Navigation of the Deep Space 1 Spacecraft at Borrelly

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Abstract

On September 23, 2001, the Deep Space 1 spacecraft flew by the short period comet Borrelly at a distance of approximately 2200 km. The navigation challenges posed by the flyby were considerable due to the uncertainty in the knowledge of the comet's ephemeris, as well as the difficulty in determining the spacecraft's ephemeris caused by relatively large non-gravitational forces acting on the it. The challenges were met by using a combination of radio, optical, and interferometric data types to obtain a final flyby accuracy of less than 10 km. In addition, a closed-loop onboard tracking system was used to maintain lock on the comet nucleus during the flyby.

Mission Overview·

The Deep Space 1 spacecraft was launched on October 24, 1998 as the first mission in the New Millennium Program. The purpose of this program was to fly a series of spacecraft whose goal was to test advanced technologies needed for future missions. Deep Space 1 carried 12 such technologies, including an ion propulsion system, an advanced solar array, and an autonomous optical navigation system. Following the successful completion of its primary mission on July 1999 (the flyby of the asteroid Braille), the spacecraft was approved for an extended science mission to flyby the short period comets Wilson-Harrington and Borrelly. Unfortunately, the onboard star tracker, used as the primary means of maintaining the spacecraft attitude, failed on November, 1999 and for the following 7 months, the spacecraft was placed in an extended safe hold configuration. During this time, new software and techniques were developed to enable the science camera to function as a replacement for the star tracker. During this period, the thrusting needed to achieve the Wilson-Harrington rendezvous was unable to be performed and was therefore dropped from the mission plan. In June 2000, the software modifications were loaded onto the spacecraft and thrusting resumed to achieve the Borrelly flyby. Finally, in September 2001, the spacecraft flew by Borrelly at a distance of roughly 2000 km, snapping the highest resolution photographs of a comet to date.

Due to the unorthodox process of using the narrow angle science camera as a substitute star tracker, the use of ion propulsion as the primary means of propulsion, and the uncertainties in determining precise ephemeredes for comets, the challenges in navigating the flyby were substantial. This paper details the navigational techniques and procedures that were used to overcome these obstacles and achieve a successful encounter.

Spacecraft Overview

DS1 was the first interplanetary spacecraft to use solar electric propulsion as its primary means of controlling its trajectory. Its single ion thruster (referred to as the IPS) was capable of producing 90 milliNewtons of thrust continuously over many days and weeks. In addition, standard hydrazine thrusters were available for attitude control around all three spacecraft axes, and for some course corrections. Power for the spacecraft was provided by the prototype solar arrays which generate 1.2 kW of power.

The primary science instrument onboard was the Miniature Integrated Camera and Spectrometer (MICAS), which had two visible, one ultraviolet, and one infrared imaging channels. For navigation purposes, only one of the imaging channels, a standard Charge-Coupled-Device (CCD) chip with a 1024 square pixel array, was used. Each pixel had a field-of-view (FOV) of about 13 μrad for a total FOV in the CCD of 1.3 mrad, or 0.76 deg. The CCD was coupled to a telescope with a focal length of 685 mm with the boresight fixed to the spacecraft (thus, the entire spacecraft had to be slewed to point at particular region of the sky). Also, the CCD had 12 bit digitization, resulting in data numbers (DN) values for each pixel ranging between 0 (no signal) and 4095 (saturation). This CCD also doubled as the substitute star tracker after the failure of the normal star tracker. In this paper, the horizontal measurement of an object in the frame of the CCD is referred to as its sample value, while the vertical is referred to as lines.

Navigation Overview

Standard navigation data types used on DS1 included Doppler and range, which measure the line-of-sight velocity and position, respectively, of the spacecraft relative to the tracking station. DS1 also used optical data obtained from the MICAS CCD; the images taken of Borrelly during the approach phase were critical in determining the spacecraft's comet relative position. Finally, DS1 also employed an interferometric data type known as Delta Differential One-Way Range (DDOR). DDOR differences the range signal received simultaneously at two tracking stations to obtain an angular measurement of the spacecraft relative to a line connecting the two tracking stations. The tracking stations used for navigation as well as commanding and telemetry downlink were the three Deep Space Network stations located at Goldstone, California, Madrid, Spain, and Canberra, Australia.

