacecraft was not locked onto its Earthpoint star. 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. At this attitude, scattered light problems that plagued 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.

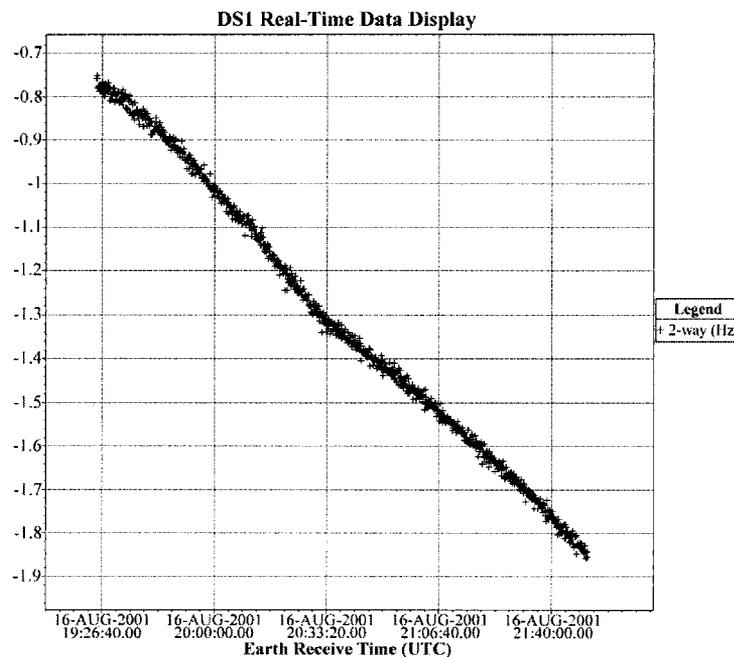


Figure 2: Doppler residuals on August 16th, 2001, showing indications of mistrusting.

The flight team spent the next two and a half days effectively squinting into the Sun. Over that time they communicated with the spacecraft using three passes borrowed from other missions, downlinked several images, downlinked dozens of centroid packets, commanded five turns to correct the HGA pointing and also attempted to lock onto a potential reference star (this last proved to be unsuccessful). After failing to reconcile the spacecraft attitude, 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 also to 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.

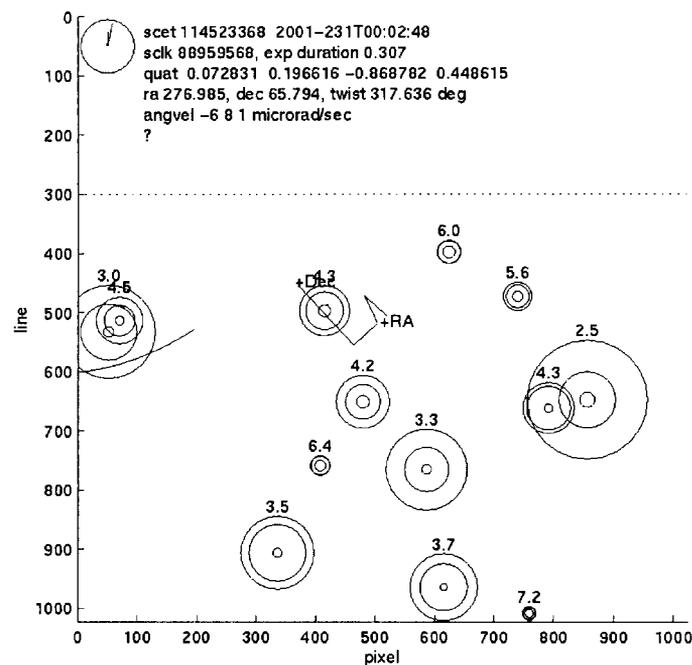


Figure 3: A recreated picture of one of the centroid data packets taken before recovery activities in LOL 5. It shows the 2.5 magnitude reference star that was locked onto. A 4.2 magnitude “companion” star is also visible, along with 11 false star signals caused by solar activity.

Modeling all of this activity sufficiently to allow for a useful OD was difficult. Of key importance was identification of the star that the spacecraft had locked onto for five full days before the sequenced turn to Earthpoint. Fortunately, the Nav 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 3). 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 shows images from which a drift rate of .3 degrees per hour can be determined. 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 TOF.

