Paper AAS 01-371

American Astronautical Society

AIAA

Navigation for NEAR Shoemaker: the First Spacecraft to Orbit an Asteroid

B. G. Williams, P. G. Antreasian, J. J. Bordi,
E. Carranza, S. R. Chesley, C. E. Helfrich,
J. K. Miller, W. M. Owen, T. C. Wang

all at
Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109

AAS/AIAA Astrodynamics Specialists Conference

Quebec City, Quebec, Canada July 30-August 2, 2001

AAS Publications Office, P.O. Box 28130, San Diego, CA 92198

AAS 01-371

NAVIGATION FOR NEAR SHOEMAKER: THE FIRST SPACECRAFT TO ORBIT AN ASTEROID

B. G. Williams, P. G. Antreasian, J. J. Bordi, E. Carranza, S. R. Chesley, C. E. Helfrich, J. K. Miller, W. M. Owen, T. C. Wang,

Navigation and Mission Design Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

When the Near Earth Asteroid Rendezvous (NEAR) Shoemaker spacecraft began its orbit about the asteroid 433 Eros on February 14, 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 an orbit about an irregularly shaped small body. Knowledge of the mass, gravity distribution, and spin state of Eros had to be quickly improved on final approach in order to predict the effect of trajectory correction maneuvers for capture and orbit control around Eros. This required the use of optical landmark tracking, which used pictures of craters on Eros as landmark information, in addition to the more traditional radio metric tracking from NASA's Deep Space Network. The operational use of optical landmark tracking was another navigation first for the NEAR mission. As part of the ongoing effort to improve the Eros physical model, altimeter data from the NEAR laser range instrument was also processed and analyzed. This paper describes the navigation strategy and results for the rendezvous and orbit phases of the NEAR mission. Included are descriptions of the new techniques developed to deal with navigation challenges encountered during the yearlong orbit phase. The orbit phase included circular orbits down to 35 km radius and elliptical orbits that targeted overflights to within 2.7 km above the surface. Many of these methods should prove useful for navigation of future missions to asteroids and comets.

INTRODUCTION

The Near Earth Asteroid Rendezvous (NEAR) mission was the first to be launched in NASA's Discovery Program. The Johns Hopkins University, Applied Physics Laboratory (JHU-APL) was responsible for designing and building the NEAR Shoemaker spacecraft, and for managing and operating the mission [1,2]. Navigation for the spacecraft was the responsibility of the Jet Propulsion Laboratory, California Institute of Technology. The goal of this Discovery mission was to determine the physical and geological properties of the near-Earth asteroid 433 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. Since it was a Discovery class mission, the NEAR project was developed with a minimum of staffing, expense and unnecessary complexity. As a result, the spacecraft had simple a design with fixed-mounted instruments and solar panels, but it included advanced capabilities (especially for ease of pointing) that made it easier to operate by a small flight team.

The unique features of navigation and mission design related to orbiting an asteroid and to designing a robust navigation system for the NEAR mission will be shown. The problem of navigating a spacecraft about an asteroid is made difficult by the relative uncertainty in the asteroid physical properties that perturb the orbit. To help solve this problem, the navigation system for NEAR used NASA's Deep Space Network radio metric Doppler and range tracking, along with the new navigation technologies of optical landmark tracking and laser ranging to the asteroid surface. The relative usefulness of each of these data types in the navigation solutions will be presented. The design of the rendezvous and orbit plan, including the low altitude flyovers performed on October 23, 2000, and during late January, 2001, were driven by science requests and requirements. The implementation of the various orbit inclination and size changes depended on the ability of the navigation system to provide accurate orbit estimates. The discussion of some of the design constraints and requirements are shown below.