Although DS1's autonomous navigation system became operational during its primary technology validation mission, the loss of the star tracker precluded its subsequent use since it relied on the MICAS CCD (which was taken over for use as a star tracker). Thus, for the remainder of the cruise to Borrelly, standard radiometric navigation techniques were used to determine its trajectory. After initial detection using the camera, optical data was added to the orbit determination process.

One important difference between this and other missions was the planning and execution of trajectory correction maneuvers (TCMs). With the IPS, course corrections were burns which could last up to several months long, punctuated at various intervals by periods of ballistic coasting. An additional complication was the fact that the spacecraft's attitude had to be maintained by locking onto a single bright star using the CCD. Since stars of sufficient brightness were not that common, the attitude used for the thrust profile was often not the optimal one for achieving the desired trajectory. The process of computing a viable thrust profile to keep the spacecraft on course was very complicated, but is out of the scope of this paper and will not be covered in more detail.

The approach phase of the mission began at the first sighting of Borrelly, which occurred roughly 40 days prior to encounter. At this stage, the optical data type became the dominant data type and was relied upon heavily to target the spacecraft to its flyby aimpoint. Due to large uncertainties in the comet's ephemeris, however, two DDOR data points were taken to help resolve discrepancies between ground and spacecraft based observations of Borrelly. In the end, the spacecraft was guided by referencing its position and target aimpoint to Borrelly itself rather than an inertial location. TCMs during this phase were originally planned to be accomplished using a combination of IPS and hydrazine thruster, but ended up being with the IPS alone. The final targeting TCM was performed at Encounter (E) - 12 hours.

Targeting at JPL is performed in the so-called B-plane coordinate system. The B-plane, shown in Figure 1 for the Borrelly flyby, is a plane passing through the center of the target body and perpendicular to the incoming asymptote, S, of the hyperbolic flyby trajectory. Coordinates in the plane are given in the R and T directions, with T being parallel to the Earth Mean Ecliptic plane of 2000; to complete the right-hand coordinate system, T is positive downwards. The angle theta determines the rotation of the semi-major axis of the error ellipse in the B-plane relative to the T-axis and is measured positive right-handed about S. The horizontal coordinate in the B-plane is referred to as B•T and the vertical is B•R.

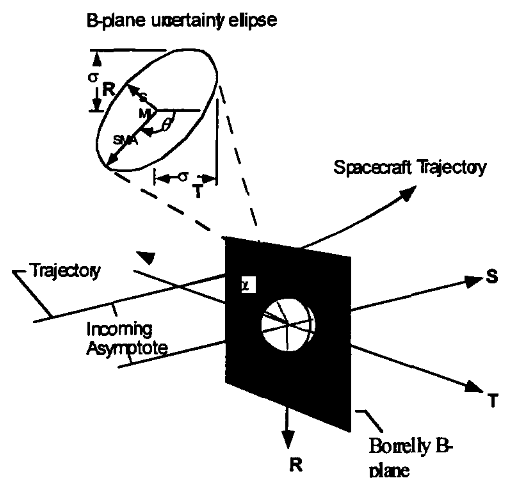

Figure 1: Borrelly B-plane

The one piece of the autonomous navigation system that remained usable was the closed-loop onboard tracking system. This system, termed RSEN (for Reduced State Encounter Navigation) enabled the spacecraft to maintain visual lock on Borrelly as it flew by. RSEN was initialized with ground -based ephemeris knowledge about 6 hours prior to encounter. Starting at E-30 minutes, RSEN shuttered images of Borrelly at a rate of about one per minute and used this information to update its estimate of the flyby trajectory. This information was passed to the onboard ACS system to point the camera in the correct location to capture Borrelly.

The following sections will describe in more detail the activities and processes used during the approach phase to navigate the Borrelly encounter.

Ground -based Comet Ephemeris Development

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

Spacecraft Observation Campaign

Starting at roughly E-40 days, an observation campaign was laid out to image Borrelly at various times during the approach. The spacing and timing of these campaigns, referred to as Spacecraft Observations of Borrelly (SOB), had to maintain a balance between obtaining enough images to use for navigation, while not unduly taxing the ground operations teams or placing the spacecraft at risk with unnecessary maneuvers. The final plan for the SOBs is listed in Table 1.

