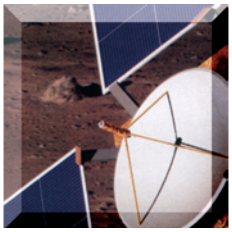

Technical Challenges and Results for Navigation of NEAR Shoemaker

Bobby G. Williams

When the NEAR Shoemaker spacecraft began its orbit about the asteroid 433 Eros on 14 February 2000, it marked the beginning of many firsts for deep space navigation. Among these were the design and estimation techniques that were necessary to plan and execute navigation of the first spacecraft to orbit and land on an irregularly shaped small body. This article describes the navigation strategy and results for the rendezvous, orbit, and landing phases of the NEAR mission. Included are descriptions of the new techniques developed to deal with navigation challenges encountered during rendezvous and the year-long orbit phase. The orbit phase included circular orbits down to a 35-km radius and elliptical orbits that targeted overflights to within 2.7 km above the surface. The orbit phase ended on 12 February 2001, when NEAR Shoemaker was guided to a soft landing on the surface of Eros.

INTRODUCTION

The Near Earth Asteroid Rendezvous (NEAR) mission was the first to be launched in NASA's Discovery Program. APL was responsible for designing and building the NEAR Shoemaker spacecraft and for managing and operating the mission.[1,2] Navigation (i.e., orbit determination and trajectory correction maneuver design) and design of orbits about the near-Earth asteroid 433 Eros were the responsibility of the Jet Propulsion Laboratory (JPL), California Institute of Technology. The goals of this Discovery mission were to determine the physical and geological properties of Eros and to infer its elemental and mineralogical composition by placing the NEAR Shoemaker spacecraft and its science instruments into close orbit about the asteroid.

This article presents some of the unique features of trajectory design and navigation related to orbiting an asteroid and to designing a robust navigation system for the NEAR mission. The problem of navigating the spacecraft about Eros was made difficult by the asteroid's irregular shape and by our relative uncertainty, before arrival, about its physical properties, which could perturb the spacecraft's orbit. To help solve these problems, the navigation system for NEAR used NASA's Deep Space Network (DSN) radiometric Doppler and range tracking in addition to the new navigation technologies of optical landmark tracking and laser ranging from the spacecraft to the asteroid surface. Some of the most important orbit design constraints and requirements are discussed here as they relate to the navigation strategy. A complete overview of the rendezvous, orbit phase, and landing for NEAR is presented in Ref. 3, and detailed descriptions of the design and navigation of the orbit phase and landing are presented in Refs. 4 and 5, respectively.

Science Requirements and Goals

Prior to the NEAR Shoemaker rendezvous with Eros, the navigation and science strategy for the orbit phase design was examined in some detail.[6] Each instrument's science team had specific goals that drove the orbit design. For instance, the NEAR Multi-Spectral Imager (MSI) team had requirements to image the surface, both globally and in detail, under various lighting geometries during the orbit phase. This coincided with the navigation requirement to build and maintain a global optical landmark database based on multiple images of landmark craters taken at different times from different viewing geometries.

Requirements for the X-Ray/Gamma-Ray Spectrometer (XGRS) observations were to bring the instrument close to the surface (as low as 35×35 km orbits) for extended periods of time while also viewing the surface at an oblique solar angle of incidence. These requirements were met by progressively lowering the orbit radius as navigation models were improved so that the viewing geometry could be reliably predicted nearly 6 weeks in advance. This allowed advance planning and checkout of the instrument pointing sequence. Because of the pointing constraints imposed by the solar arrays and science instruments being fixed to the spacecraft body, the orbit plane was constrained to lie within 20° to 30° of the Eros day/night terminator, and this provided the necessary viewing geometry for the XGRS.

The NEAR Laser Rangefinder (NLR) had a requirement to cover the complete asteroid surface with laser range returns at altitudes lower than 100 km. This was accomplished by designing polar orbits with both 50- and 35-km radii. These low orbits also satisfied the radio science and navigation requirements for determining the gravity field of Eros. The trajectory design for the rendezvous and orbit phases was further influenced by the NEAR Infrared Spectrograph (NIS) instrument's goal to image Eros at nearly zero phase, i.e., with the Sun directly behind the line of sight of the NIS to the illuminated surface of Eros.

Rendezvous with Asteroid 433 Eros

The original rendezvous with 433 Eros was planned as a sequence of maneuvers scheduled to begin on 20 December 1998. However, the initial maneuver was terminated prematurely owing to a spacecraft anomaly. As a result, the spacecraft performed a high-speed flyby within 3900 km of Eros on 23 December 1998. Control of the spacecraft was recovered just prior to this flyby, and images were obtained and processed along with the DSN Doppler and range tracking data to provide initial estimates for some of the physical parameters of Eros.[7] After the aborted maneuver and the flyby, the mission design team at APL designed a large maneuver ($\Delta V \cong 932$ m/s), executed on 3 January 1999, to target a new rendezvous with Eros nearly a year later on 14 February 2000.[8] Although this new trajectory took about a year to return to Eros, it had the advantage of a much slower approach speed of about 20 m/s.

In the months before February 2000, maneuvers were determined to target the Eros orbit insertion maneuver (OIM) at about 300 km from the center of the asteroid on 14 February 2000. On that date, the orientation of the spin axis of Eros resulted in the north pole region being sunlit and the south pole region being in darkness. *A priori* knowledge of spin axis orientation (good to about 5°) placed the Sun directly over Eros' equator in June 2000, so the rendezvous and early orbit were designed to accommodate science observations of the sunlit northern polar region. This was the only opportunity to image the northern region during the year-long orbital phase. The lighting conditions can be inferred from Fig. 1, which shows the subsolar latitude during the orbit phase. Since Eros' pole lies nearly in its orbit plane, the seasons of dark and light at either pole persist for several months. The new rendezvous was designed so that the first zero-phase flyover for the NIS instrument occurred for the north polar region just before the OIM.[6] A second zero-phase flyover of the south polar region was planned for 14 October 2000, but it was later canceled owing to failure of the NIS instrument in May 2000.

Prior to the OIM, simulations helped determine the range of initial radius of periapsis and apoapsis due to navigation errors. To illustrate the effect for one of these errors, the variation of initial orbit radius for a range of OIM pointing errors is shown in Fig. 2. For

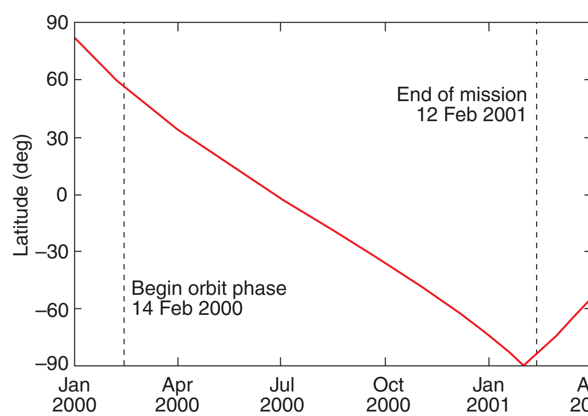

Figure 1. Latitude of the Sun on Eros during the orbit phase. Eros pole (right ascension, declination) = 11.37° and 17.23°, respectively.

