

THE SUCCESSFUL CONCLUSION OF THE DEEP SPACE 1 MISSION: IMPORTANT RESULTS WITHOUT A FLASHY TITLE

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In September 2001, Deep Space 1 (DS1) completed a high-risk and flawless encounter with comet 19P/Borrelly. Its data provide a detailed view of this comet and offer surprising and exciting insights. After this successful conclusion of its two-year extended mission, DS1 undertook its hyperextended mission, devoted to new tests of the advanced technologies that were evaluated in the primary mission. Following this period of extremely aggressive operations, with no further technology or science objectives, the mission was terminated on 18 December 2001, with the powering off of the spacecraft's transmitter. By the end of its mission, DS1 had returned a wealth of important science and engineering data.

INTRODUCTION

Conceived in 1995, Deep Space 1 (DS1) was the first flight of NASA's New Millennium program (NMP). As all NMP missions, DS1's purpose was to test high-risk, advanced technologies in an operational spaceflight. The technology experiments on DS1 were selected by NMP on the bases of their importance to subsequent space and Earth science programs, the significant advancements they offered over the state of the art, the high risk they presented to the first user, and the need for in-flight testing to reduce that risk.

DS1's primary mission was devoted to the testing and evaluation of 12 technologies:

- solar electric propulsion
- solar concentrator arrays
- autonomous onboard optical navigation
- beacon monitor operations
- autonomous remote agent
- miniature integrated camera and imaging spectrometers
- miniature integrated ion and electron spectrometers
- small deep-space transponder
- K_a-band solid-state power amplifier
- low-power electronics
- power actuation and switching modules
- multifunctional structure

Perhaps the most important of these was solar electric propulsion, implemented on DS1 as an ion propulsion system (IPS).

DS1 launched on 24 October 1998 on the first Delta 7326-9.5. By the end of its primary mission in September 1999, it had met or exceeded all of its mission success criteria, producing a wealth of data on the performance of the payload. Detailed descriptions of each of the technologies, the results of the testing, and the major activities of the primary mission have been presented elsewhere.^{1,2} After the technology testing was completed in July 1999, the spacecraft conducted a bonus encounter with asteroid (9969) Braille.³ The encounter was partially successful, capturing all of the ion, electron, magnetic field, and plasma wave data planned, but limited images and infrared spectra.

Following its primary mission, DS1 embarked on an extended mission devoted to comet science, although it had not been designed for a comet encounter. In November 1999, the spacecraft suffered the loss of its commercial stellar reference unit (SRU), its only source of 3-axis attitude knowledge. Although this was considered initially to be a catastrophic failure, the operations team completed an ambitious two-phase, seven-month recovery that included the development of extensive new software and new

methods for operating the spacecraft. Rayman and Varghese described the details of the failure of the SRU, the complicated rescue that supervened, and the progress of mission operations through September 2000.³

One feature of the recovery was the use of the visible CCD camera in the miniature integrated camera/spectrometer (MICAS), one of the technologies tested during the primary mission, as an attitude sensor. Despite the seriousness of losing the SRU and the significant differences between the camera and the SRU, the replacement system worked remarkably well, allowing the project to refocus on delivering the spacecraft to comet 19P/Borrelly and preparing for the encounter. Detailed plans for the encounter as well as mission operations activities through the beginning of September 2001, including the installation of new software to increase the probability of obtaining remote-sensing data at the comet and in-flight tests of the encounter, were reported by Rayman.⁴

PRE-ENCOUNTER OPERATIONS

The problem of navigating to the vicinity of the comet's nucleus was different from that of reaching a typical planetary encounter, because the uncertainty in the comet's ephemeris dominated the navigation errors.⁵ A campaign of ground-based observations to improve the ephemeris was supplemented by navigation images acquired by the spacecraft. From 25 August to 10 hours before the closest approach on 22 September, DS1 conducted 11 imaging sessions, spanning ranges to the comet of 40.3×10^6 km to 6×10^5 km.

Several factors led to the limitation in the number of imaging sessions. Because the operations team was so small, controlling the workload was particularly important. It also was essential to conserve the critical resource of hydrazine for the reaction control system (RCS). The possibility that the spacecraft would exhaust this propellant prior to the encounter was among the most significant risks managed in the extended mission.⁴ The imaging of the comet consumed hydrazine for the large turns between the attitudes required for thrusting with the IPS, pointing MICAS to Borrelly, and pointing the high-gain antenna (HGA) to Earth.

DS1 had completed the thrusting necessary

to achieve a ballistic trajectory to Borrelly on 1 May 2001. As one of the hydrazine conservation measures however, continued thrusting was necessary to allow the attitude control system (ACS) to control 2 spacecraft axes with the IPS instead of the RCS. During the mission, another benefit of this thrust vector control (TVC) mode was recognized. To control attitude with the IPS, ACS commanded the IPS thruster gimbals with a proportional controller. In TVC, angular deadbanding rates were lower than when ACS used the impulsive "bang-bang" controller for the RCS. Therefore, although RCS control was used for turns, TVC was applied to provide a more stable platform for the optical navigation observations.

