The NEAR Spacecraft's Flyby of Asteroid 253 Mathilde

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Abstract

The terminal navigation of the NEAR spacecraft during its close flyby of asteroid 253 Mathilde involved coordinated efforts first to determine the heliocentric orbits of the spacecraft and Mathilde and then to determine the relative trajectory of the spacecraft with respect to Mathilde. From ground-based optical observations alone, the error of Mathilde's ephemeris at the time of encounter was less than the size of the asteroid itself. Optical navigation images of Mathilde made from the NEAR spacecraft were utilized to reduce the impact plane targeting uncertainty to less than 9 kilometers at closest approach and to less than 4 seconds in the time of closest approach. The gravitational perturbation

of Mathilde upon the passing spacecraft was apparent in the spacecraft Doppler tracking data. Asa result of the accurate targeting achieved, this tracking data could be used to determine Mathilde's mass as (1.024 +/- 0.058) x 10^{20} g. Coupled with a preliminary volume estimate provided by the NEAR imaging team, this mass suggests a surprising low bulk density for Mathilde of 1.3 g/cm^3 and a relatively high porosity of over 50%.

Introduction

The Near-Earth Asteroid Rendezvous (NEAR) spacecraft was successfully launched using a Delta 2 rocket on February 17, 1996. As the first launch of NASA's Discovery program, the NEAR spacecraft was designed to rendezvous with asteroid 433 Eros in January 1999 and spend 13 months in close orbits about this near-Earth object. As such, the design and instrumentation of the NEAR spacecraft were optimized for the close orbits of Eros. While refining the trajectory required to effect an Eros rendezvous, the NEAR project identified an opportunity to fly past the unusual and relatively large asteroid 253 Mathilde on June 27, 1997, one and one half years prior to the Eros rendezvous. Despite the added complexity and slight fuel penalty of diverting the spacecraft to effect a close flyby of Mathilde, the NEAR project recognized the importance of such an opportunity and made the commitment to include the Mathilde flyby in the mission plans (l). While the Galileo spacecraft had made successful flybys of asteroids 951 Gaspra and 243 Ida in 1991 and 1993, both of these asteroids were relatively bright and of the spectral class termed *S*, while Mathilde was thought to be very black and of the spectral class C (2). In addition, the relatively large size of Mathilde and the close flyby distance of about 1200 km provided the possibility that Mathilde's mass could be determined, thus providing the first mass estimate of an asteroid determined from its perturbation on a passing spacecraft.

The primary objective of the NEAR mission is to orbit asteroid Eros beginning in January 1999. Once in orbit about Eros, NEAR will make the first comprehensive investigation of an asteroid's physical properties and surface composition. The Multi-Spectral Imager (MSI) will map Eros' form and color variations at 3-4 meter resolution. The Near Infrared Spectrometer will map the mineral properties of Eros' surface to 250 meter resolution. The X-ray and gamma ray spectrometers will measure the abundances of several key elements in Eros' surface layer, including aluminum, magnesium, silicon, iron, calcium, and sulfur. These abundances will then be compared to those of a variety of meteorite samples on Earth to determine whether this type of asteroid could be the source for certain meteorite types. The NEAR magnetometer will ascertain whether Eros has an intrinsic magnetic field and the laser rangefinder (lidar) will be used to determine the shape and topography of Eros' surface to an accuracy of 10 meters, The mass and mass distribution of Eros will be investigated while the NEAR spacecraft is in orbit about Eros by making use of the spacecraft's radio metric tracking data along with the imaging and lidar data. Table 1 gives a brief introduction to the NEAR science investigations. Figure 1 gives the NEAR spacecraft trajectory profile including the 2 year Earth return orbit that is being used to help re-shape the spacecraft's initial orbit into one that closely matches that of asteroid Eros. It was during this latter orbit that the Mathilde flyby occurred.