Science Goals

Prior to NEAR Shoemaker rendezvous with Eros, the mission and science strategy for the orbit phase was examined in some detail [4]. 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 geometry during the orbit phase. This coordinated well with the navigation requirement to build and maintain an optical landmark database, as described below. The X-ray/Gamma-Ray Spectrometer (XGRS) team had requirements to bring the instrument close to the surface (as low as 35 x 35 km orbits) while also maintaining an oblique solar flux angle. This requirement was met by progressively lowering the orbit radius as navigation models were improved so that the viewing geometry could be reliably predicted nearly six weeks in advance. The NEAR Laser Rangefinder (NLR) had a requirement to cover the complete surface with laser range returns at altitudes lower than 100 km. This was accomplished by designing polar orbits with both 50 km and 35 km radius. Of particular importance to the mission design for rendezvous and orbit phases was the science goal of the NEAR Infrared Spectrograph instrument 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 December 20, 1998. The initial burn was terminated prematurely due to a spacecraft anomaly, and the remainder of maneuver sequence was not perfomed. As a result, the spacecraft performed a high-speed flyby within 3900 km of Eros on December 23, 1998. Control of the spacecraft was recovered just prior to this flyby, and images were obtained and processed to provide initial estimates for some of the physical parameters of Eros[4]. After the aborted maneuvers and the flyby, a maneuver was performed on January 3, 1999, that was designed by the mission design team at JHU-APL to target a rendezvous with Eros nearly a year later in February 2000[5]. 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, the navigation team was busy testing interfaces with the Mission Operations Team at JHU-APL, planning a new orbit phase, and validating the combined radio metric and optical landmark orbit navigation scenario. In addition, maneuvers and uncertainties were determined to target the Eros orbit insertion maneuver (OIM) at about 200 km from the center of Eros on February 12, 2000. On this date, the Northern pole region of Eros was in sunlight, but the Sun would cross Eros' equator in April, 2000, so the rendezvous and early orbit were designed to accommodate science observations of the Northern polar region. The new approach was designed for the first and only zero phase fly over of the north polar region for the NIS instrument.

The nominal OIM was designed to accommodate the uncertainty in both maneuver execution and the mass of Eros. The nominal OIM was chosen both so the initial orbit would not pass excessively close to Eros, and so the spacecraft would be captured at Eros. The maneuver parameters affecting the initial orbit were the pointing and magnitude uncertainty. Prior to the OIM, simulations were performed to determine the initial radius of periapsis and apoapsis range due to maneuver errors. For pointing errors of +/-2 degrees along the line to the center of Eros (the worst case direction), the initial orbit remained bounded with minimum periapsis radius of 116 km. For pointing errors of +3 degrees and larger, the post-OIM trajectory became hyperbolic. For magnitude errors of up to +/-4 per cent, the initial orbit remained bounded with minimum periapsis radius of 270 km and maximum apoapsis radius of 741 km. The resulting orbit radius at periapsis and apoapsis due to uncertainty in Eros' mass of up to +/-25 per cent is shown in Figure 1.

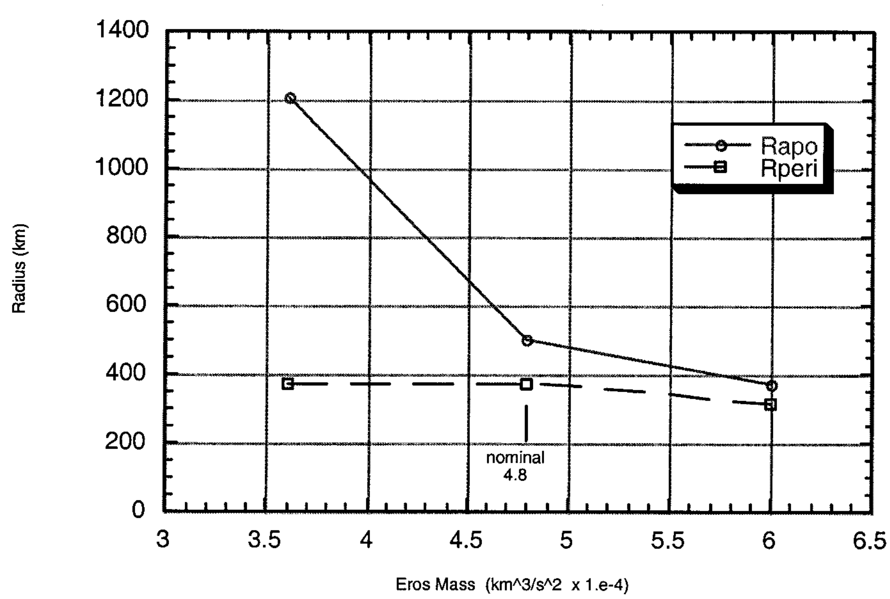

Figure 1. Initial variation in radius of periapsis and apoapsis after orbit insertion manuever for up to 25 per cent variation in Eros' GM about nominal value.