MICAS needed to be pointed to an isolated bright ($m_v < 6$) star in order to provide attitude data to ACS. In the absence of an acceptable reference star in the same field as Borrelly, the imaging sessions relied on inertial measurement units (IMUs). By the end of each such activity, the errors caused by the IMUs' biases raised the risk that when the spacecraft turned to point the HGA to Earth, it would not find the associated reference star (known as an "Earthstar"). Limiting the number of Borrelly observations thus aided in managing this risk.

As the encounter plans depended upon turn rates, specific attitude reference stars, and other strategies and control modes that had not been used a great deal during the mission, some of the optical navigation observations were used as opportunities to conduct focused tests. These complemented the earlier encounter rehearsals with the spacecraft and the extensive program of testbed simulations.

Prior to the SRU failure, the autonomous onboard optical navigation system (AutoNav) was operated a great deal, thereby reducing work for the operations team in addition to testing this technology. The rapid pace of the recovery from the loss of the SRU did not permit modification of AutoNav so it could function with the new design of ACS. As a result, the optical navigation images on approach to Borrelly were analyzed by the navigation team rather than onboard the spacecraft.

The initial detection of the comet required co-addition of the images, but as the range between the comet and spacecraft diminished, the

comet became detectable in individual frames. The optical navigation data proved to be very powerful.

The cometary ephemeris as determined from the optical navigation images differed by 1500 km from the ephemeris derived from the much denser and longer set of ground-based observations. To determine whether this discrepancy might have been a result of errors in knowledge of the spacecraft's trajectory, the Doppler and range data were supplemented with another data type. Delta differential one-way range (Δ DOR) data were acquired on 14 and 15 September. Δ DOR achieves very high accuracy in the determination of a spacecraft's angular position using simultaneous measurements from two Deep Space Network (DSN) stations. Each DSN station alternated between observing the spacecraft and observing a quasar within 5° to remove or reduce the effects of many of the uncalibrated error sources. The Δ DOR observations proved that the spacecraft's trajectory was not the source of the ephemeris discrepancy.

Further work with the ground-based optical data showed that the two ephemeris solutions would match if the brightest pixel were used rather than a symmetrical Gaussian fit to the brightness distribution of the coma.

The requirement to continue IPS thrusting at a low throttle level ("impulse power"), to let ACS operate in TVC mode to conserve hydrazine, necessitated a novel strategy for the approach to Borrelly. The trajectory was designed with the use of thrusting at impulse power alternating between ecliptic north and ecliptic south every 1 to 2 weeks in the months leading to the encounter. Encounter targeting was controlled by making small adjustments to the throttle level or attitude, although all thrusting continued to require a suitable reference star in the camera's field of view.

The two trajectory correction maneuvers (TCMs) in the 28 hours before the encounter were planned to be executed with the RCS rather than the IPS. The greater acceleration that could be attained with the RCS would allow larger TCMs than with the IPS in the limited time. Moreover, long TCMs might have required the spacecraft to be in attitudes unfavorable for telecommunications for many hours, thus leaving it unavailable for careful monitoring, and that

would have added risk close to the encounter.

RCS TCMs had been executed during the primary mission in tests of AutoNav and for the encounter with Braille, but with the significant modifications to ACS in the rescue from the loss of the SRU, a test was judged to be a worthwhile contributor to reducing risk to the Borrelly encounter. On 29 August, the RCS was used for a 0.20-m/s maneuver, large enough to yield confidence in the performance of spacecraft systems and the command sequence yet small enough to protect the hydrazine supply. (This test had been included in the hydrazine budget formulated when the rescue was completed.)

On 5 September, north/south impulse power thrusting ended. Subsequent IPS thrusting was in the attitude that allowed communications through the HGA, with the camera locked on an Earthstar. This would have enabled prompt response to any spacecraft problems before the encounter.

The plan for the final IPS thrusting was not designed for the lowest throttle level that allowed ACS sufficient control authority for TVC. Rather, it assumed a higher level to afford additional encounter targeting control authority through decreases or increases in the throttle level without attitude changes (see below).

Dedicated IPS TCM opportunities were built into the pre-encounter plan, each timed in part to allow incorporation of recently down-linked optical navigation data into the TCM solution. Despite the interruption of JPL's activities because of the terrorist attacks, the first TCM was commanded and executed on 11 September.

Although locking ACS to a bright reference star with MICAS after the failure of the SRU proved remarkably robust, occasionally ACS lost track of the star. Systems were in place on the spacecraft to minimize the cost of such a loss, and the operations team had procedures in place to restore the lock. Nevertheless, these rare incidences presented significant risk to the encounter by consuming hydrazine, causing trajectory errors (through IPS thrust vector errors), interfering with scheduled spacecraft activities, and distracting the small team from other work.

The fifth Borrelly observation, on 13

September, was combined with a transition from one Earthstar to another, keeping up with the changing orbital geometry. The spacecraft failed to lock to the new Earthstar when it turned back from the comet. The signature of this inability to lock was different from others, with clear evidence that the Earthstar was in the camera's field of view. The system may have been unable to lock because the Earthstar was a visual binary. Rather than devote the time to investigating the anomaly, it was decided to command the spacecraft back to the previous Earthstar, accepting the consequent degradation in communications performance from the less favorable HGA pointing. The cost of this loss of attitude lock was a few hours, in contrast to some earlier ones that took a few days to correct.