Table 1: Spacecraft Observations of Borrelly

SOB #	Date	Range to comet (km)
1	Aug. 25	40,313,000
2	Aug. 29	34,800,000
3	Sep. 7	21,750,000
4	Sep. 10	17,900,000
5	Sep. 13	13,200,000
6	Sep. 15	10,880,000
7	Sep. 16	9,120,000
8	Sep. 18	6,610,000
9	Sep. 20	3,220,000
10	Sep. 21	2,050,000
11	Sep. 22	621,000

Image Processing

Based on predictions for the brightness of Borrelly's nucleus and coma, and the known sensitivities and noise characteristics of the CCD, it was highly unlikely that Borrelly would be visible in any single frame in the initial observation sets. Thus, the signal-to-noise ratio was increased by co-adding the individual frames together to produce a composite image. The procedure was started by first determining the inertial pointing direction of the camera boresight. This was done by locating a minimum of two stars in the image and then using a high precision cross-correlation technique to compute their centroids[2]. This technique typically achieved centroiding accuracies of 0.1 to 0.3 pixels. The computed locations of the stars in the FOV, combined with their known right ascension (RA) and declination (DEC) enables a least-squares computation of the boresight pointing direction in inertial space. Then, with the latest best estimate of the spacecraft and comet ephemeredes and knowledge of the boresight pointing, the nominal sample/line location of the comet in the camera FOV can be computed. In each frame of the observation set, an nxn subframe was extracted around the nominal center location and these were added together to form the composite. The subframe size n was chosen such that it encompassed a region larger than the expected errors in the comet's ephemeris errors; the size varied from 20-40 pixels. This co-addition technique was used up to SOB5, after which the comet was bright enough to centroid in individual frames.

Orbit Determination Strategy

Determining the heliocentric location of the comet was a difficult process requiring careful combination of ground-based and spacecraft observations. However, because the planning of targeting maneuvers was very time critical, waiting for results of this analysis was not a practical way to conduct the encounter. Fortunately, the optical data type offered a means to determine the spacecraft's trajectory independent of the inertial heliocentric orbit of the comet. Since the optical data provided a target relative measurement , it could be used to effectively tie the spacecraft's location to Borrelly; all maneuvers were then computed in this relative coordinate frame. The orbit determination (OD) procedure used was to first obtain the best fit trajectory based on the radio data alone. Then, starting from an initial position and velocity from this estimate, the optical data was used to shift just the spacecraft's position (the velocity was held fixed). Thus, the comet-relative asymptote of the trajectory would not be changed, but its location was translated to where the optical data placed it relative to the comet. Table 2 chronologically lists the various OD solutions, each labeled by the month and day of the last radio data used in the fit, along with the last optical observation used (starting with SOB2 since SOB1 was not accurate enough to use in the fit).

Maneuver Strategy

Maneuver planning and implementation was considerably different on DS1 than on spacecraft with standard chemical propulsion systems. Because the IPS is continuously thrusting over long periods of time, a substantial portion of the trajectory is devoted to performing a maneuver, as compared to chemical maneuvers which occur nearly instantaneously. In addition, IPS thrusting could be separated into two categories - the first is a "mission burn", whereby the thrust is needed to impart enough energy to the orbit to achieve a rendezvous, and the second is a trajectory correction maneuver (TCM), where the course is fine tuned to achieve a specific flyby target. By the time of the approach operations, the former had already been accomplished; only TCMs were needed for hitting the correct flyby aimpoint. For spacecraft safety reasons, the aimpoint distance was chosen to be at 2000 km since it was assumed that at this range, the chance of particle impacts was not severe. For spacecraft geometry reasons, it was to be along the sunline; the combination resulted in the aimpoint chosen to be at a B•R of 2000 km, and a B•T of 0 km.

Two factors were primarily responsible for complicating maneuver planning. The first was the fact that DS1 was continually thrusting at a low level regardless of the need for mission burns or TCMs. It was found early on in the mission that gimbals on the IPS engine allowed enough thrust vectoring to maintain the spacecraft attitude without the use of the hydrazine-fueled ACS thrusters. Thus, in order to preserve scarce hydrazine for large attitude adjustments, general attitude control was done using the IPS. Although this strategy was critical to mission success, it made the maneuver planning process very difficult. In particular, since maneuvers are planned by first propagating the spacecraft's trajectory forward to the target conditions, a good prediction of the non-gravitational forces acting on the spacecraft between the current time and time of encounter is necessary. Since it was difficult to predict exactly the future attitude maintainence thrust parameters with the IPS, the accuracy of the propagated trajectory was not always very good.