Ironically, by taking several passes to re-orient the spacecraft there were now several hours of doppler data with which to fit a model. There was also one pass of ranging data, which was made possible in part by the downlinking of centroid previews of images taken on the spacecraft. Since previews reduced the need to downlink as many images as possible in the hopes that at least one would contain an identifiable star field, they effectively freed up much of the signal bandwidth. This allowed the Nav Team to take ranging measurements during the 70-meter antenna passes after the spacecraft was reoriented to a retrograde attitude. All of these data made possible the estimation of the effects of the recovery activities on the spacecraft trajectory.

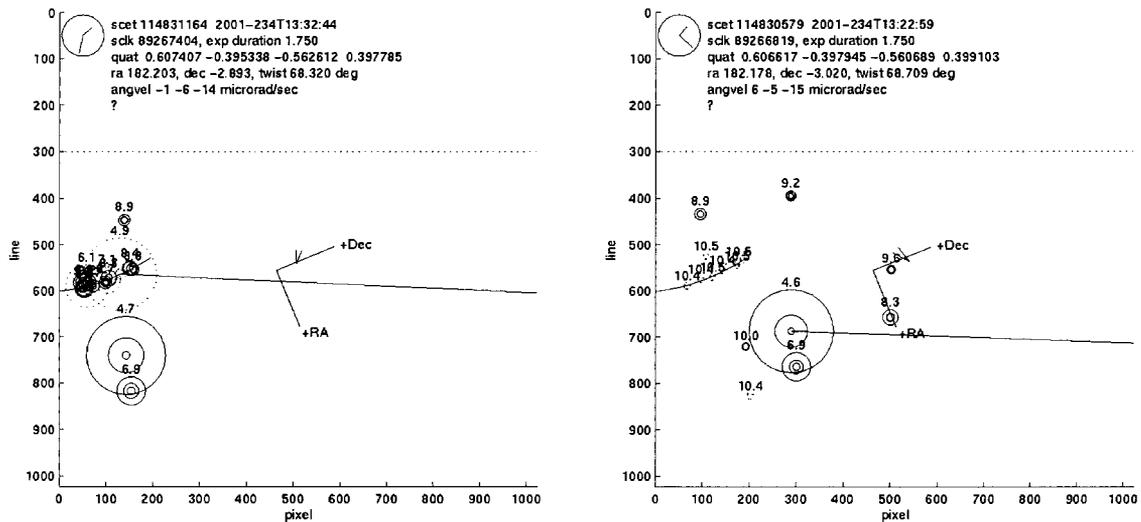


Figure 4: Centroid images taken 10 minutes apart. These images show three stars in the camera FOV, with magnitudes of 4.5, 7 and 9. Other signals are stray light artifacts or cosmic rays.

Loss of Lock 6

Less than a week and a half before the encounter, the flight team had to deal with another tracking software anomaly. On September 13, following the fourth observation of Borrelly, the spacecraft failed to lock up on its new Earthpoint reference star. By this time, the team was getting fairly skilled with the recovery process. As soon as the lock failure was noted, the Flight Director sent up a command to activate the centroid sequences. The Nav and ACS teams were immediately called in to analyze potential star centroid data being downlinked. After repeated

failures to lock onto the new reference star¹⁷, it was decided to turn the spacecraft to the previous, known reference star. Since the estimates of the gyro biases were still valid, the reacquisition was successful, and the inertial attitude was restored before the end of the pass. The net effect of this last LOL on the OD modeling was the required estimation of one single ion thrust arc. An *a priori* corrective slew of 0.5 degrees over that eight hour arc along with models for the RCS mosaic activity were the sum total of the modeling. This, combined with the changed attitude to point at a previous star, resulted in a B-plane shift of 2,072 km in B•R, 441 km in B•T and -19 seconds in TOF. Before this shift, the approach conditions were 1422 km in B•R, 942 km in B•T and -24 seconds in TOF. After analyzing this change in the B-plane conditions, it was decided that the upcoming TCM was no longer necessary, so it was canceled [1].

APPROACHING BORRELLY

Aside from Earth communications passes, the 3-day South burn at the end of August and the 6-day North burn at the beginning of September were the last two non-TCM burn arcs. After the estimation of the effects of LOL 5, both of these were modified to bring DS1 back on course to Borrelly. Further understanding of the effects of the LOL was gained as more data arrived in the form of Borrelly Observations, conventional radiometric measurements and DDOR measurements.