Following the sixth Borrelly observation, on 15 September, TVC was no longer used, except during optical navigation observations and IPS TCMs. With no IPS thrusting, the 1% uncertainty in IPS thrust, negligible during interplanetary cruise, would not contribute errors to the final navigation solutions. IPS thrusting imparted about 5 m/s/day, whereas the effect of using RCS thrusters for control was to add about 0.1 m/s/day.

The fourth, fifth, and sixth observations of Borrelly showed two peaks in the comet's brightness, separated by ~ 1000 km, with the smaller one closer to the Sun and about 45° from the line between the Sun and the larger one. The plan had been for the spacecraft to pass on the Sun-nucleus axis about 2000 km from the nucleus between the Sun and the nucleus. The appearance of two peaks brought this plan into question.

Targeting DS1 for the brighter peak might have placed the spacecraft too close to the smaller one, increasing risk to the spacecraft's safety. If the smaller one were targeted, it could have turned out that there would have been little of significant scientific interest to observe by the time the spacecraft arrived; furthermore, the closed loop tracking system might have had more difficulty with a small target. Although intended to cover a very wide range of possibilities, the parameters had been selected for a larger body.

If the two peaks were the result of a recent nuclear fragmentation, the increased dust could

have greatly elevated the risk to the spacecraft. (Because it was designed and built for technology testing, not for encountering a comet, the spacecraft did not have shielding to protect it from the cometary environment.) As dust fluence was expected to be inversely proportional to distance from the nucleus, moving the point of closest approach sufficiently far out to yield a significant difference in the fluence would have reduced the potential science return too much to render such a change acceptable.

In the end, making no changes in the plans was considered to be the lowest risk. The separate peak did not present further problems.

Protection from dust was only one of the bases upon which the closest approach distance had been selected. It also was important to fly far enough from the nucleus that the geometry in which the well understood attitude-dependent scattered light in MICAS would disappear would be reached while ACS could still track the accelerating target.

Encounter targeting was biased so that TCMs were likely to be in directions that required neither complex turns nor decomposition into multiple thrust vectors to achieve the effect of thrusting in one prohibited attitude. In addition, the geometry was such that IPS thrusting with the HGA pointed to Earth would control how far from the Sun-nucleus axis the aim point would be. The encounter design depended only weakly on the delivery distance along the Sun-nucleus axis but was more sensitive to this orthogonal coordinate. Deviation of the impact parameter from the planned 2000 km was accepted if it allowed TCMs to be conducted without turning the spacecraft, thus reducing risk to the encounter. In addition, if the HGA could remain Earth-pointed, there would be less of a need to limit the duration of TCMs. This increased the likelihood that they could be conducted with the IPS, thus conserving hydrazine. The largest single term in the hydrazine budget was the 2.0 kg allocated for TCMs totaling 10 m/s.

This strategy worked extremely well. Five of the scheduled TCMs proved not to be necessary, and of the 4 that were, none required turning the spacecraft. As a result, all of them used the IPS. The final TCM, beginning 18.5 hours before closest approach, lasted 2.5 hours.

Following this TCM and the last pre-encounter optical navigation observation of Borrelly, the operations team's final planned tasks were to deliver important updates to the spacecraft in order to maximize the probability of a successful encounter. Default values for the location and time of the closest approach had been loaded on the spacecraft several days before the encounter. To help the convergence of the filter in the reduced state encounter navigation (RSEN), the core of the autotracking system,⁴ these were updated with the best estimates shortly before the encounter. The estimated time of closest approach also was used in a one-command sequence to control the time at which the cascaded set of encounter sequences was activated.

In addition to the encounter coordinates, the integration times for MICAS' visible images and infrared spectra could be updated shortly before the encounter. The spacecraft could not adjust these integration times autonomously; following careful consideration, implementing such a capability had been rejected during development of the encounter software. To account for the substantial uncertainty in the photometric properties of the nucleus and the coma, the data acquisition sequence included a range of integration times. Alternate sequences were stored onboard, allowing other sets of integration times to be used with a minimum of commanding. Based on analyses of the optical navigation images of Borrelly, it was decided to use the default sequence.

ENCOUNTER

Despite the risks from the environment, the spacecraft already being handicapped, and a very complex design involving 685 commands and more than 3000 parameters in 44 sequences, the encounter was essentially flawless and exceeded expectations. The plans described in Ref. 4 were executed remarkably faithfully.

On approach to Borrelly, DS1 viewed the comet near the south ecliptic pole. The spacecraft's closest approach of 2171 km was at 22:29:33 UTC on 22 September 2001, with $v = 16.58$ km/s. The encounter took place 1.36 AU from the Sun, 8 days after the comet's perihelion.