The second complicating factor was caused by the loss of the star tracker. Because bright stars were needed by the camera to lock onto, TCMs could not be performed in completely arbitrary directions. Thus, the IPS thrust vector that would be ideal for reaching the target was not often met. Instead, a suboptimal direction dictated by the nearest bright star was used.

Table 2: Approach OD Solutions

OD Solution	Last Used Borrelly Observation
0907	SOB3
0910	SOB4
0912	SOB4
0913	SOB5
0915	SOB6
0916	SOB7
0918	SOB8
0920	SOB9
0921	SOB10
0922	SOB11

The maneuver strategy that was used during the approach phase turned out to be unusually complicated, partly due to the above two factors, but also due to other constraints placed on the spacecraft attitude. In particular, it was desired to place the spacecraft in an orientation such that the high gain antenna was always pointed towards the Earth to maintain a constant communication link. Because of the peculiar geometry of the approach, the line-of-sight direction from Earth to DS1 was almost completely in the B-plane, and at a roughly 45 deg angle. With the spacecraft high gain in this orientation, any IPS thrust would move the spacecraft in the B-plane roughly along this line, pushing the aimpoint negatively in B•R, positive in B•T. Thus, as long as the spacecraft's trajectory placed the flyby in the bottom left quadrant of the B-plane, it could be corrected by simply throttling up on the IPS without the need to change the attitude. On the other hand, if accumulated OD and IPS execution errors overshot the aimpoint (above and to the right in the B-plane), the spacecraft would have to be rotated 180 deg. to correct the error, which was highly undesirable from an operations viewpoint. For this reason, the targeting was always performed to bias the aimpoint to the lower left quadrant; as the spacecraft got closer to Borrelly and the OD improved, the aimpoint would be moved closer to the desired location along the line, but never overshooting it. In all, seven TCMs were planned, but only three were actually executed. Table 3 lists the dates of the maneuvers which were actually executed.

Table 3: Table 3: Executed IPS Trajectory Correction Maneuvers

TCM ID	Date
2.1	Sep. 17
4.1	Sep. 21
4.2	Sep. 22

Approach Phase

The approach phase of the mission began with the first spacecraft observation set for Borrelly, SOB1. Using the co-addition technique, 8 frames from SOB1were processed. The result showed a faint signal, barely above the background, which appeared very near the predicted location of Borrelly. The result, though, was not conclusive. Four days later, 12 co-added frames from SOB2 showed a distinct signal about 180 DNs above the background noise. The centroid of this signal (determined relative to the centroids of two co-added stars from the same frames) was roughly 1.8 pixels away from its predicted location, indicating an ephemeris mismatch of about 1500 km, much larger than the predicted value based on ground-based comet observations.

By the time of SOB3, the comet had brightened enough that a composite of 4 frames provided enough signal-to-noise to enable good centroiding. Thus, two sets of composites were produced from the eight usable frames in this set. Due to the closer range to the comet, the observed minus computed location of Borrelly in the FOV had increased to roughly 5 pixels, consistent with the 1500 km error seen in SOB3.

At this point, the cause of the large discrepancy was unknown and could have been due to a gross error in the estimate of either the comet's or the spacecraft's trajectory. Due to the fact that the ground observations of Borrelly were very consistent and the addition of each day's observations showed only minor changes, the spacecraft was suspected. In order to resolve this, a DDOR campaign was scheduled. It was hoped that the addition of this data type might uncover a subtle error in the Doppler/range based estimates of the spacecraft's trajectory.

In the meantime, the OD and maneuver planning was still implemented using the comet-relative strategy described above. Figure 2 shows the OD results in the B-plane for all the solutions up to September 18 (the ellipses are the formal, 1 sigma uncertainties in the solutions). The shift between solutions 0907 and 0910, which both used observations up to SOB3, was caused by various mismodellings of the attitude control IPS thrusting which occurred in the days between the solutions. This level of B-plane drift is indicative of the general OD accuracy achievable with the difficulty in predicting IPS thrusting events. Changes in IPS thrust on/off times, thrust level knowledge and attitude knowledge inaccuracies are all systematic effects which were difficult to predict and contributed to drifts in the B-plane.