ORBIT DESIGN

One example of the impact of imprecise knowledge about Eros before arrival was the uncertainty in the orientation of its rotation pole. The pre-arrival estimates of the orientation for the rotation pole of Eros varied by more than 4 degrees. After obtaining the initial landmark tracking during the early orbit phase, the navigation team was able to estimate the pole orientation to within 0.05 degrees, one sigma. This was important not only to orient the gravity field model for subsequent orbit determination and prediction, but it also impacted the mission design by placing a more precise date at which Sun would cross Eros' equator. As a result of this update, a maneuver originally designed to place the spacecraft into a polar orbit in July 2000, was moved by more than a week.

Similarly, the plan for orbit size and orientation during the year long science gathering phase was updated a total of seven times in response to increased knowledge of the physical parameters and to improved navigation performance as the data taking and processing methods were refined. Because of spacecraft pointing constraints and the requirement to keep the solar arrays illuminated, the orbits were designed to lie within 30 degrees of the "Sun plane-of-sky" (SPOS), the plane normal to the Sun-Eros line. The orbit phase lasted from the insertion burn on February 14, 2000 to the landing on February 12, 2001. Figure 1 shows the NEAR trajectory for the entire orbit phase projected into the SPOS. The end of mission descent to landing is shown as the crooked line near the origin. The orbit radius and inclination relative to the Eros equator were varied during this phase to accommodate various science instrument observations at low altitude. Specifically, NEAR spent about 75 days in a 50 x 50 km polar orbit, about 10 days in a 35 x 35 km polar orbit, and about 57 days in a 35 x 35 km equatorial (retrograde) orbit. The direct orbits at these altitudes were avoided since they were found generally to be unstable. The elongated shape of Eros, with maximum radius of about 18 km, resulted in frequent passes at altitudes less than 17 km. There were also several transition orbits up to 200 km by 200 km where global observations were obtained.

Improving Physical Models

The placement of optical navigation pictures and TCMs has been iterated between 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 by the MSI, NLR and XGRS instruments. The asteroid Eros is shaped irregularly, and the principle semi-axes were measured at about 16.5, 8.0, and 6.5 km. One example of the impact of imprecise knowledge about Eros before arrival was the uncertainty in the orientation of its rotation pole. The pre-arrival estimates of the orientation for the rotation pole of Eros varied by more than 4 degrees. After obtaining the initial landmark tracking during the early orbit phase, the navigation team was able to estimate the pole orientation to within 0.05 degrees, one sigma. After additional data were processed, Eros' rotation pole right ascension was estimated to be 11.369 +/-0.003 deg, one sigma, and pole declination was 17.227 +/-0.006 deg, one sigma in J2000 coordinates[4].

The spin orientation and rate was important not only to orient the gravity field model for subsequent orbit determination and prediction, but it also impacted the mission design by placing a more precise date at which Sun would cross Eros' equator. As a