Science data were acquired with 3 instru-

ment suites. All were body-fixed, so pointing required spacecraft maneuvers. MICAS' 1024 × 1024 CCD with 13- μ rad pixels collected panchromatic images in the range of 0.5 μ m to 1.0 μ m. MICAS also obtained spectra from 1.3 μ m to 2.6 μ m with a sampling interval of 7 nm. Ion and electron energy and angle spectra and ion mass/charge measurements were made with another instrument included on the flight as a technology experiment for the primary mission, the plasma experiment for planetary exploration (PEPE). Over its 2.8π sr field of view, PEPE was sensitive between 8 eV and 32 keV, with a resolution of 5% in energy and in mass/charge. Magnetic field and plasma wave measurements were made with sensors that had been carried as part of the assessment of the IPS. These IPS diagnostic sensors (IDS) measured the effects of the IPS on the spacecraft and space environment during the primary mission⁶ and were reprogrammed in flight to collect science data at the comet.

Some of the optical navigation observations proved to be of scientific interest as well. Dedicated science data acquisition however began with PEPE and IDS measurements 12 hours before closest approach (CA).

At about CA - 83 minutes (m), MICAS acquired some visible images for coma science and some to initialize RSEN; a subset of the images served both purposes. That was followed by the acquisition of infrared spectra at about CA - 65 m (the range to the comet then was too large for the spectrometer to resolve the nucleus), after which the spacecraft turned to lock to an attitude reference star. The operation of MICAS as an attitude sensor precluded its uninterrupted use as a science instrument during the approach to Borrelly.

At CA-32 m, MICAS was pointed to Borrelly again and 1 image was acquired for RSEN every 30 s. Because of limited data storage space, only a preselected subset of the images could be retained. (This strategy was guaranteed to return some without the nucleus, as images were saved from the two mosaics, designed for protection from pointing errors.) But for every image processed by RSEN in which the software detected the nucleus, the portion of the image containing the putative nucleus was saved, thus increasing the number of views of the nucleus that could be returned.

The autotracking system was designed to accommodate the complicated scene with a partially illuminated nucleus (the appearance of which would change with the solar phase angle), jets, the coma, cosmic ray tracks, background stars that could produce streaks as the spacecraft tracked the nucleus, and stray light. To achieve the science target of capturing an image of the nucleus spanning 50 pixels, it would have been necessary to track the nucleus at least to CA - 12 m and probably much later, depending upon the projected size of the irregular nucleus from the spacecraft's view. DSI kept MICAS pointed at the nucleus long enough for the image at CA - 160 s to be in the field of view. By the time the next CCD image was taken 30 s later, the nucleus was no longer in the field.

In fact, RSEN continued to predict the position of the nucleus to an accuracy smaller than the camera's field of view, but ACS, not designed to track a body through such a flyby, was not able to keep up with the predicted position. This was not a limitation of RCS control authority; rather, it apparently was the result of a lag in ACS that was manifested only in the case of a significant angular acceleration of the target. This was of no importance for the primary mission's technology testing requirements, and there were insufficient resources to address this limitation in the extended mission, particularly because it was not an obstacle to achieving the science goals.

Beginning at CA - 97 s, by the time the probability of the nucleus being out of the CCD field of view was very high, the slit of the infrared spectrometer was swept across a range predicted to include the nucleus.

This maneuver also was used to begin achieving the attitude required for PEPE measurements through closest approach. In addition to attaining the optimal orientation for PEPE, the spacecraft stopped attempting to track the nucleus and instead assumed a constant angular rate. This greatly reduced RCS firings, thus minimizing the possible interference of hydrazine decomposition products with PEPE's measurements. It also served to reduce the amount of RCS solenoid activity that could register in IDS magnetometer measurements during this important portion of the encounter.

The plan did not include obtaining any outbound remote sensing data. After remaining quiescent during the period of highest priority PEPE and IDS data acquisition, the spacecraft began its turn to point the HGA to Earth at CA + 30 m.

There were significant risks not only to the acquisition of the science data, but also to the receipt of those data on Earth. In the event, the spacecraft survived its passage through the coma. The subsequent transmission of the data required the HGA to be near Earth-point, and there had been no assurance that ACS would be able to locate the Earthstar after relying on IMUs for so long and maneuvering so much during the encounter. All image-file storage locations were full, so before ACS could lock to the Earthstar, some of the encounter images in MICAS' internal buffer and in the spacecraft computer's image-file space had to be removed. Therefore, even after the turn to Earth was complete, attitude was held with the IMUs while space was created for the Earthstar images. When the search for the Earthstar was enabled, ACS locked to it smoothly.

Although the encounter plan filled the available data storage space, it had been highly uncertain how much useful science data, if any, might be collected at Borrelly; nevertheless, failing to return data because the encounter consumed too much of the remaining hydrazine had been determined to be a scenario to avoid. To continue to extend the hydrazine supply, the IPS was restarted, and TVC resumed at CA + 2 hours.

ENCOUNTER RESULTS

All MICAS, PEPE, and IDS science measurements worked as planned, and more science data were returned than had been expected. Overviews of the observations are described here, with interpretations published elsewhere. The first analyses of MICAS data were reported by Soderblom *et al.*,⁷ and further results will be published. Initial PEPE⁸ and IDS^{9,10} results are forthcoming.