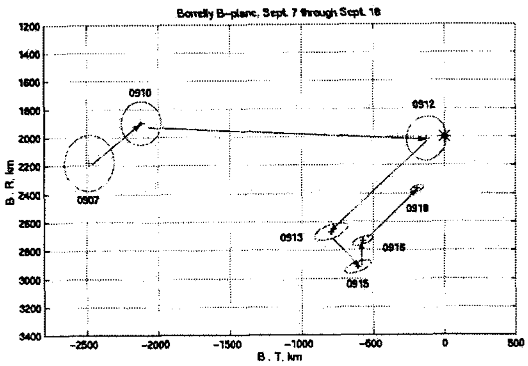

Figure 2: B-plane Solutions Prior to Sept. 18, 2001

The shift between solution 0910 and 0912, was caused by a larger effect. Originally, TCM 1.1 was planned to move the flyby location to a B•R of 2500 km and B•T of -750 km, which lies roughly along the preferred thrust line direction. Unfortunately, due to the September 11 events, work at JPL was not possible that day and the commands were not sent. Furthermore, the spacecraft lost lock on its star and therefore was unable to maintain attitude, with the result that the spacecraft thrust vector wandered slowly across the sky. This combination shifted the flyby to a location that was coincidently very near the desired flyby location.

This result was not desired, however, due to the concern that the flyby point might wander above the target, requiring the need for large attitude changes to correct. Fortunately, it was noted that reducing the thrust level at the current orientation would move the flyby point towards the lower left in the B-plane, where it was originally intended to be. Solution 0913 shows the result of this implementation.

With the addition of SOB6, the SSD group delivered an updated ephemeris which included several apparitions worth of ground data as well as spacecraft data through SOB6. Solution 0916 was the first to use the new ephemeris, and shows the flyby point to be relatively stable from the 0913 solution. At this time, the OD solutions were accurate enough, and it was getting near enough to the encounter, that a planned TCM, 2.2, was executed to adjust the trajectory to a location nearer to the target. Solution 0918 shows the result after the execution of TCM 2.2.

One disconcerting piece of data was seen in the composite frames of SOB4 and 5. The image of the comet showed several distinct brightness peaks, separated by several hundred km, with the orientation roughly 45 deg away from the sun. The phenomenon was not an effect of the image processing as it appeared in two successive frames with the angular separation of the peaks increasing as would be expected. There was some debate as to whether the secondary peaks was actually the nucleus, and more importantly, whether the comet had fragmented, posing a danger to the spacecraft. Ultimately, it was decided not to change the flyby aimpoint.

On September 14 2001, two DDOR data were taken and folded into the radio solutions. Comparisons of radio based estimates of the spacecraft orbit with and without the DDORs, and trying different combinations of filter assumptions (eg, varying the relative weights of Doppler, range and DDOR, using arcs of differing lengths) showed remarkable consistency. The variation in the B-plane was only on the order of 25-30 km, indicating that the spacecraft's trajectory was probably correct.

With this piece of data, the focus shifted to determining why the ground-based comet ephemeris did not agree with the spacecraft observations. Eventually, it was found that if the center-of-brightness computed from the ground observations used the brightest pixel, rather than the standard Gaussian fit to the brightness profile, the results agreed considerably better with the spacecraft. Furthermore, observations taken at Palomar Observatory and processed using the bright pixel method, now were in fairly good agreement with the spacecraft. Nevertheless, discrepancies still existed which were eventually attributed to the lack of an accurate model for outgassing used in the comet orbit estimates. Recently, it was found that an acceleration model which had jets at the assumed comet pole, and varying with the angle between the pole and the sun, resulted in the ability to fit longer data arcs from the ground when combined with spacecraft data[3].

Figure 3 shows the evolution of the solutions following TCM 2.2 and through the encounter. During this period, the spacecraft had switched to using the RCS thrusters for attitude maintenance. Since these thrusters were not balanced, they imparted a net velocity change to the spacecraft. This is reflected in the roughly 200 km shift between solutions 0918 and 0920. Also, following SOB8, the SSD group delivered the final Borrelly ephemeris to the project. An additional observation set, SOB10, showed the trajectory to be fairly stable in the short span of time between solutions 0920 and 0921.