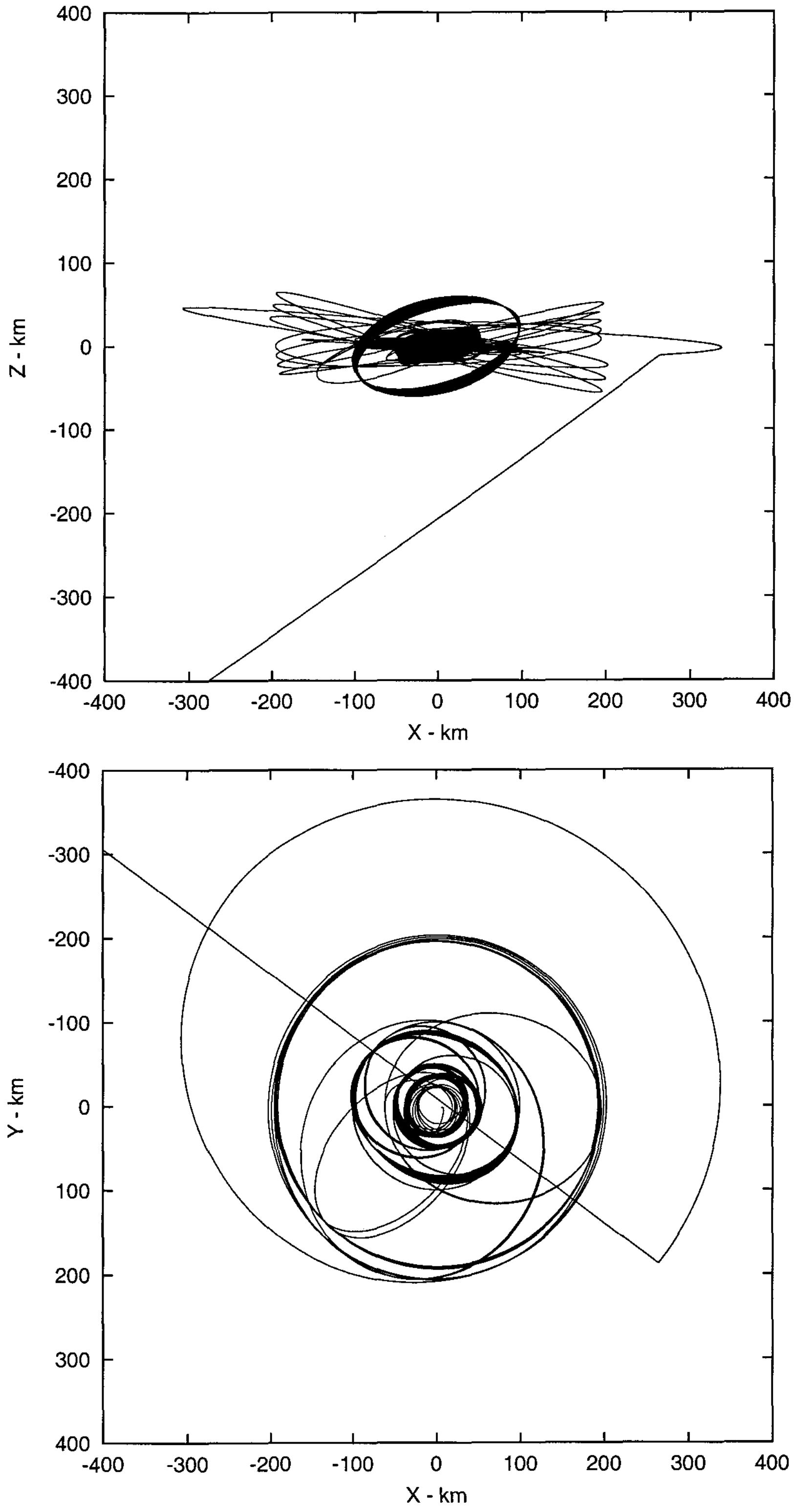

Figure 2. Approach (diagonal line) and orbit phase of NEAR covering February 14, 2000 to February 12, 2001, shown (bottom) in the plane normal to the Sun-Eros line (the Sun plane-of-sky), and (top) in an orthogonal top view. The origin is at the center of mass of the asteroid 433 Eros.

result of this update, a maneuver originally designed to place the spacecraft into a polar orbit in July 2000, was moved by more than a week. Similar updates to physical models and improvements in navigation accuracy resulted in the orbit phase being re-planned by the navigation team a total of seven times after orbit insertion. The end-of-mission close flybys scheduled after January 24, 2001 were re-planned at least 3 times.

CLOSE FLYBYS

The first close flyby of Eros' surface was initiated by orbit correction maneuver number 16 (OCM-16) on October 25th that targeted a close flyby at about 5km altitude above one end of the 'long' axis. The basic technique for the close flyby was to place the spacecraft in an eccentric orbit with true anamoly 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 October 12 with OCM-14 that lowered periapsis from the 100 x 100 km orbit to 50 km. This was followed by OCM-15 which circularized the orbit at 50 x 50 km on October 20. After OCM-16 and the close approach on October 25, OCM-17 occured at the apoapsis after the flyby, about 20 hours after OCM-16, to return to a 200 x 200 km orbit. The delivery schedule for OCM-14, -16, and -17 was designed to adapt to changes caused by execution errors in each of those burns. Beginning about October 9, the predicted time of closest approach was varying up to 20 min. This was compensated by the late update for OCM-17 on Oct 26th at 07:00 UTC. 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 of 1% magnitude overburn (bias) and 1% over in each component (pointing), and extreme execution errors of 20% magnitude overburn (bias) and 10% over in each component (pointing). Neither set of assumptions resulted in an impacting trajectory. The worst case from this set had a minimum flyby altitude of 277m.

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 eleven months of orbiting Eros, another series of low-altitude fly overs was planned for late January, 2001. This came at the end of a long interval of 35 x 35 km retrograde, equatorial orbits that began on December 13, 2000, that were designed to meet XGRS viewing requirements. The approach this time was to establish an eccentric orbit measuring 35 x 21 km on January 24^{th}, remain in that orbit for several days, stabilize the orbit determination estimates and trajectory predictions, and then lower periapsis further on January 28, 2001 (OCM-22), to 35 x 19 km so that the target altitude of less than 3 km, but no closer than 2 km, was achieved. The OCM-22 maneuver resulted in the closest over flight of about 2.7 km on January 28, 10:24 UTC, and was followed about 16 hours later by OCM-23 which returned to the 35 x 35 km circular orbit. The geometry of the close flyby orbit, showing the highly perturbed orbit is shown projected into the Eros equator plane in Figure 3.