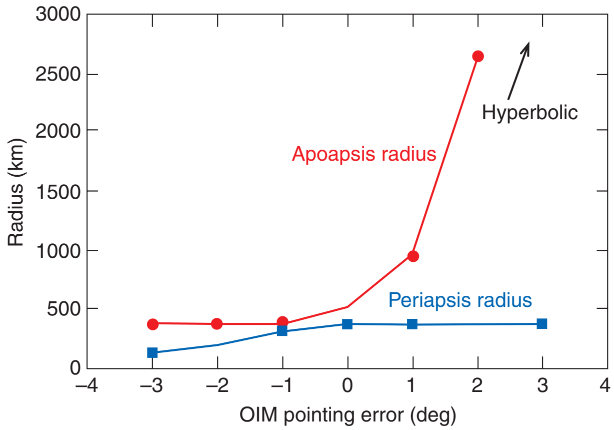

Figure 2. Initial variation of apoapsis and periapsis radii after orbit insertion due to OIM.

pointing errors of ±2° along the line to the center of Eros (the worst-case direction), the initial orbit remained bounded with a minimum periapsis radius of 186 km. For pointing errors of +3° and larger away from Eros, the post-OIM trajectory became hyperbolic. Considering only maneuver magnitude errors of up to ±4%, the resulting initial orbit remained bounded with a minimum periapsis radius of 270 km and maximum apoapsis radius of 741 km. Considering only downtrack prediction errors of up to ±100 km, the orbit inclination change was less than the required 30°. Note that the expected range of errors was much less than the values used in these simulations, since execution errors experienced for this type of maneuver were generally less than 1% in magnitude and less than 1° in pointing. Finally, for variations due to uncertainty in Eros' mass, the post-OIM orbit was perturbed for mass errors of up to ±25%. For all these cases, the orbit remained bounded with a minimum periapsis radius of 310 km and maximum apoapsis radius of 1200 km. After a series of design updates, the post-OIM orbit was targeted 2 days before the insertion on 14 February 2000 to a nominal 327 × 452 km; the orbit achieved was 321 × 366 km because the mass of Eros was 9% larger than expected.

ORBIT DESIGN

The trajectory design of the orbit phase about Eros departed from that used for previous planetary orbiter missions. For planetary missions, a precise spacecraft ephemeris is designed well in advance of arrival and insertion into orbit. This is possible because the *a priori* knowledge of the planet's mass and size is good enough to predict orbit behavior. For orbits about small bodies, however, the relatively low gravitational attraction means that the orbital velocity is also low. For NEAR Shoemaker the typical orbital velocity in a 50 × 50 km orbit about Eros was about 3 m/s. Small perturbations to orbit velocity could thus lead to either escape or impact with the surface. Also, since the irregular shape of Eros resulted in a nonuniform gravity field, there were concerns about stability for the low orbits. Orbit behavior about Eros is analyzed in Ref. 9. The stability analysis in Ref. 9 found that low-altitude (with semi-major axis less than about 50–70 km), direct orbits about Eros are generally unstable. A direct orbit is one in which the orbit angular momentum vector points in the same hemisphere as the Eros angular momentum vector; i.e., the orbit velocity is in the same general direction as the surface velocity of the rotating body. Using the right-handed convention definition for the Eros north rotation pole, direct orbits can also be identified as orbits having inclination i such that $0 \leq i < \pi/2$ relative to Eros' north pole.

The orbit phase lasted from the insertion burn on 14 February 2000 to the landing on 12 February 2001. A summary of the maneuver times and the resulting orbit geometry is presented in Table 1. In the table, the post-maneuver orbit size and inclination to Eros' true equator are indicated beginning on the day of year of the maneuver. The initial orbit inclination was chosen to reduce the number of burns needed (to save fuel) and to expedite the transition to lower orbits (before the Sun set in the northern hemisphere). The orbit radius for these initial direct orbits was large enough to avoid excessive instability, and by the time the lower orbits were reached in April, the orbit inclination had been made polar so that the orbits were stable (see Ref. 9). Note that targeting details resulted in orbits slightly different from the idealized circular orbits; i.e., the first "50 × 50 km" orbits established on 30 April 2000 were actually closer to 49 × 52 km. Also indicated in Table 1 is the approximate time spent in each orbit. The 30-day period in the large 203 × 206 km orbit was used for global mapping and for initial tuning of navigation models for Eros. The navigation strategy that allowed orbit and physical parameter estimates to stabilize at a higher altitude before proceeding to the next lower orbit radius is evident in the early part of the table.

Figure 3 shows the NEAR trajectory for the entire orbit phase projected into the "Sun plane-of-sky" (SPOS) coordinate system. The SPOS is the plane normal to the Sun–Eros line that passes through the center of mass of Eros. The "x" axis in the SPOS coordinate system is defined by the line of intersection of the Earth's mean equator of 2000 with the SPOS, and is positive in the direction of decreasing right ascension. The "z" axis is on the Sun–Eros line and is positive in the direction from Sun to Eros. The "y" axis completes a right-handed, orthogonal Cartesian coordinate system centered at Eros. Because spacecraft pointing was constrained because of the fixed-mounted instruments and solar arrays, and because the solar arrays had to remain illuminated at less than a 30° incidence angle, all orbit planes were designed to lie within 30° of the SPOS. The

Table 1. Summary of Eros orbit phase (approximate total $\Delta V = 29.8$ m/s).