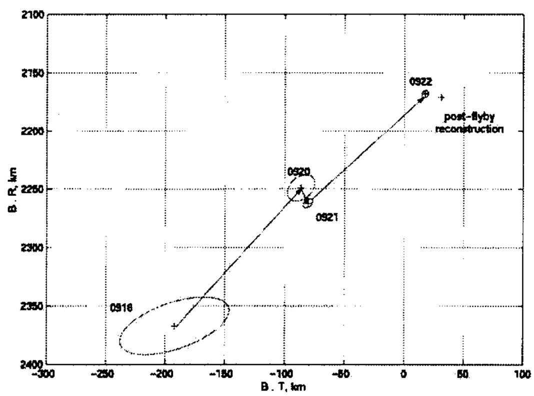

Figure 3: Borrelly B-plane Solutions after Sept. 18, 2001

At this time, less than 24 hours remained until the encounter. TCMs 4.1 and 4.2 were executed to close the remaining gap between the current flyby point and the target, although the roughly 150 km bias in B•R remained. Solution 0922, computed 10 hours before encounter using all the observations, shows a slight drift in the positive B•T direction, but not significant enough to cause concern. In any case, no further maneuvers were planned, so remaining targeting errors at this time could not be corrected. Solution 0922 was the final one performed on the ground prior to the flyby; this was uplinked to the spacecraft about 8 hours before the encounter to initialize the RSEN autotracking system.

Encounter Target Tracking

Unlike encounters with planets, the largest error source when targeting a flyby of a small body is the knowledge of the body's ephemeris. Since the gravitational bending of the spacecraft's path is usually negligible, optical images of the target are the only means of precise targeting. However, due to a combination of the high speed of the flyby, light times on the order of tens of minutes, narrow camera FOVs, and the need to load an observation sequence well before the encounter, even the optical data does not provide enough accuracy to know exactly where the target will be in the camera FOV near closest approach. Therefore, a sequence is loaded which performs a mosaic; that is, images are taken which cover the 3-sigma navigation uncertainties projected into the camera focal plane. Thus, in order to guarantee an image of the object, multiple frames are returned with empty sky. This is how previous flybys of small bodies, such as Galileo's encounters with Gaspra and Ida, and NEAR's encounter with the asteroid Mathilde, were performed.

With an autonomous closed-loop system onboard, however, the images taken in the tens of minutes prior to encounter can be used to update the spacecraft's target relative position. Such a system was developed as part of DS1's autonomous navigation system. The target tracking portion was coined RSEN, for Reduced State Encounter Navigation (RSEN). RSEN uses target images to update the spacecraft's position relative to the comet. It performs image processing to locate an approximate center-of-brightness of the target, and, after a number of images have been processed, updates the spacecraft state using a least-squares filter. In order to improve speed, the dynamics are reduced to straight line motion relative to the target body; since the gravity effects are minimal, this does not lead to loss of accuracy. In addition, since DS1 relied on gyroscopes to maintain inertial attitude during the encounter, the gyroscope drifts and biases also had to be estimated in the filter. A more complete description of the RSEN system can be found elsewhere[4].

At approximately 8 hours before encounter, the final ground-based navigation solution, 0922, using all available observations, was uploaded to initialize RSEN. Although the formal error ellipse of this solution in the B-plane was only several km, RSEN was initialized with a 20x20 km ellipse to account for systematic errors which may have crept into the solution. At about E-1.5 hours, RSEN snapped its first set of images. These images were processed and the results sent to the ground, but were not actually used. At about E-30 minutes, RSEN started its encounter imaging sequence, shuttering images about every 30 seconds. As each image was processed, its computed comet center location was stored, but the spacecraft state was not updated at this stage. Finally, at slightly before E-10 minutes, all the accumulated observations were used to estimate a new spacecraft position relative to the comet. The updated ephemeris was provided to the onboard ACS system so that the new information would be used to point the camera. At this point, the solution was updated with every image to keep track of the comet. RSEN was terminated at about E - 2 min., 13 sec.. Figure 4 shows the succession of images at several times during the final approach. Note the comet drifting slowly out of the FOV as the ephemeris error becomes larger than the FOV; with the state update at the E-10 minute point, the comet returns to near the center of the FOV.