Because the tracking software located the nucleus in all but one of the images that contained it, 52 images of the nucleus were returned, many also showing details of the coma

and dust jets. In the final view, the nucleus spanned about 175 pixels, or 3.5 times the target for the best image. No spatially resolved infrared spectra were required, as their acquisition initially had been expected to place too much risk on the image data (in part because of the attitude changes needed to acquire the spectra and the consequent forfeiture of data for RSEN). However, the scan of the IR slit across the nucleus (an activity that was designed and implemented relatively late in the encounter planning) succeeded, yielding 45 spatially separated swaths across the nucleus, each ~ 165 m in its shorter dimension.

The highest resolution visible image is 47 m/pixel, taken at a solar phase of 52° and a range of 3560 km. (See Figure 1.) Only 13 bodies in the solar system have been imaged with resolution better than this somewhere on their surfaces.¹¹ Preceding images are at solar phases up to 88° , thus permitting reconstruction of 3-dimensional views of the nucleus, coma, and jets.



Figure 1. Nucleus image with resolution of 47 m/pixel. Sunlight comes from the bottom of the frame.

The 8-km-long nucleus displays highly variegated terrain with large albedo variations. The surface is rugged on each end, with smooth, rolling terrain between. In contrast to all asteroids and small moons that have been

investigated, no clear impact craters on scales of 200 m or larger can be identified on Borrelly. The smaller end of the nucleus (at the lower right in Figure 1) is tipped $15^\circ - 20^\circ$ from the region on the other side of the narrowest part of the nucleus. The albedo ranges between about 0.01 and 0.035.

The infrared spectra of the nucleus display two principal features: a strong red slope and an absorption line at about $2.39 \mu\text{m}$. There is no evidence of water.

Several collimated jets and broader fans of dust are observed emanating from the nucleus. The strongest jet is at least 100 km long and is directed 30° from the Sun-nucleus axis. The jet originates from a broad basin near the center of the nucleus. Optical navigation images taken during the 34 hours prior to the encounter show evidence that the direction of the jet was stable over times longer than the nuclear rotation period.

On the inbound leg of the encounter, about 3.5×10^5 km from the nucleus, PEPE detected a slowing of the solar wind as it accelerated newly ionized cometary gas, losing momentum and energy to the cometary ions. The cometary bow shock was reached at about 1.5×10^5 km from the nucleus. On the outbound leg, the comparable plasma boundaries were displaced by a significant amount towards the Sun-nucleus axis compared to their locations on the inbound leg. The center of the ion coma, as determined by PEPE measurements of plasma fluid parameters, was offset by 1500 km from the nucleus. Such strong asymmetries were unexpected and have not been observed with *in situ* measurements made at other comets.

PEPE found a peak ion density about 1000 km before reaching the Sun-nucleus axis. The IDS magnetometers observed a peak magnetic field of 100 nT about 5000 km from the Sun-nucleus axis after closest approach.

IDS detected dust impacts within 6×10^5 km of the nucleus both before and after closest approach. The plasma wave spectra and electric field pulses indicate a variety of processes in the coma that will be reported.

Borrelly was at a solar elongation of 63° at

the time of DS1's encounter, permitting complementary observations from Earth. In addition to ground-based measurements, Hubble Space Telescope obtained visible images and ultraviolet spectra¹² and Odin acquired spectra at 557 GHz;¹³ observations planned for Chandra X-ray Observatory were missed because of a temporary spacecraft problem.

In addition to the direct scientific return, DS1's data are of engineering value to other missions planning to visit comets.

Stardust, already on its way to collect samples of the coma of comet 81P/Wild 2 in January 2004, will benefit in several ways from these data.¹⁴ Prior to the encounter with Borrelly, DS1 used models of the dust environment based on fits to photometric data. These models were derived from those developed by Stardust. Now these models can be calibrated and updated using observations of the actual dust distribution (based on data from MICAS and the IDS plasma wave instrument). The possibility of the significant spatial variability of the dust that was observed at Borrelly was not included in the models, so they may be enhanced now to reflect this.

The autonomous nucleus tracking system, which operated so successfully on DS1, will be employed by Stardust for its encounter. This flight-proven software will increase the probability of obtaining images of the nucleus, an important secondary science objective. In addition, the observed photometric characteristics of Borrelly's nucleus and coma provide the opportunity for Stardust to improve its imaging science return.

Some of DS1's operational experience of encountering a comet has been transferred to the Stardust project by having some people working on both missions as well as selected Stardust team members participating as guests in the Borrelly encounter.

Deep Impact will launch in December 2004 for an encounter with comet 9P/Tempel 1 in July 2005. The mission will include an impactor to excavate a crater on the nucleus and an instrumented flyby vehicle that will observe the dynamics of the cratering as well as the exposed subsurface material. DS1's science data have led to several changes in Deep Impact's plans.¹⁵

The large-scale topographical relief observed on Borrelly raises the possibility of shadows complicating the impactor targeting. Thus, Deep Impact has decided to incorporate a scene analysis algorithm in its targeting system to ensure that the impactor hits an illuminated region of the nucleus that will remain visible from the flyby spacecraft throughout the planned imaging period.

As with Stardust, the new photometric data will be used in the selection of integration times for imaging and spectrometry. In addition, the range of integration times will be increased to allow for significant albedo variations, as DS1 observed. The dust fluence data provide increased confidence in Deep Impact's environmental models.

