Navigation of the Deep Space 1 Spacecraft at Borrelly

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The Deep Space 1 spacecraft was launched on October 24, 1999 as the first mission of the New Millennium program. Its primary mission was to test advanced technologies in space and validate them for use on future missions. Examples of the technologies demonstrated include the ion propulsion system, a low mass and power integrated camera and spectrometer (MICAS), and onboard autonomous navigation. The primary mission ended on July 29, 1999 when it flew by the comet Braille. Following this, an extended science mission to encounter two additional targets was approved. Due to the loss of the onboard star tracker in November 1999, however, the first of these targets was bypassed in order to reconfigure the spacecraft to use the MICAS camera as a substitute for the star tracker. On September 23, 2001, the Deep Space 1 spacecraft flew by the short period comet Borrelly at a distance of approximately 2200 km. The flyby was an unqualified success, with the spacecraft returning images of the comet nucleus at a resolution of 40 m per pixel, the highest taken of a comet to date.

Due in part to the loss of the star tracker, but also due to the general lack of knowledge of the cometary nucleus and environment, navigation of the spacecraft to its desired flyby location posed many challenges. In particular, the location of the nucleus in the coma during the tens of days prior to encounter was unknown. Also, the dynamic modeling of the spacecraft's trajectory was complicated by the extensive use of the ion propulsion system, both for trajectory correction maneuvers and attitude control. Thus, in addition to the standard Doppler and range data, an interferometric data type known as Delta Differential One-way Range (DDOR), and optical images of the comet using MICAS were employed as data types for navigation. The purpose of this paper is to describe in detail the navigation challenges and how these data types were used to determine the spacecraft's path during the approach and flyby of Borrelly.

The Borrelly approach phase of the mission started at 40 days prior to encounter when the first set of optical navigation (opnav) images were taken. At this time, the comet was not visible in any single image; however, by co-adding images together, the signal to noise level was brought up to a level where a faint detection could be seen. Subsequent observations taken at 23 and 16 days before encounter confirmed the detection. This data showed that the spacecraft's estimate of Borrelly's location differed from that predicted by ground telescopic observations by roughly 1500 km. Since this was a significant fraction of the planned 2000 km flyby distance, the resolution of this discrepancy was a high priority. This involved ensuring that the spacecraft's position estimate wasn't grossly in error as well as closer examination of the ground-based results. For the former, two DDOR points were taken which confirmed the spacecraft's location to within 50 km of the radio-based solution. For the latter, intensive analysis of the ground data revealed that the type of centroiding on the image of the comet performed by the ground observers influenced the estimated location by roughly the observed discrepancy. Thus, reprocessing of the ground observations was performed which removed much of the discrepancy.

While this effort was going on, the spacecraft was being guided to its flyby target by effectively tying the spacecraft to Borrelly's ephemeris. The procedure used was to first obtain a solution to the complete spacecraft state (position, velocity, and other dynamic parameters such as solar radiation pressure, non-gravitational accelerations) using Doppler and range only. The optical data would then be used to obtain a correction to just the position components of the best fit radiometric solution. This methodology resulted in the spacecraft's true heliocentric state being incorrect, but its state relative to Borrelly being accurate. Thus, the problems with Borrelly's absolute heliocentric position do not affect targeting to a relative flyby aimpoint. The approach asymptote is fixed by the radio data and the optical data simply translates the asymptote to match Borrelly's position.

Using the above methodology, the spacecraft was maneuvered to achieve the desired flyby using the ion thrusters. At approximately 18 hours prior to encounter, the final targeting maneuver was performed which placed the flyby at roughly 2200 km from the nucleus on the sunward side of the comet. At 11 hours prior to encounter, the final opnav images were taken which fine tuned the knowledge of the spacecraft's encounter conditions to roughly 20 km in the crosstrack direction. This information was used to initialize the onboard autonomous tracking system, whose purpose was to keep the nucleus centered in the camera field-of-view during closest approach. The autonomous tracking was initiated at 30 minutes prior to encounter. Post-flyby results indicated that the system maintained lock on the nucleus to its planned time of about 2 minutes prior to closest approach. Figure 1 shows the best resolution image obtained during the flyby.

Figure 1: Best resolution image of comet Borrelly taken by the Deep Space 1 spacecraft.