The plans for the NEAR Shoemaker's end-of-mission in February 2001 were reviewed by the Science and Mission Operations Teams. The end-of-mission phase began on January 10, 2001 and ended on February 14, 2001. The Science Team requested the following additional orbit conditions be included in the last weeks of the mission: (1) at least 10 high-inclination orbits at less than 35-km radius, (2) at least two

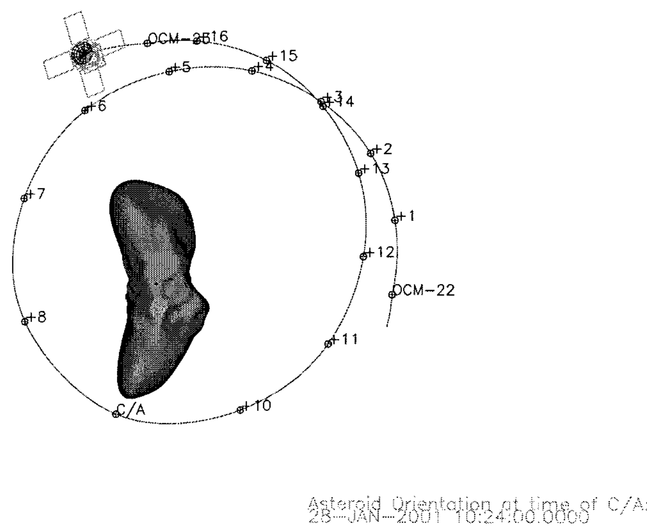

Figure 3. Orbit for January 28 close flyby. Eros is oriented at time of closest approach (C/A).

low-altitude (2-5 km) flyovers at scientifically interesting sites. The minimum altitude was chosen to minimize risk (i.e., it depended on latest navigation error estimates), (3) imaging at two or more sites with resolutions of about 10 cm or better. (This requires altitudes of roughly 500 meters.), and (4) magnetometer measurements in wake region (i.e., Eros' shadow region). The Mission Operations Team concluded that a passage through Eros' shadow region would involve unacceptable risk (battery required for power), and might end the mission prematurely, so the orbit design was constrained to avoid solar occultation. The other requests were met with the exception that only one site was imaged at 10-cm resolution (the landing site) because there was not enough fuel to consider a second site. This paper will not discuss the landing of NEAR, as that topic is covered in a companion paper submitted to this conference[3].

ORBIT ESTIMATION

Navigation with Radio Metric Tracking

DSN radio metric data was used for navigation of NEAR. The radio metric data types available included (1) 2-way, X-band Doppler and range, (2) 2-way minus 3-way Doppler (Narrow band VLBI), and (3) 1-way, X-band Doppler (not processed). The 2-way Doppler was weighted at 0.1 mm/s for 60 s count time, and the 2-way range was weighted at 200 m. The range was deweighted 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 routine processing used only the 2-way Doppler and range. During approach and rendezvous, a combination of 2-way Doppler and range and the 2-way minus 3-way narrow band VLBI was used as a consistency check. When processed in the orbit determination filter, the DSN inter-complex timing offset for the two antennae was used to calibrate the VLBI points.

Navigation with Optical Landmark Tracking

The optical landmark tracking process for NEAR had two characteristics. One was the initial identification and determination of a set of landmark craters (the landmark database), and the other was finding and using those same landmarks 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 landmarks while also building up the landmark database. Hence, the picture planning process had to provide enough pictures to build a reasonable number and distribution of landmarks, and it had to provide designated optical tracking images of previously identified landmarks. The tracking information from optical landmark images is in measuring the apparent motion of a landmark in a series of pictures where viewing geometry is changing due to the relative motion of Eros spinning about its axis and the orbit of the spacecraft. Note that a single picture was thus useless as navigation tracking data.

The building and maintaining of the landmark database was an ongoing process throughout most of the orbit phase because of the unique lighting conditions at 433 Eros. Upon arrival, only the North polar region of Eros 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 1 presents a summary of some characteristics of the optical landmark process for NEAR. The details of optical landmark processing and results are given in Owen, et al[9].