Date	Maneuver	Day of year	Orbit (km × km)	Period (days)	Inclination (deg) ATE[a]	Approx. length (days)	ΔV (m/s)
14 Feb 2000	OIM[b]	45	321 × 366	21.8	35	10	10.00
24 Feb 2000	OCM-1[c]	55	204 × 365	16.5	34	8	0.13
3 Mar 2000	OCM-2	63	203 × 206	10.1	37	30	0.22
2 Apr 2000	OCM-3	93	100 × 209	6.7	55	9	0.50
11 Apr 2000	OCM-4	102	99 × 101	3.5	59	11	0.37
22 Apr 2000	OCM-5	113	50 × 101	2.2	64	8	0.45
30 Apr 2000	OCM-6	121	49 × 52	1.2	90	68	1.92
7 Jul 2000	OCM-7	189	35 × 51	1.0	90	7	0.32
14 Jul 2000	OCM-8	196	35 × 39	0.8	90	10	0.24
24 Jul 2000	OCM-9	206	36 × 56	1.1	90	7	0.34
31 Jul 2000	OCM-10	213	49 × 52	1.2	90	8	0.50
8 Aug 2000	OCM-11	221	50 × 52	1.2	105	18	1.01
26 Aug 2000	OCM-12	239	49 × 102	2.3	113	10	1.40
5 Sep 2000	OCM-13	249	100 × 103	3.5	115	38	0.96
13 Oct 2000	OCM-14	287	50 × 98	2.2	130	7	1.31
20 Oct 2000	OCM-15	294	50 × 52	1.2	133	5	0.58
25 Oct 2000	OCM-16	299	19 × 51	0.7	133	0.8	0.76
26 Oct 2000	OCM-17	300	64 × 203	5.4	145	8	1.66
3 Nov 2000	OCM-18	308	194 × 196	9.4	147	34	0.54
7 Dec 2000	OCM-19	342	34 × 193	4.2	179	6	0.96
13 Dec 2000	OCM-20	348	34 × 38	0.8	179	43	1.23
24 Jan 2001	OCM-21	24	22 × 35	0.6	179	4	0.54
28 Jan 2001	OCM-22	28	19 × 37	0.6	179	0.7	0.56
29 Jan 2001	OCM-23	28	35 × 36	0.8	179	5	0.68
2 Feb 2001	OCM-24	33	36 × 36	0.8	179	4	0.02
6 Feb 2001	OCM-25	37	36 × 36	0.8	179	6	0.01
12 Feb 2001	De-orbit	43	—	—	135	—	2.54

[a]ATE = asteroid true equator.
[b]OIM = orbit insertion maneuver.
[c]OCM = orbit correction maneuver.

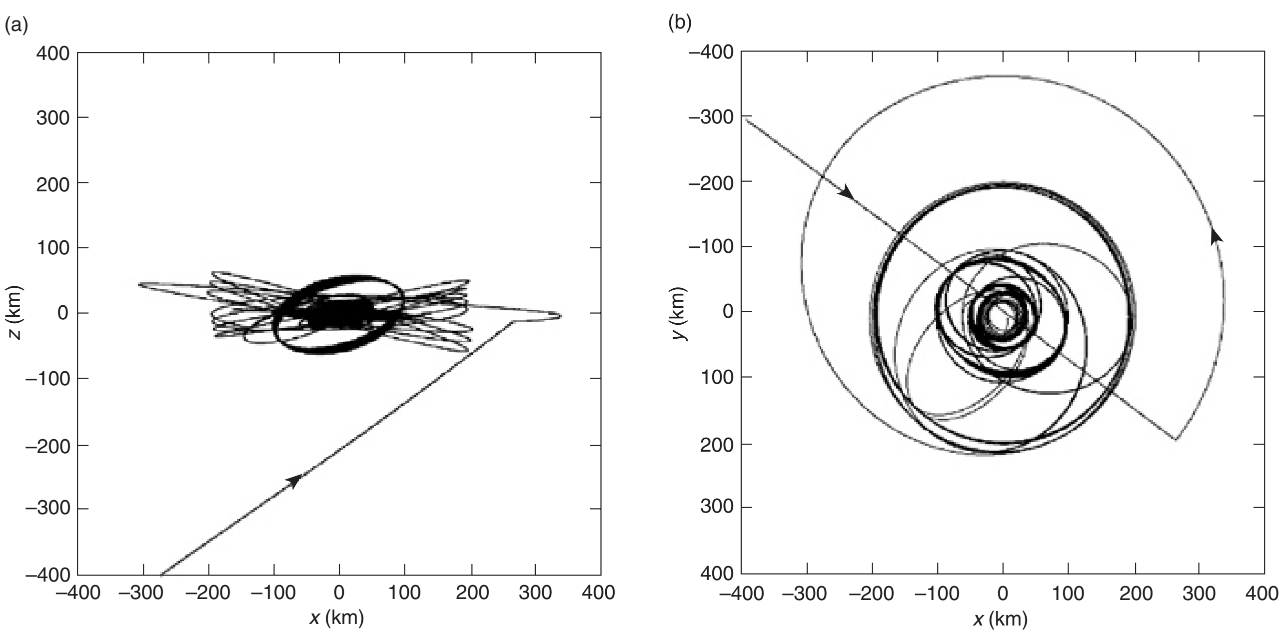

Figure 3. Approach (diagonal line) and orbit phase of NEAR covering 14 February 2000 to 12 February 2001 shown (a) in a view orthogonal to the Sun–Eros line and (b) in the plane normal to the Sun–Eros line (the Sun plane-of-sky). The origin is at the center of mass of the asteroid 433 Eros.

top view in Fig. 3a, looking normal to the Sun–Eros line along the y axis, illustrates the 30° orbit inclination constraint by showing how all orbits align within 30° of the $z = 0$ line. The end-of-mission descent to landing is shown to scale as the crooked line near the origin in the view from the Sun shown in Fig. 3b.

The orbit radius and inclination relative to the Eros equator were varied throughout the orbit phase to accommodate various science instrument observations at low altitude. Specifically, NEAR spent about 76 days in a 50 × 50 km polar orbit, about 10 days in a 35 × 35 km polar orbit, and about 58 days in a 35 × 35 km equatorial (retrograde) orbit. Mission design avoided direct orbits (inclination < 90°) at these lower altitudes owing to their general instability. The elongated shape of Eros, with a maximum radius of less than 18 km, resulted in frequent passes at altitudes of less than 17 km in the 35 × 35 km orbits. There were also several transition orbits of up to 200 × 200 km where global observations were obtained.

Improving Physical Models

The placement of optical navigation pictures and orbit correction maneuvers (OCMs) was iterated among the mission design, science, navigation, and spacecraft engineering teams to operate within constraints throughout the orbit phase. The overall shape and size of Eros had to be determined early during the orbit phase to enable the close-in orbits desired for the MSI, NLR, and XGRS instruments. By using both landmark locations and the NLR data, the asteroid's irregular shape was determined; the principal radii were measured to be about 16.5, 8.0, and 6.5 km.[10] The orientation of Eros' spin axis was important for timing orbit plane change events, but the spin axis direction and rate also oriented the gravity field model, which was critical for subsequent orbit determination and orbit prediction. After additional data were processed, Eros' rotation pole right ascension was estimated to be 11.369 ± 0.003° 1-σ, and pole declination was 17.227 ± 0.006° 1-σ in J2000 coordinates.[11] Similar updates to physical models (especially the Eros gravity model) and improvements in navigation accuracy resulted in the orbit phase being replanned by the navigation team a total of seven times after orbit insertion. The end-of-mission close flybys scheduled after 24 January 2001 were replanned three times in response to improvements in orbit prediction accuracy.