Because the NEAR spacecraft was designed to orbit Eros, the Mathilde flyby introduced several challenges to the project. First amongst these was the necessity to point the MS] at the asteroid during the encounter. Because the imager is mounted to the spacecraft without an articulating platform, the spacecraft's solar panels had to be pulled off the sun's direction during the flyby and they were not able to provide enough power to operate more than the MSI. The imaging science objectives at Mathilde are noted in a companion paper by Veverka et al. (3). This article deals primarily with the spacecraft navigation issues and the mass determination of Mathilde that resulted. In the next section, we briefly discuss the efforts that were required to navigate the NEAR spacecraft to the Mathilde encounter. Therein, we discuss the ground-based efforts to improve Mathilde's position predictions (ephemeris) followed by a discussion of how the spacecraft's optical navigation images of Mathilde were used to refine our knowledge of the relative positions of the spacecraft and asteroid at the time of the encounter. Then follows a section on the combined solution for the spacecraft and Mathilde orbits and the resultant mass determination for Mathilde. In the final section, we discuss the mass determination estimate of Mathilde that resulted from the accurate navigation efforts and the preliminary estimates of the asteroid's bulk density.

Targeting for a Close Encounter with Asteroid 253 Mathilde

Accurate navigation of the NEAR spacecraft's flyby of asteroid Mathilde was required in order to realize any of the science objectives (4). The NEAR spacecraft flew past Mathilde at about 10 km/s close to the planned flyby distance of 1200 km. The flyby distance was selected as a trade- off between a distance that was close enough to provide high resolution images (150 m at closest approach) yet far enough so that the angular slew rate would not be too high and there would be enough time for slewing the spacecraft and camera to image the entire area of the sky within which Mathilde was expected. The imaging sequence onboard the NEAR spacecraft could tolerate an error of about 20 seconds in the time of closest approach before the closest encounter images would be lost, A major error source for the NEAR spacecraft's targeting error was the uncertainty in the predicted position of Mathilde (ephemeris uncertainty) at the time of encounter, and this could be improved using approach optical navigation imaging data (Opnav images) taken onboard the spacecraft itself.

The Mathilde ground-based ephemeris development effort began in late 1994 after the asteroid was identified as a potential flyby target for the NEAR spacecraft. The initial Mathilde orbits included only 60 observations over the interval 1927 May 3-1994 January 6. In January 1995, Edwin Goffin made available a data set wherein he had re-reduced many of the existing observations with respect to more modern reference star catalogs and extended the observational interval back to the time of this asteroid's discovery in mid-November 1885. An observing campaign was mounted for the 1995 and 1996 opposition times when the Earth, Sun, and asteroid were favorably placed for observations. The final pre-encounter orbit of Mathilde (JPL reference orbit 49) was based upon 610 position observations from December 5, 1885 through June 24, 1997. Extensive sets of observations were received from a number of observatories, including McDonald (Texas), Klet (Czech Republic), Modra (Slovakia), Siding Spring (Australia), Oak Ridge (Massachusetts), the Carlsberg Automatic Meridian Circle (Canary Islands), and the U.S. Naval Observatory Flagstaff Station (Arizona). Some of the observations from Flagstaff were reduced with respect to extragalactic radio sources; these observations were given increased weight in the orbit determination process because they were relatively unaffected by the systematic errors present in most reference star catalogs(5).

Observations taken in the three months prior to the flyby were instrumental in providing an accurate Mathilde ephemeris to the flight project. Beginning on April 7, 1997 observations became available from the observatories of Gordon Garradd (Australia), Mauna Kea (Hawaii), and Table Mountain (California). Through the efforts of two of us (WMO and SPS), many of the observations from Table Mountain were reduced with respect to reference stars from the Hipparcos and Tycho star catalogs and were thus upweighted in the orbital solutions because these positions were considered an order of magnitude more accurate than observations reduced with respect to traditional reference star catalogs. Some 24 of these observations became available covering the dates of 1997

May 21, May 30, May 31, June 17, June 20, June 22, and June 24. Through the courtesy of Michael J. Perry man of the Hipparcos project, these reference star positions were provided in advance of publication. Were these Hipparcos-based positions of Mathilde not available prior to the encounter, and had we not weighted them strongly in our final orbital solution, the ephemeris errors at encounter would have been at least an order of magnitude larger than those real ized.