Table 1. Operational summary of optical landmark tracking for NEAR over the entire approach and orbit phase.

Optical Landmark Processing Characteristic	Quantity	Percent of Total
Total number of pictures taken starting 12/17/1999	181,393	
Number of pictures downloaded to JPL for analysis	33,968	(18.73 %)
Number of useful pictures (at least 1 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	

Navigation with Laser Ranging

The NEAR Laser Range (NLR) instrument provided useful altimeter range measurements to the surface of Eros whenever the range to the surface was less than a couple of hundred kilometers. This information was used to assist navigation in two ways. The first method is 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 is to use the NLR data to solve for an accurate shape model of Eros which can then be 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 the 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. The direct use of NLR data for orbit determination was never used for NEAR navigation operational deliveries, but the technique was used as a consistency check on the production orbits that were produced by processing DSN radio metric Doppler and range combined with optical landmarks. The navigation performance when using NLR data is described in Bordi, et al[7].

SUMMARY

The NEAR Shoemaker spacecraft was the first to orbit a small body, the asteroid 433 Eros. The design and estimation techniques necessary to plan and execute its orbit about an irregularly shaped small body had to be developed and tested as 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 Eros. The navigation challenge for the orbit phase was to adapt the orbit plan while adjusting for the crudely known asteroid physical parameters. Improvements in the estimates of Eros' 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) meant that the spacecraft could easily escape or crash into the surface of Eros with small changes in velocity. This placed additional demands on navigation accuracy while also imposing a generally shorter response time than usual for planetary orbit missions.

The weak, non-spherical 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 radio metric 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 radio metric tracking from NASA's Deep Space Network. To improve the spacecraft pointing knowledge for landmark image processing, occasionally the spacecraft would turn to point the imager at reference stars. 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 asteroid

433 Eros. The navigation team responded by developing new tracking data types and new processing methods specifically for NEAR navigation. Many of these methods should prove useful for navigation of future missions to asteroids and comets.

ACKNOWLEDGMENTS

The research described in this paper was carried out ~~by~~ at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

REFERENCES

1. Farquhar, R. W., Dunham, D. W., and McAdams, J. V., "NEAR Mission Overview and Trajectory Design," *J. Astron. Sciences*, Vol 43, No 4 , Oct.-Dec. 1995, pp. 353-371.

2. Landshof, J. A. and Cheng, A. F., "NEAR Mission and Science Operations," *J. Astron. Sciences*, Vol 43, No 4 , Oct.-Dec. 1995, pp. 477-489.

3. Antreasian, P.G., et al., "The Design and Navigation of the NEAR Shoemaker Landing on Eros," AAS/AIAA Astrodynamics Specialists Conference, Quebec City, Quebec, Canada, July 30-August 2, 2001, Paper AAS-01-372.

4. Miller, J. K., A. S. Konopliv, P. G. Antreasian, J. J. Bordi, S. Chesley, C. E. Helfrich, W. M. Owen, D. J. Scheeres, T. C. Wang, B. G. Williams and D. K. Yeomans, "Determination of Shape, Gravity and Rotational State of Asteroid 433 Eros," *Icarus*, in review.

5. Dunham, D. W., et al., "Recovery of NEAR's Mission to Eros," International Astronautical Congress, Paper IAF-99-Q.5.05, Amsterdam, The Netherlands, October 4-8, 1999.

6. Antreasian, P. G., et al., "Preliminary Planning for NEAR's Low-Altitude Operations at 433 Eros," AAS/AIAA Astrodynamics Specialists Conference, Girdwood, Alaska, August 16-19, 1999, Paper AAS-99-465.

7. Bordi, J. J., et al., "The Impact of Altimeter Range Observations on NEAR Navigation," AIAA/AAS Astrodynamics Specialists Conference, Denver, Colorado, August 14-17, 2000, Paper AIAA 2000-4423.

8. Holdridge, M. A., et al., "433 Eros Orbital Mission Operations - Implementing the First Orbital Operation Around a Small Body," AAS/AIAA Astrodynamics Specialists Conference, Quebec City, Quebec, Canada, July 30-August 2, 2001, Paper AAS-01-375.

9. Owen, W. M., et al., "NEAR Optical Navigation at Eros," AAS/AIAA Astrodynamics Specialists Conference, Quebec City, Quebec, Canada, July 30-August 2, 2001, Paper AAS-01-376.