October 2000 Close Flyby

The first close flyby of Eros' surface was initiated on 25 October by OCM-16, which targeted the flyby at about a 5.5-km altitude above one end of the "long" axis of Eros. The basic technique for the close flyby was to place the spacecraft in an eccentric orbit with true anomaly and periapsis oriented so that the spacecraft would fly over an "end" of Eros at the proper time. The series of OCMs targeting the flyby began on 13 October with OCM-14, which lowered periapsis from the 100 × 100 km orbit to about 50 km. This was followed by OCM-15, which circularized the orbit at 50 × 50 km on 20 October. After OCM-16 and the close approach on 25 October, OCM-17 occurred at the apoapsis after the flyby, about 20 h after OCM-16, to return to a nominal 200 × 200 km orbit.

The delivery schedule for OCM-14 through OCM-17 was designed to adapt to changes caused by execution errors in each of those burns. Beginning about 9 October, the predicted time of closest approach was varying up to 20 min. This was compensated for by the late update on 26 October at 07:00 UTC for OCM-17, just 10 h, 40 min before the maneuver execution time. A Monte Carlo analysis of the October flyby was performed by generating 200 samples from simulations of the maneuver to target the flyby (OCM-16) using both expected and extreme execution errors. Expected execution errors were 1% magnitude overburn (bias) and 1% over in each component (pointing); extreme execution errors were 20% magnitude overburn (bias) and 10% over in each component (pointing). Neither set of assumptions resulted in an impact trajectory, and the worst case from this set (extreme errors) had a minimum flyby altitude of 277 m, so the flyby was deemed relatively low risk.

End-of-Mission Plan

After the main science goals of the mission had been met and the navigation models and experience had been tuned by 11 months of orbiting Eros, another series of low-altitude flyovers was planned for late January 2001. This came at the end of a long interval of 35 × 35 km retrograde equatorial orbits that began on 13 December 2000. These low orbits were designed to meet XGRS viewing requirements. The design approach was to establish an eccentric orbit measuring 35 × 22 km on 24 January, remain in that orbit for several days, stabilize the orbit determination estimates and trajectory predictions, and then lower periapsis further on 28 January 2001 (OCM-22) to 37 × 19 km so that a target altitude between 2 and 3 km was achieved. The OCM-22 maneuver resulted in the closest overflight of about 2.7 km on 28 January, 10:24 UTC, and was followed about 16 h later by OCM-23, which returned to the 35 × 35 km circular orbit. The geometry of the close flyby orbit, which was highly perturbed, is projected into the Eros equator in Fig. 4. The locations of the south rotation pole and the sunlit southern hemisphere of Eros are also shown for reference.

Landing Design and Navigation

The descent trajectory was designed primarily to maximize the number of images of the surface from altitudes below 5 km. Minimizing the impact velocity was

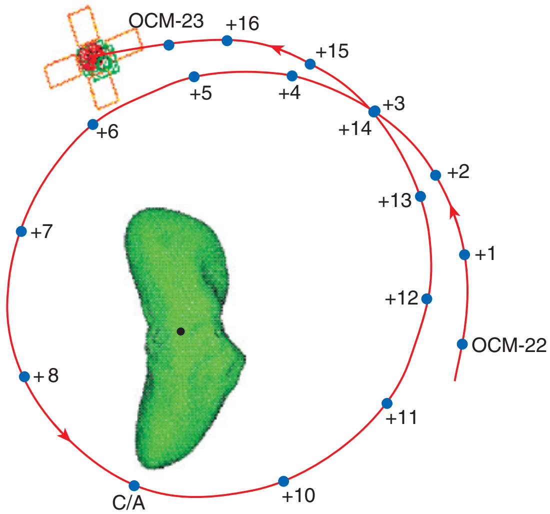

Figure 4. Orbit for 28 January 2001 close flyby noting hours after OCM-22. Eros is oriented at time of closest approach (C/A), where altitude = 2.7 km (orbit and Eros to scale; spacecraft not to scale).

a secondary goal. It was also decided that the spacecraft would maintain continuous high-gain antenna contact with the Earth to maximize image downlink capability. Since the NEAR Shoemaker spacecraft had fixed instruments, radio antennas, and solar arrays, this Earth-pointing requirement limited the possibilities for imager pointing to a roll about the spacecraft–Earth line during the descent. As seen in Fig. 1, the solar latitude during February 2001 was south of −85°. This meant that the southern latitudes of Eros were in constant sunlight and the northern regions were in constant darkness. Early in the design phase, the descent trajectory was targeted to impact near Eros' south pole to minimize the relative velocity and remove the requirement to synchronize the descent with the rotational phase of Eros. However, the geometry between Sun direction, Earth direction, and illuminated surface of Eros constrained the opportunities for imaging to the last 2 min before impact, and so this option was abandoned.

Since NEAR was initially in an equatorial retrograde orbit, whereas the landing site was at latitude −35°, the descent trajectory design had to include a sizeable plane change in addition to the de-orbit maneuver that placed periapsis below Eros' surface. Gravity perturbations from the irregular shape of Eros deflected the trajectory and helped to change the orbit inclination from the value immediately following the de-orbit burn (about 135°) to that necessary to impact the target (about 145°). Also, since the standard spherical harmonic expansion of a body's gravity field diverges for distances less than the body's maximum radius (18 km for Eros), the overall gravity field for orbit radii less than 18 km was modeled by performing a volume integral over a polyhedral representation of Eros' surface.

The longitude of the touchdown site was selected so that the spacecraft could maintain continuous Earth contact and have its imager pointed at the surface of Eros during descent. A site near the lip of the large depression Himeros, along the smaller radius of Eros, was chosen for the landing. During simulations it was noted that landing sites along the smaller axis of Eros had descent trajectories that were less sensitive to orbit determination timing errors as compared to those on the long axis owing to the shape of the gravitational potential around each of these sites. If a long axis end had been chosen for the landing site, much more stringent control of the trajectory approach before the de-orbit burn would have been required so that the spacecraft would arrive at a precise time over the end. If the spacecraft were early or late, the trajectory would be deflected to either side because of the saddle shape of the gravity equipotential surface over the ends of Eros, thus making predictions of the landing site unreliable.

The descent portion of the NEAR trajectory showing the placement of maneuvers is seen in Fig. 5. Prior to the descent trajectory, the spacecraft was in a near-circular 34×36 km retrograde orbit. The timing and orientation for this orbit were set by small OCMs on 2 and 6 February 2001, so that the spacecraft arrived at a predetermined time over an inertial-fixed location relative to the center of Eros. This time was chosen so that the Earth and Sun direction constraints mentioned previously were satisfied. The descent trajectory and image sequence were simulated to check that the illuminated surface was visible to the imager and that the solar array off-Sun angles were acceptable while continuously pointing the high gain antenna at Earth. The final design of the de-orbit maneuver and the first braking maneuver were performed about 24 h before the execution of the de-orbit burn, which changed the orbit inclination from 180° to 135° relative to Eros' equator.