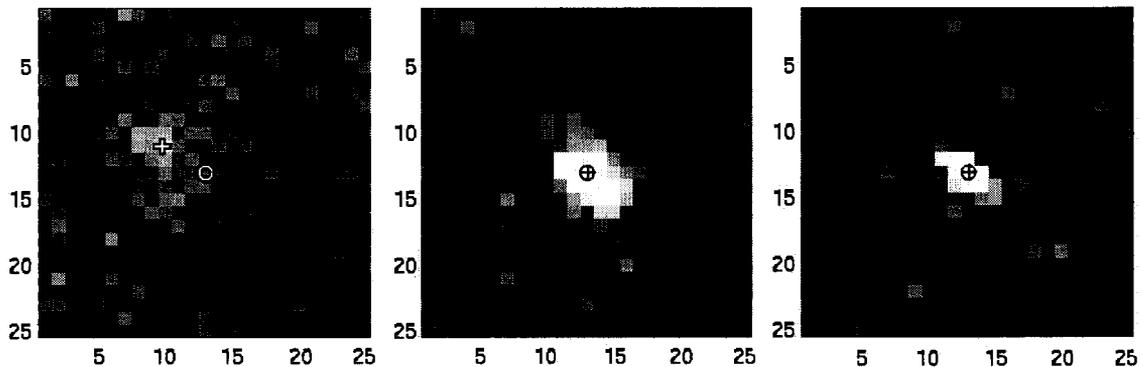


Figure 5: Left frame: Observed (+) vs. predicted (o) location of Borrelly using co-added images. Middle and Right frame: Registration performed on two stars seen in co-added images.

Even though the OD from 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 first observations taken in early September showed a 1000-1500 km difference between the predicted and observed locations of the comet. Figure 5 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 this distance to the comet (22 million km), each 13-microradian pixel spans 282 km. This placed the predicted location of the comet nucleus within 1100 km of where the images showed it to be. Much of this error was believed to have been caused by uncertainties in the comet ephemeris [1], but this was not known until later.

¹⁷ It was never determined what caused the software to fail to lock onto the star.

TCMs would have required that the spacecraft be reoriented into a prograde attitude, and this would have been a difficult, fuel-consumptive and dangerous maneuver.

The second TCM, 1.3, was scheduled for September 14. Due to the response required by LOL 6, the TCM was cancelled¹⁸. 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.

Following TCM 2.1, the spacecraft B-plane target moved closer to the desired aim point (Figure 6 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 6.) 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. On September 22, at 22:30:36 ET, Deep Space 1 flew past Borrelly at 2171.2 km in B•T, 31.2 km in B•R. This was 6 seconds earlier than predicted.

SUMMARY

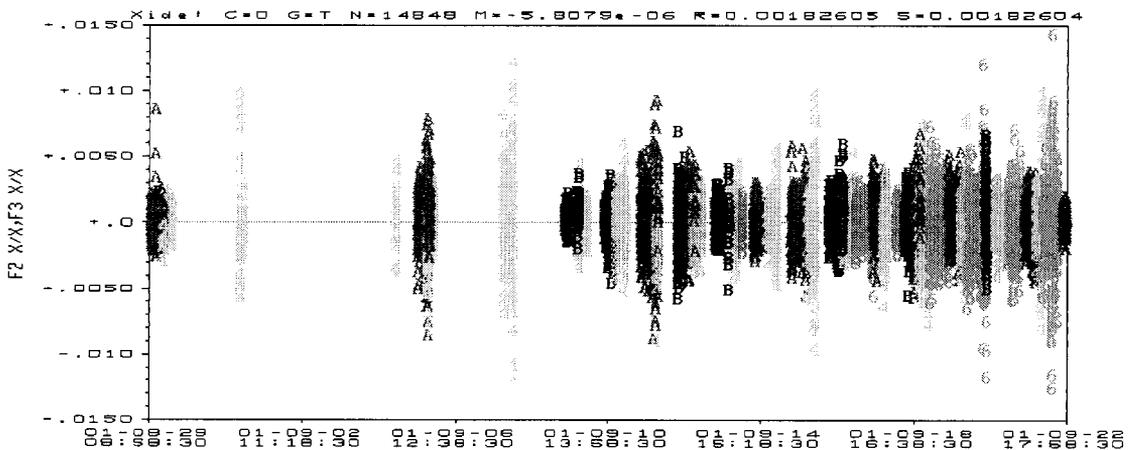


Figure 7: A doppler residual plot from one of the last radiometric OD solutions delivered before the encounter with Borrelly.