HYPEREXTENDED MISSION

The return of the data from Borrelly marked the conclusion of DS1's two-year extended mission. Because of the risks to the spacecraft's survival from the cometary environment and the extremely small hydrazine supply, further spacecraft operations had been considered unlikely. The spacecraft was undamaged by the encounter however, perhaps in part because so much of the dust was concentrated in a large jet, which the spacecraft did not directly encounter. The many measures taken to conserve hydrazine during the 15 months leading up to the encounter, including conducting the final TCMs with the IPS, allowed the spacecraft to continue operating after the extended mission.

With no remaining science objectives, DS1's hyperextended mission was dedicated to renewed testing of the advanced technologies onboard. With the mission then at more than three times the duration of the primary mission, this offered an excellent opportunity to obtain previously unplanned data on the effects of long-term operation in space. Tests were conducted with 8 of the 9 hardware technologies during the hyperextended mission, with a focus on the IPS. (The small deep-space transponder continued to be operated regularly, but it was not subjected to special testing.)

The IPS had been operated extensively during the extended mission to reach Borrelly and to reduce the expenditure of hydrazine, but this new technology testing campaign allowed

the system to be operated in modes that were too risky when the mission was devoted to comet science. Xe flow rates and electrical parameters of the cathode and neutralizer were varied to explore new operating regimes. In addition, some tests that had been conducted during the primary mission were repeated to look for changes in performance. For example, the thrust at standard throttle levels was determined with Doppler measurements. Brophy *et al.*¹⁶ describe the test program in detail and the preliminary results.

Although the solar arrays had been used continuously throughout the mission, there were no dedicated characterization tests during the extended mission. Repetition of tests from the primary mission afforded the opportunity to augment the long-term performance model.

PEPE experienced an internal discharge in November 1999 that required a change in its operating parameters.⁴ Because of some concerns that the instrument's lifetime might have been limited as a consequence, it was operated only when necessary during the remainder of the extended mission. Hence, its use was confined to tests of new software and new voltages for the time-of-flight cylinder, encounter rehearsals, and the encounter. During the hyperextended mission however, PEPE was operated for about 2 months, demonstrating reliable and stable performance and returning excellent data, as it had at Borrelly. PEPE data also were collected to support some of the IPS characterization tests.

MICAS continued to be used as an attitude sensor. Some additional calibration data were acquired for the infrared channel as well.

The K_a-band amplifier had been operated occasionally during the extended mission to provide signals for the DSN to use in its tests of new systems to prepare for operational support of K_a-band. Additional tests were conducted during the hyperextended mission, providing further data on the amplifier performance as well as aiding the DSN.

The low power electronics, power actuation and switching modules, and multifunctional structure had not been operated since the primary mission. The standard tests conducted frequently in 1999 were repeated in the hyperextended mission. None of the devices showed

changes in performance. The low power electronics experiment included a dosimeter that indicated it had been exposed to 450 Gy (45 krad) by the end of the hyperextended mission.

The pace of tests during the hyperextended mission was significant, with at least one major new test being conducted almost every week, in addition to repetitions or minor modifications of other activities. As the majority of the operations team had transferred to other projects, most of the work was carried out by a team of about 5 full time equivalents. Greater risk was accepted during this mission phase than during the extended mission following the recovery from the loss of the SRU. Still, all tests were completed successfully, providing extensive new data on the IPS and other technologies.

END OF MISSION OPERATIONS

The spacecraft's lifetime was quite limited by the end of the hyperextended mission. Enough hydrazine was onboard for about 2 months of RCS control. Hydrazine could have been conserved by operating in TVC mode, as in the extended mission, but the remaining Xe supply would have supported less than 3 months of IPS thrusting, even at impulse power. Having no reaction wheels, the spacecraft needed propellant to keep the solar arrays Sun-pointed.

Concepts were devised for extending the lifetime, but limited NASA resources and the absence of science or technology objectives made the development of these schemes unnecessary.

To end spacecraft operations, DS1 would be placed in a state that would remain stable and allow predictable telecommunications until the hydrazine was exhausted. The DSN requested that the downlink signal be forced off, so fault protection was modified to prevent it from turning the X-band or K_a-band exciters or amplifiers on. Files and parameters were changed to prevent buffer overflows, command loss response, or other problems that might occur after extended untended operation.

On 18 December 2001, following the last IPS test and the dumping of some final data, a command was transmitted to place the spacecraft in one of its safe states, now with the downlink

off. This last command product was the 9905th of the mission. At the expected time, the DSN lost the downlink. The DSN searched for the carrier but did not find it.¹⁷

The trajectory from launch through the end of the mission is illustrated in Figure 2. As DS1 was the first mission to rely on solar electric propulsion for reaching its destinations, designing this trajectory required the development of new techniques that may prove useful to

subsequent missions.¹⁸

During the course of the flight, the IPS accumulated 16,265 hours of operation and expended 73.4 kg of Xe for a $\Delta v = 4.3$ km/s. (More than 2000 hours of this thrusting was at impulse power, consuming less than 4 g/hour at a relatively low $I_{sp} = 2200$ s.) Following the initial unsuccessful attempts to commence and sustain thrusting,¹ the IPS promptly initiated thrusting on all 199 attempts.