Twelve optical navigation images, acquired and downlinked less than 1 hr, 40 min after the de-orbit burn, were used to compute and upload a time offset to the spacecraft maneuver and imaging sequence. Earlier Monte Carlo analyses indicated that this timing update would be required if the estimated trajectory was more than 3 s different from nominal. The optical navigation processing detected three landmark craters in four of the images and passed these on to be combined with the radiometric data only 15 min after receipt of the images. The orbit determination process then determined that the spacecraft was about 17 s late along the nominal path, so a command was uplinked to the spacecraft to subtract 17 s from the mission elapsed time counter. With this adjustment, the remainder of the four braking maneuvers were preprogrammed to execute at fixed intervals. These were Brake-1 (6.48 m/s) at 19:16:26, Brake-2 (3.47 m/s) at 19:31:48, Brake-3 (4.03 m/s) at 19:47:48, and Brake-4 (2.70 m/s) at 19:58:48 (all

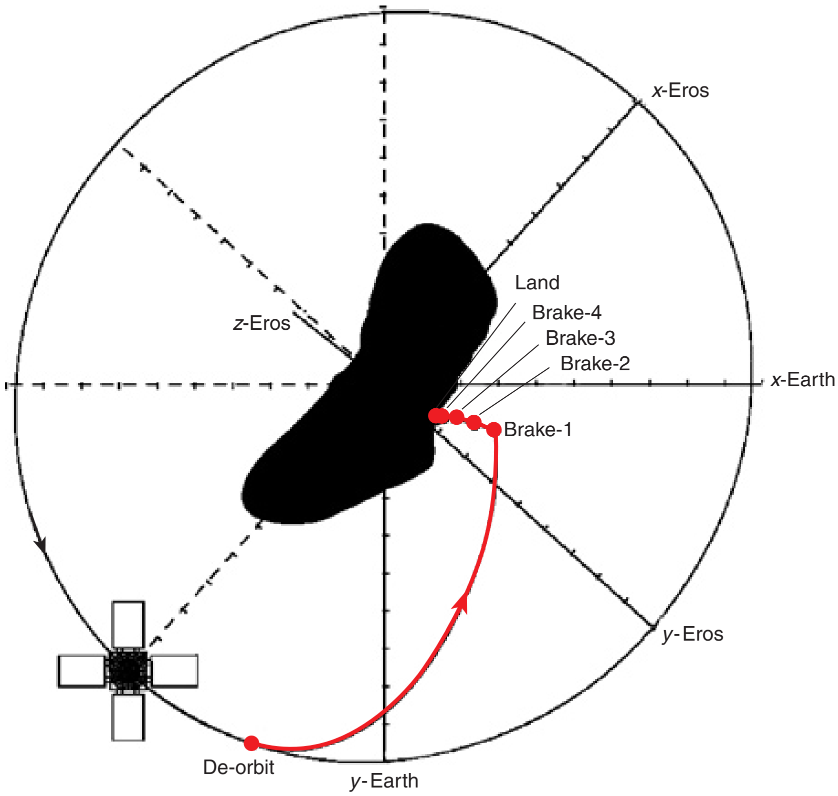

Figure 5. Landing orbit showing de-orbit burn and braking maneuvers as seen from Earth (orbit and Eros to scale; spacecraft not to scale).

times are Earth-received UTC in hours:minutes:seconds, where the one-way light time from the spacecraft to Earth was 17 min, 34.5 s).

In all, the 4.5-h controlled descent used five open-loop maneuvers in the sense that real-time trajectory tracking information was not used to update subsequent maneuver vector components. The exception was the time update of the maneuver and imager sequence after the first maneuver, as explained previously. The time of impact was determined to be 20:01:51 UTC from the radiometric Doppler tracking. This was about two-thirds of the way through the execution of Brake-4. The postlanding analysis indicates a vertical impact velocity of 1.5 to 1.8 m/s and a transverse impact velocity of 0.2 to 0.3 m/s. The touchdown site was determined to be at 40.0°S, 279.3°W, which was within about 500 m of the nominal site.[5]

ORBIT ESTIMATION

Orbit determination techniques for the orbital phase of NEAR were developed prior to launch.[12] Through simulations and covariance analyses, it was resolved that the orbit determination filter design and operations for Eros would have to be different from those used for previous planetary orbiters. The two main changes in strategy were (1) the need to simultaneously estimate the spacecraft orbit, nongravitational accelerations, and Eros' physical parameters related to the spacecraft orbit dynamics, and (2) the need to augment the DSN Doppler and range tracking with optical landmark tracking.

Typically, the operational orbit determination solutions included parameter estimates for a 14th degree and order gravity harmonic model and location estimates for up to 47 landmarks. Each orbit determination solution consisted of the spacecraft position and velocity along with dynamic and geometric model coefficients for a total of about 359 estimated parameters. Table 2 lists the estimated parameters and their *a priori* uncertainty in the filter setup for a typical long arc orbit determination. During the ongoing validation and improvement of the orbit determination process in flight operations, orbit estimates were made using the laser range data to determine the utility of the data as an auxiliary tracking data type. The orbit determination performance prediction was validated during orbit operations, and even though the actual orbit scenario changed owing to the later insertion date, the technique of progressively improving model resolution and reducing the orbit radius performed as predicted by the analysis in Ref. 12.

In practice, the orbit determination filter was run on both short and long data arcs, ≈5 and ≈30 days long, respectively. By comparing results from the two arcs, the sensitivity of the physical parameter estimates to data and modeling errors was determined. The most reliable solutions were usually obtained from the longer arcs once the orbit determination filter was properly tuned. Orbit determination performance during the early orbit phase, when the model improvement was most dramatic, is shown in Fig. 6a for the longer data arc fits. The figure shows the root-sum-square position error for both 2- and 5-day-long predictions compared to truth orbits, where truth orbits were reconstructed using the final improved dynamical models. The vertical lines in the figure denote times of OCMs, and the intervals of nominal circular orbit phases of 200 × 200 km, 100 × 100 km, and 50 × 50 km are labeled between the appropriate maneuver lines. Notice that the vertical scale is logarithmic, labeled from 10 m to 10 km.

The initial improvement after OIM to the 100-km circular orbits reduced the prediction error from over

Table 2. Orbit determination filter assumptions.

Estimated parameters	*A priori* uncertainty ($1\ \sigma$)	Number of parameters
Spacecraft state; i.e., $\{x, y, z, \dot{x}, \dot{y}, \dot{z}\}$ at epoch	100 m position, 0.1 mm/s velocity	6
Solar pressure on spacecraft[a]; i.e.,		
Emissivity	0.1	12
Reflectivity and specularity	1×10^{-2} to 1×10^{-4}	
Spacecraft nongravitational acceleration; i.e., $\{\ddot{x}, \ddot{y}, \ddot{z}\}$ as an exponentially correlated stochastic parameter	2×10^{-12} km/s^2 with correlation time of 2 h	3
Spacecraft maneuvers; i.e., usually four propulsive maneuvers in a typical arc	1–5% of nominal, spherical error	12
DSN station locations; i.e., cylindrical coordinates	1.5 m radial, 15 m z-height, 0.001° longitude	9
Eros gravity field (normalized); i.e., coefficients through 14th degree and order	100% of coefficient value predicted from shape and constant density	168
Eros central body term; i.e., μ [km^3/s^2]	10% of nominal	1
Eros spin state; i.e.,		
Pole right ascension, declination	0.1°, 0.1°	2
Spin rate	0.0002°/day	1
Prime Meridian	0.3°	1
Spin rate	5×10^{-9}°/s	3
Landmark locations; i.e., 47 body-fixed locations $\{x_i, y_i, z_i\}$	100 m, 100 m, 100 m	141
	Total estimated parameters	359

[a]For four geometric shapes representing front and back of solar arrays, parabolic antenna, and bus.