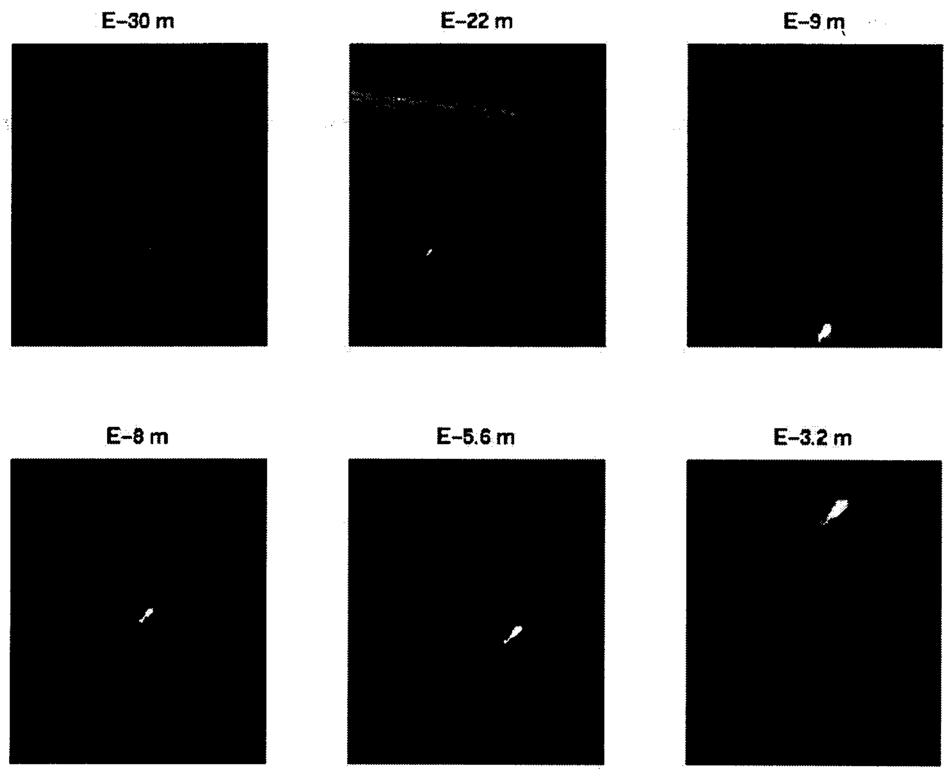

Figure 4: Sequence of RSEN Images During Final Approach

Conclusion

The successful flyby of Borrelly provided the science community with the highest resolution images of a comet nucleus to date, adding considerably to the body of knowledge of these mysterious solar system bodies. Figure 5 shows the final image snapped by the spacecraft about two minutes prior to closest approach, taken at a range of 3514 km, with a surface resolution on the comet of 46 m/pixel. The navigation challenges presented by this encounter were considerable, and was met by the introduction of several first-of-a-kind technologies. These included the use of an ion propulsion system for course changes, and an autonomous nucleus tracking system. It is hoped that DS1 has paved the way for future missions to use these technologies with confidence, ensuring even greater science returns.

Acknowledgements

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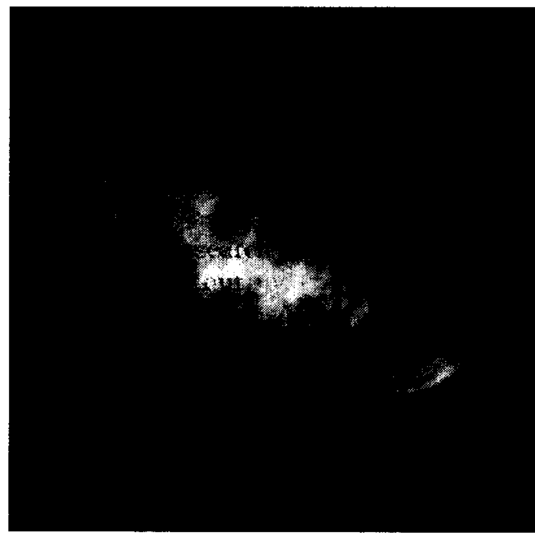

Figure 5: Best Resolution Image of Borrelly