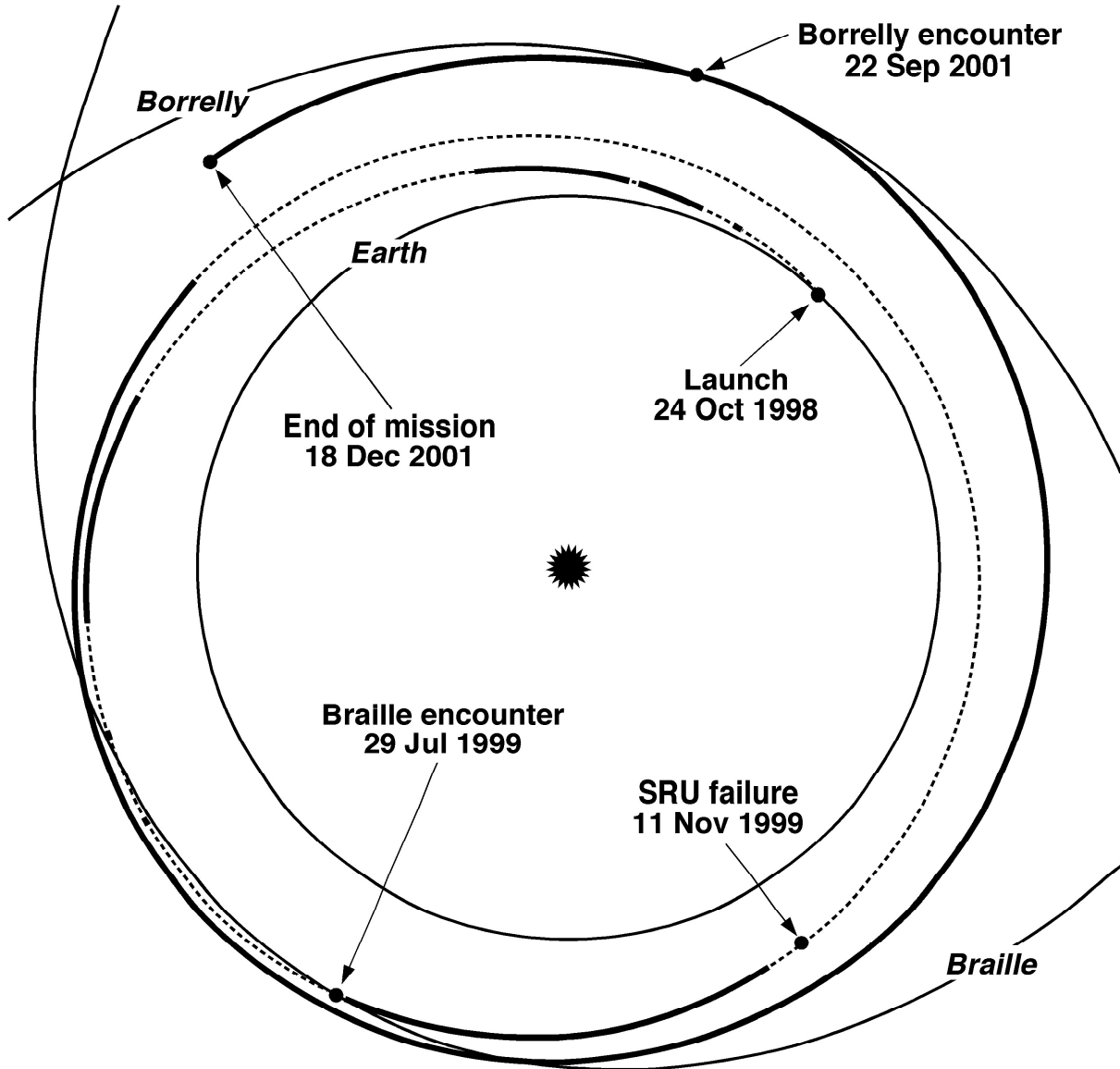


Figure 2. DS1 trajectory. The dotted portions indicate periods of coasting, and the solid portions show when the IPS was thrusting. The majority of thrusting prior to the failure of the SRU was to test the IPS and to reach the encounter targets. The thrusting after the SRU failure was to reach comet Borrelly and to conserve hydrazine. In the hyperextended mission, following the comet encounter, the thrusting was for new IPS tests and further hydrazine conservation.

RENEWED OPERATIONS ATTEMPT

Early in 2002, some new tests were conceived to enhance the understanding of turbulent weather on a K_a-band downlink. Apart from DS1, no spacecraft in flight then had the capability to provide the needed signals. These experiments would have been easy to accomplish while DS1 was operational, but by this time they were difficult to implement and quite unlikely to be successful

For operational simplicity, the tests were planned with the spacecraft remaining in its safe state, with the K_a-band antenna pointed at the Sun. This avoided the necessity of resuming 3-axis control, a difficult procedure without the SRU. The spacecraft was going to pass through opposition on 10 March 2002, so with no changes in spacecraft attitude, Earth would be in the K_a-band beam for a few weeks around that date. Although it was improbable the spacecraft would have had enough hydrazine to be functioning then, plans were formulated to try to reestablish contact.