1 km to less than 100 m. The dramatic change after going to the 100×50 km transfer orbit at about day-of-year 115 shows the sensitivity of prediction in the lower orbit to Eros model errors that have not yet been improved. Also, position errors are affected when the orbit is predicted from an orbit fit that includes an OCM. The long time in the 50×50 km mapping orbit allowed some experimentation on estimated parameters and filter setup that led to further improvements so that the average prediction error by the end of the plot in Fig. 6a is 10 to 20 m or less. By the end of this period, orbit determination position knowledge within the fit arc was 1 to 2 m.

The error in predicted orbit timing was especially important for the sequence planning process applied to NEAR operations. This process used navigation predictions of OCM execution times and the resulting orbital shape and orientation to plan sequences up to 4 weeks in advance.[13] For MSI advanced image sequence planning, the predictions were extended to as much as 8 weeks in advance. The orbit timing errors for the same early orbit period covered by Fig. 6a are shown in Fig. 6b. The timing error is proportional to the downtrack position error for each prediction. Note that early in the orbit phase

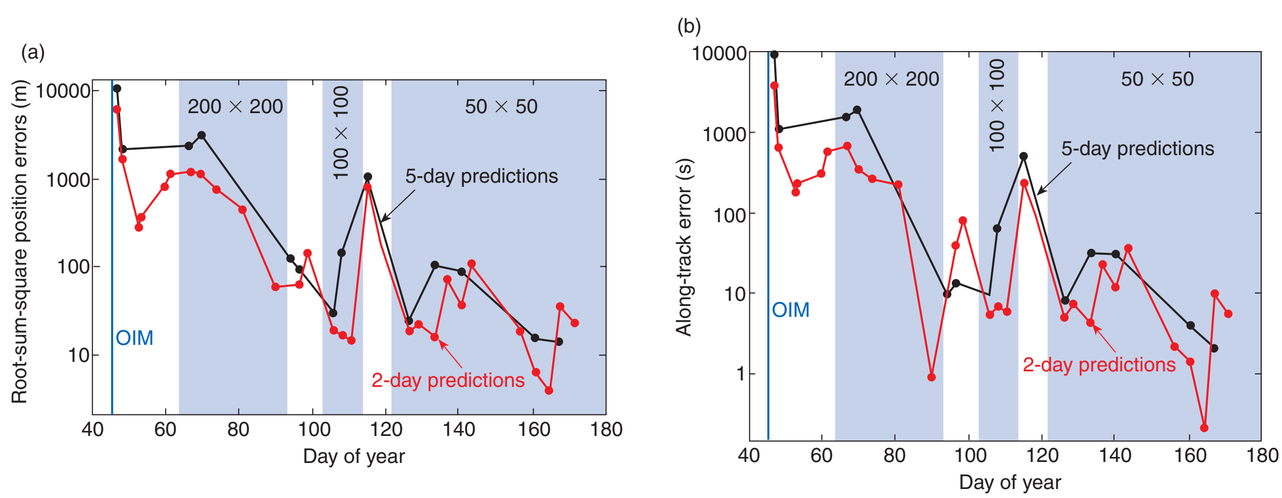

Figure 6. Orbit determination position (a) and along-track (b) prediction performance for the first few months of the orbit phase.

it was difficult to predict the time of upcoming maneuvers to better than several minutes, even for the short prediction times shown in Fig. 6b. It was even more difficult to predict the times of later burns in a multiburn sequence design, since the orbit determination was degraded by having to solve for several maneuvers in the fit. This effect is seen in Fig. 6b where the timing error rises after a burn even for the short prediction times. The impact of this behavior was the need to provide trajectory predictions for both preliminary planning of an OCM about a week in advance and a trajectory prediction for a final update of an OCM about 2 days in advance. This meant that the navigation team usually generated two orbit prediction deliveries per week except during intervals where OCMs were more than 3 weeks apart.

Radiometric Tracking

DSN radiometric data were one of the data types used to navigate NEAR. The radiometric data types available included two-way X-band Doppler and range, two-way minus three-way Doppler (narrowband very long baseline interferometry [VLBI]), and one-way X-band Doppler (not processed). The two-way Doppler was weighted at 0.1 mm/s for a 60-s count time, and the two-way range was weighted at 200 m. The range was de-weighted during the orbit phase since it primarily contained information for adjusting Eros' ephemeris, while the Doppler was much more useful for determining the spacecraft orbit relative to Eros. The two-way Doppler and range was used for routine processing. During approach and rendezvous, a combination of two-way Doppler and range plus available two-way minus three-way narrowband VLBI (differenced Doppler from DSN station overlap coverage) was used as a consistency check. When processed in the orbit determination filter, the DSN inter-complex timing offset between the two antennas (measured to a few nanoseconds) was used to calibrate the differenced Doppler points.

After the initial model tuning phase indicated in Figs. 6a and 6b, the Doppler data taken during a 30-day arc in the 50×50 km orbit were fit to about 0.05 mm/s, root mean square (rms). The range data, being de-weighted in the orbit determination filter, had systematic trends in the post-fit residuals as large as several hundred meters; however, the range data were only used to loosely control the Eros ephemeris estimate, and did not affect the spacecraft orbit estimate relative to Eros for the short arcs (relative to Eros' orbit period) used in production. Later processing of long arcs of range data weighted at 3 m, which is a more realistic precision, was used to improve the overall estimate of Eros ephemeris.[14]

Optical Landmark Tracking

The optical landmark tracking process for NEAR had two characteristics: (1) the initial identification and determination of a set of landmark craters (the landmark database) and (2) finding and using those same landmark craters in subsequent pictures as tracking data. These two functions overlapped since the initial optical navigation task in orbit was to refine the location estimate of landmark craters from images while also building up the landmark database. A landmark "point" is defined as the center of a circle defined by the rim of a landmark crater. Hence, the picture planning process had to provide enough pictures to build a reasonable number and distribution of landmarks and also provide designated optical tracking images of previously identified landmarks.