Following the loss of the SRU, autonomous OD using Autonav was no longer possible, and radiometric OD was needed for the cruise and approach phases of the mission. The groundwork for effective ground OD of a low-thrust spacecraft was carefully laid out in validating Autonav

¹⁸ It should be noted that the B-plane locations described earlier in LOL 6 are based on an early comet ephemeris [1], and did not take optical observations of the comet into account. The magnitude of the shift was still the same.

during the DS1 main mission. It was possible to carry out OD of DS1's low-thrust trajectory using these radio Nav techniques. Figure 7 shows a Doppler residual plot from a solution delivered just before the encounter.

Lessons learned from LOLs 1-4 helped with the OD of the spacecraft through LOL 5 and LOL 6. Given how these latter two anomalies occurred at critical times in the mission, the learning appeared to be quite timely. Providing useful radio OD up to the encounter was important in order to support the optical OD, since target-only optical observables are insensitive to TOF errors unless sufficient parallax is apparent. Also, since the heliocentric orbital out-of-plane errors mapped almost directly into time of flight uncertainty, minimizing these was required in order to determine the time of the encounter well enough to fall within the flexibility of the tracking software, and the encounter sequencing. By providing an accurate *a priori* assessment of the TOF, these OD efforts helped acquire high-quality flyby images of the comet nucleus (See Figure 8) as well as excellent IR spectra, and particles and field measurements from PEPE and the IDS.

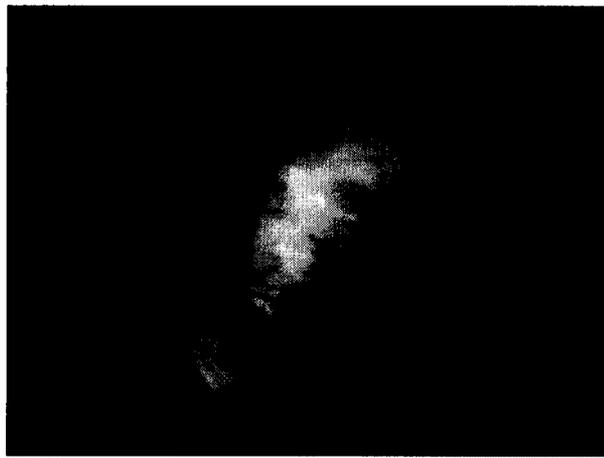


Figure 8: The Comet Borrelly.

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REFERENCES

- [1] Bhaskaran, S., and others, "Navigation of the Deep Space 1 Spacecraft at Borrelly," AIAA/AAS Astrodynamics Specialist Conference, Monterey, CA, August 5-8, 2002.
- [2] Rayman, M.D, and Varghese, P., "The Deep Space 1 Extended Mission," *Acta Astronautica* **48**, No. 5-12, pp. 693-705 (2001).
- [3] Collins, S., and others, "Deep Space 1 Flight Experience: Adventures of an Ion Drive," 25th Annual AAS Guidance and Control Conference, Breckenridge, Colorado, February 6-10, 2002.
- [4] Vanelli, T., (JPL, Deep Space 1 ACS Engineer) personal communication, March of 2001.
- [5] McElrath, T. P., and others, "Radio Navigation Of Deep Space 1 During Ion Propulsion Usage," 15th International Symposium of Space Flight Dynamics, Biarritz, France, June 2000.
- [6] Rayman, M.D. "The Deep Space 1 Extended Mission: Challenges in Preparing for an Encounter with Comet Borrelly," *Acta Astronautica* **51**, No. 1-9, pp. 507-516 (2002).
- [7] Coverstone-Carroll V., Williams, S. N., "Optimal Low Thrust Trajectories Using Differential Inclusion Concepts," AAS/AIAA Space Flight Mechanics Meeting, Cocoa Beach Florida, USA, Feb. 1994
- [8] Bhaskaran, S., and others, "Orbit Determination Performance Evaluation of the Deep Space 1 Autonomous Navigation System," AAS/AIAA Space Flight Mechanics Meeting, Monterey, California, February 1998.
- [9] Riedel, J.E., and others, "Navigation for the New Millennium: Autonomous Navigation for Deep Space 1," 12th International Symposium on Space Flight Dynamics, Darmstadt, Germany, June 1997.
- [10] McElrath, T., (JPL) personal communication, January of 2003.