As DS1's mission operations system had been disassembled, tests were conducted of generating commands, flowing them to the DSN, and flowing data back to JPL using alternate systems. These proved successful, so attempts to contact DS1 were made on 2 March and 6 March. Two DSN stations were used so that a failure to detect a signal from the spacecraft would not be attributable to any part of the ground system.

To cover a range of possible cases, many contact attempts were made. For example, given the accuracy of the final orbit solution, the uplink conditions comfortably accounted for the uncertainty in the spacecraft position as well as the Doppler compensation required for the command subcarrier frequency (because the receiver had a very narrow subcarrier tracking loop bandwidth). As expected, no evidence of a spacecraft signal was found.

CONCLUSION

The end of the DS1 mission marks the conclusion of a project that overcame numerous daunting obstacles and returned many important results, from development through the hyperextended mission. DS1 was inherently risky, even

before launch, as it used technologies that were chosen in part because of the high risk they presented to the first user. Indeed, if a technology did not pose some important risk, its testing in an NMP mission would not be needed. Further, as another objective of NMP, DS1 probed the limits of schedule and cost for development and cost for operations. From the beginning of the pre-phase A study to launch was 39 months. The total cost for development, launch service, and operations through the conclusion of the primary mission in September 1999 was less than \$150 M (in real-year dollars). This includes the development cost of some of the technologies in DS1's payload and the integration costs of all of them. The additional cost of the extended and hyperextended missions plus science data archiving and analysis will be less than \$10 M.

Despite its very aggressive schedule and small budget, DS1 met or exceeded all of the primary mission success criteria. The knowledge gained during development and operations will be of significant help to many future missions, as the costs and risks of using the technologies that formed its payload have been significantly reduced. The benefits accrue not only from the quantification of their performance during flight, but also from the insight derived from incorporating the new capabilities into the spacecraft, ground segment, and mission design, thus illuminating implementation issues that would not have arisen in typical technology development or conceptual mission studies. This will provide helpful information to subsequent users on how to take advantage of the new systems, which in some cases require new approaches.

Many missions now are being enhanced or enabled through the results of DS1's intensive testing of technologies in the primary and hyperextended missions. For example, Dawn will use ion propulsion after its 2006 launch to rendezvous with (4) Vesta, where it will spend about 11 months gathering visible images, infrared, gamma-ray, and neutron spectra, and altimetric, magnetic field, and gravitational field measurements. The baseline plan calls for it then to leave orbit and rendezvous with (1) Ceres, where it will make the same measurements. Such a mission would be unaffordable with chemical propulsion, and Dawn would have been too risky for NASA to undertake without

DS1's use of ion propulsion.

Deep Impact is a beneficiary not only of DS1's comet data but also of the results of developing and testing AutoNav. Deep Impact will rely on AutoNav for its targeting of the nucleus of Tempel 1. The impactor will navigate to the designated impact site, designing and executing TCMs without ground intervention, while the flyby craft will compute and track the predicted point of impact to enable the science data acquisition.

Comparisons between DS1's X-band and K_a -band for telemetry, Doppler, and ranging are allowing preparations for future missions to rely on K_a -band, and the DSN's upgrades to provide operational support of K_a -band depended upon tests with DS1. Beginning with Mars Odyssey, launched in 2001, the majority of NASA missions beyond the moon at least through 2007 use the small deep-space transponder because it was proved on DS1 to work so well. These and other informed users will encounter lower risk and cost by building upon the successful results of the DS1 project.

The successes of DS1 also are important for further technology development. The detailed performance data are being incorporated into new, even more capable systems. New developments in ion propulsion, solar concentrator arrays, autonomous systems, and microelectronics devices are building upon the results of tests conducted on DS1. Further, in some cases, the technologists had not had experience with flight projects, so the knowledge they acquired in development and in operations should prove helpful in their work on more advanced versions of their technologies. The successful operation of some of the advanced systems on DS1 also proved instrumental in making funds available for subsequent technology programs.

The science return from NMP flights is in the subsequent missions that take advantage of the technology results. These are missions that would be unaffordable without the new capabilities provided by the advanced technologies. After DS1 completed its primary mission and was no longer in NMP, it became a science mission. Reaching comet Borrelly and returning data from it were not simply continuations of the activities of the primary mission but rather rep-

resented an entirely new focus. Comet encounters present significant challenges, even for spacecraft built for that purpose, and the problems faced by DS1 were still greater. The successful recovery from the loss of the SRU, as impressive as it was, would have been much less meaningful had it not enabled the return of a wealth of scientific data. With the information from Borrelly, important advances in the understanding of comets are being made. As another benefit, dedicated comet missions will face lower risks by learning from DS1's experiences.

Because DS1 had limited resources, thoughtful decisions in the management of risk were an essential ingredient in its success throughout its life cycle. A careful but ambitious spacecraft development enabled difficult operations well beyond the duration and scope of the requirements. The level of risk that was considered acceptable varied significantly as the mission progressed through different phases. Without accepting higher risk at some times, DS1 would not have been able to overcome some of its greatest challenges. At other times, the strong emphasis on lower risk was critical to assuring success.

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