The tracking information from optical landmark images is contained in the apparent motion of a landmark in a series of pictures where viewing geometry is changing because of the relative motion of Eros spinning about its axis and the orbit of the spacecraft. By processing many such landmark images in the orbit determination filter, both orbit and landmark locations can be estimated. Once calibrated, the optical landmark crater locations obtained during a 60-day arc in the 50×50 km orbit were fit to about 15 m, rms. Note that a single picture of a landmark is useless as navigation tracking information.

Building and maintaining the landmark database occurred throughout most of the orbit phase because of lighting conditions on 433 Eros. Upon arrival, only the asteroid's north polar region was in sunlight. During the first few critical months of the orbital phase, there were optical landmarks only in that lit hemisphere. As Eros moved in its orbit about the Sun, the southern hemisphere was eventually lighted, and landmarks from that hemisphere were added to the database. Table 3 presents a summary of some characteristics of the optical landmark process for NEAR. Details of the processing and results are given in Ref. 15.

Laser Range Tracking

The NLR instrument provided useful altimeter range measurements of the surface of Eros whenever the range was less than a couple of hundred kilometers. This information was used to assist navigation in two ways. The first method was to use the NLR data in the orbit determination filter, either alone or in combination with other tracking data, to solve for the spacecraft orbit. The second method was to use the NLR data to solve for an accurate shape model of Eros, which was then used to determine an *a priori* gravity harmonic model for Eros (assuming uniform density). In addition, an accurate shape model also was a benefit to optical landmark processing, both by providing a convenient way to catalog the landmarks on the surface and by providing better *a priori* locations for landmarks with a small sample size.

Table 3. Operational summary of optical landmark tracking for NEAR over the entire approach and orbit phase.

Optical landmark processing characteristic	Quantity	Percentage of total
Total number of pictures taken starting 17 Dec 1999	181,393	
Number of pictures downloaded to JPL for analysis	33,968	18.73%
Number of useful pictures (at least one landmark)	17,601	
Number of accepted pictures (some incorrect attitude)	17,352	
Number of star calibration pictures	1,424	
Number of valid landmarks in database	1,590	
Number of landmark observations	134,267	
Number of misidentified landmark observations	1,314	0.98%
Number of landmark observations in pictures with incorrect attitude	1,616	1.20%
Number of useful landmark observations	131,337	97.82%
Average number of useful observations per landmark	82.6	
Average number of useful observations per picture	7.6	

NLR data were never used directly for orbit determination for NEAR navigation operational deliveries, but the technique was applied as a consistency check on the production orbits that were obtained by processing DSN radiometric Doppler and range combined with optical landmarks. Navigation performance when using NLR data either alone or in combination with the radiometric and optical landmark tracking is described in Ref. 16.

By holding the orbits computed with radiometric and optical data fixed, the altimeter range data were successfully used to estimate an Eros shape model, which is shown in Fig. 7. This model was determined by solving for a 34th degree and order spherical harmonic expansion of the asteroid's radius. Note that the figure shows some possible aliasing around the minimum radius "belt," but there is also good resolution of some of the larger craters there. Tests show that the navigation shape model is good to about 50 m, rms. The poorest determined shape areas are in the concave region near the lower center in Fig. 7 (where the large crater can be seen) and toward the two long radius "ends." In these poor regions, the shape is only good to about 100 m, rms. Surprisingly, even this level of fit can be obtained for a spherical harmonic model considering the nonspherical shape of Eros.

During this process, estimates for the NLR pointing error, range bias, and altitude degradation factor were also obtained. The value for the pointing error is close to the independently observed pointing error for the camera, making the estimate more credible. The shape model also agrees at the 100-m level with the landmark heights, which are determined through the optical tracking data. The landmarks are consistently biased above the shape model, which is reasonable since the landmark point is idealized as the center of the circle defined by the crater rim.

The orbits computed with the combined NLR and radiometric data agree with the operational orbits at about the 40- to 50-m level. Even after estimating a pointing error, range bias, and degradation factor, the NLR data seem to bias the orbits at this level, especially in the transverse direction. The complete cause and fix for this biasing have yet to be determined. Likely causes could be time tag errors, instrument performance issues, or additional pointing errors that are not accounted for in the orbit determination process.

SUMMARY

The NEAR Shoemaker spacecraft was the first to orbit a small body. The design and estimation techniques necessary to plan and navigate its orbit about an irregularly shaped small body had to be developed and tested as

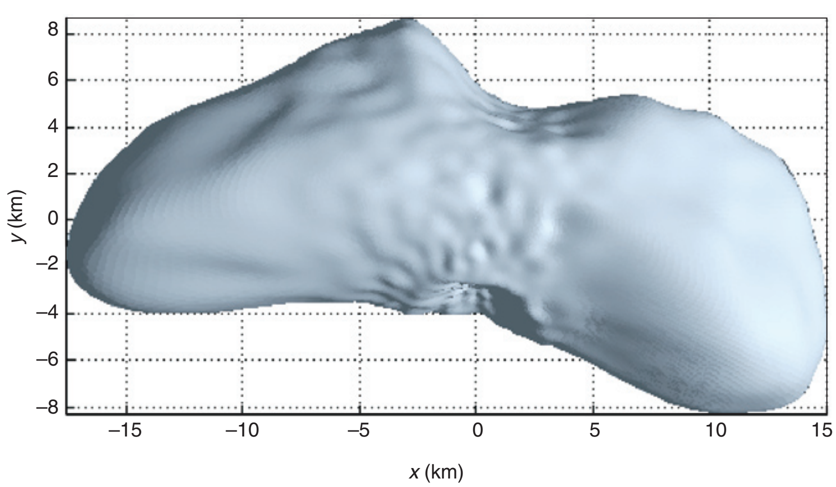

Figure 7. The 34th degree and order spherical harmonic shape model for Eros derived from laser ranging. The south pole is shown at origin.

the mission progressed. Knowledge of the mass, gravity distribution, and spin state of Eros had to be quickly improved on final approach and during the orbit phase in order to predict the effect of trajectory correction maneuvers for capture and orbit control around the asteroid. The navigation challenge for the orbit phase was to adapt the orbit plan while adjusting for Eros' crudely known physical parameters. Improvements in the estimates of these physical parameters as the spacecraft approached and inserted into orbit about the asteroid were crucial to mission success. Unlike a planetary orbiter, the very low gravity of Eros ($\mu = 4.46 \times 10^{-4}$ km^3/s^2, Ref. 11) meant that the spacecraft could easily escape or crash into its surface with small changes in velocity. This placed additional demands on navigation accuracy while also imposing a shorter response time than that usual for planetary orbit missions.

Figure 8. The NEAR navigation team on the morning of 15 February 2000, in front of the JPL mission status board. Standing, left to right: James K. Miller, Bobby G. Williams, Peter J. Antreasian, Cliff E. Helfrich, William M. Owen, and Eric Carranza. Kneeling, left to right: Steven R. Chesley, Tseng-Chan Wang, Jon D. Giorgini, and John J. Bordi.

The weak, nonspherical gravity field around Eros, combined with solar pressure accelerations, resulted in the low-altitude NEAR orbits being highly perturbed, non-Keplerian, and difficult to predict. To estimate these orbits, the gravity field and its orientation in space also had to be estimated, and when using only radiometric data these estimates were slow to converge. This required the use of optical landmark tracking, which used pictures of craters on Eros as landmark information, in addition to the more traditional radiometric tracking from NASA's DSN. The operational use of optical landmark tracking for a deep space mission was another navigation first for the NEAR mission.

The NEAR mission posed several new and difficult challenges for spacecraft navigation. Many of these resulted from the fact that NEAR was the first mission to send a spacecraft to rendezvous with, orbit about, and finally land on an asteroid. The navigation team responded by developing new tracking data types and new processing methods specifically for NEAR navigation. The NEAR navigation team, sized for 6 full-time-equivalent engineers during the orbit phase, consisted of the 10 people shown in Fig. 8. The outstanding abilities of these team members, most of whom worked part-time on other tasks, are demonstrated by the successful navigation of NEAR Shoemaker.

REFERENCES

[1]Farquhar, R. W., Dunham, D. W., and McAdams, J. V., "NEAR Mission Overview and Trajectory Design," *J. Astron. Sci.* **43**(4), 353–371 (Oct–Dec 1995).

[2]Landshof, J. A., and Cheng, A. F., "NEAR Mission and Science Operations," *J. Astron. Sci.* **43**(4), 477–489 (Oct–Dec 1995).

[3]Farquhar, R. W., Dunham, D. W., and McAdams, J. V., "NEAR Shoemaker at Eros: Rendezvous, Orbital Operations, and a Soft Landing," Paper AAS 01-370, AAS/AIAA Astrodynamics Specialists Conf., Quebec City, Quebec, Canada (30 Jul–2 Aug 2001).

[4]Williams, B. G., Antreasian, P. G., Bordi, J. J., Carranza, E., Chesley, S. R., et al., "Navigation for NEAR Shoemaker: The First Spacecraft to Orbit an Asteroid," Paper AAS 01-371, AAS/AIAA Astrodynamics Specialists Conf., Quebec City, Quebec, Canada (30 Jul–2 Aug 2001).

[5]Antreasian, P. G., Chesley, S. R., Miller, J. K., Bordi, J. J., and Williams, B. G., "The Design and Navigation of the NEAR Shoemaker Landing on Eros," Paper AAS 01-372, AAS/AIAA Astrodynamics Specialists Conf., Quebec City, Quebec, Canada (30 Jul–2 Aug 2001).

[6]Helfrich, C. E., Miller, J. K., Antreasian, P. G., Carranza, E., and Williams, B. G., "Near Earth Asteroid Rendezvous (NEAR) Revised Orbit Phase Trajectory Design," Paper AAS 99-464, AAS/AIAA Astrodynamics Specialists Conf., Girdwood, AK (16–19 Aug 1999).

[7]Miller, J. K., Antreasian, P. J., Gaskell, R. W., Giorgini, J., Helfrich, C. E., et al., "Determination of Eros Physical Parameters for Near Earth Asteroid Rendezvous Orbit Phase Navigation," Paper AAS 99-463, AAS/AIAA Astrodynamics Specialists Conf., Girdwood, AK (16–19 Aug 1999).

[8]Dunham, D. W., Farquhar, R. W., McAdams, J. V., Williams, B. G., Miller, J. K., et al., "Recovery of NEAR's Mission to Eros," *Acta Astron.* **47**(2–9), 503–512 (2000).

[9]Scheeres, D. K., Miller J. K., and Yeomans, D. K., "The Orbital Dynamics Environment of 433 Eros," Paper AAS 01-373, AAS/AIAA

Astrodynamics Specialists Conf., Quebec City, Quebec, Canada (30 Jul–2 Aug 2001).

[10]Yeomans, D. K., Antreasian, P. G., Barriot, J-P., Chesley, S. R., Dunham, D. W., et al., "Radio Science Results During the NEAR Shoemaker Spacecraft Rendezvous with Eros," *Science* **4289**, 2085–2088 (22 Sep 2000).

[11]Miller, J. K., Konopliv, A. S., Antreasian, P. G., Bordi, J. J., Chesley, S., et al., "Determination of Shape, Gravity and Rotational State of Asteroid 433 Eros," *Icarus* **155**, 3–17 (2002).

[12]Miller, J. K., Williams, B. G., Bollman, W. E., Davis, R. P., Helfrich, C. E., et al., "Navigation Analysis for Eros Rendezvous and Orbital Phases," *J. Astron. Sci.* **43**(4), 453–476 (Oct–Dec 1995).

[13]Holdridge, M. A., Nelson, R. L., and Whittenburg, K. E., "433 Eros Orbital Mission Operations—Implementing the First Orbital Operation Around a Small Body," Paper AAS 01-375, AAS/AIAA Astrodynamics Specialists Conf., Quebec City, Quebec, Canada (30 Jul–2 Aug 2001).

[14]Konopliv, A. S., Miller, J. K., Owen, W. M., Yeomans, D. K., Giorgini, J. D., et al., "A Global Solution for the Gravity Field, Rotation, Landmarks, and Ephemeris of Eros," in *Proc. Int. Symp. on Space Flight Dynamics*, CD-ROM, Pasadena, CA (3–6 Dec 2001).

[15]Owen, W. M., Wang, T. C., Harch, A., Bell, M., and Peterson, C., "NEAR Optical Navigation at Eros," Paper AAS 01-376, AAS/AIAA Astrodynamics Specialists Conf., Quebec City, Quebec, Canada (30 Jul–2 Aug 2001).

[16]Bordi, J. J., Miller, J. K., Williams, B. G., Nerem, R. S., and Pelletier, F. J., "The Impact of Altimeter Range Observations on NEAR Navigation," Paper AIAA 2000-4423, AIAA/AAS Astrodynamics Specialists Conf., Denver, CO (14–17 Aug 2000).

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THE AUTHOR

BOBBY G. WILLIAMS holds degrees in aerospace engineering from the University of Texas (B.S. and M.S.) and the University of Southern California (Ph.D.), and is a member of Sigma Gamma Tau, the national honor society for aerospace engineering. As an employee of the Jet Propulsion Laboratory, California Institute of Technology, he participated in and eventually headed the orbit determination teams at JPL for the Viking missions to Mars, the Pioneer Venus Orbiter mission, and the Earth oceanographic mission TOPEX/Poseidon. He has supported navigation trade studies and design for many Discovery proposals and has been the navigation lead for all three successful Discovery proposals from APL. Dr. Williams served as navigation team chief for NASA's NEAR mission. Currently he is the technical supervisor of the Outer Planet Navigation Group in the Navigation and Mission Design Section at JPL. His e-mail address is Bobby.Williams@jpl.nasa.gov.