For fast flybys of target bodies, position errors are often expressed in the so-called "impact plane" of the spacecraft. This impact plane coordinate system is defined by the unitized relative velocity vector between the spacecraft and asteroid at intercept (S), a unit vector **(T)** that is parallel to the Earth mean equator (J2000) and normal to S, and by the unit vector **R = S x T.** The vector **R** points south and **T** points west. Vectors **R** and **T** define the impact plane while vector S is directed along the relative velocity vector and perpendicular to the impact plane. By using the optical navigation images of the asteroid as seen by the spacecraft (described below), a best estimate of the asteroid's actual position in space at the time of the encounter was determined. The consistency of the results as more and more pre-encounter, ground-based observations were included in orbital solutions and the very small differences between the observed and predicted positions of Mathilde (generally less than 0.05 arc second) allowed a mid-course maneuver to be performed so accurately nine days prior to the encounter that a risky maneuver at encounter minus 12 hours was cancelled. We note that the actual Mathilde ephemeris error, based only upon pre-encounter, ground-based astrometry, was only 9 km and 27 km in the **T** and **R** directions. The corresponding error in the direction of the spacecraft's relative velocity was 12.6 km or, expressed in terms of the time-of-flight error, 1.3 seconds. From ground-based observations alone, the error of Mathilde's ephemeris, at the time of encounter, was less than the size of the asteroid itself.

The accuracy of the ground-based ephemeris facilitated the initial asteroid acquisition from the NEAR spacecraft because the search could be restricted to a few pixels near the asteroid's predicted position. This was a fortunate circumstance since the initial optical navigation images of Mathilde had extremely low signal-to-noise ratios.

The NEAR flight team took a total of 96 navigation pictures of Mathilde against a star background during the last two days before the flyby. Since Mathilde was only 40 degrees from the sun, the spacecraft had to be turned so that the solar panels pointed 50 degrees from the sun. The resulting loss of power made these maneuvers risky, and it was decided to take pictures at only six different times, beginning at 41 hours before close approach and continuing at approximately six-hour intervals until 11 hours before close approach. The MS1 obtained 16 one-second exposures through the clear filter at each opportunity. The spacecraft attitude was commanded to drift slightly during the 31 seconds required for the exposures, so that Mathilde and the stars would move by two pixels between the first and last exposure. The CCD chip in the MSI is a frame transfer device, and one quarter of each pixel is not sensitive to light. This slow drift provided protection against Mathilde's image landing on the light-insensitive part of a pixel, and the number of frames protected against data outages and also enabled us to co-add pictures to reduce the background noise.

Observing Mathilde at a solar elongation of only 40 degrees presented two other problems. First, the MSI was not designed to look this close to the sun, and there was a significant amount of stray sunlight in the field, amounting to about 370 DN on the right (sunward) side of the field, increasing to over 1000 DN on the left side. ("DN" is a data number giving the pixel brightness on a linear scale.) Mathilde was centered in the field, where the stray light amounted to 550 +/- 6 DN. The increased background noise made detection more difficult and, in effect, raised the minimum detectable star brightness by about one magnitude (6). Second, Mathilde presented a thin crescent to the spacecraft. Not only did its high phase angle cut down on its total brightness, it also displaced its center of brightness relative to its center of mass. We were able to treat Mathilde's image as if it were a point source, and then we computed the photocenter offset and applied it to our centroids(7).

Mathilde's magnitude was expected to be between 7.9 and 8.9 at the time of the first Opnav frames, brightening to 6.8 +/- 0.5 for Opnav 5 and 5.8 +/- 0.5 for Opnav 6. We were expecting to see Mathilde in co-added frames by Opnav 2, and in individual frames possibly as early as Opnav 3. Mathilde was not detected at all in Opnav 1, even when eight frames were added together. The first tentative detection was in the sum of the last eight frames from Opnav 2, at 6 DN above background and a signal-to-noise (S/N) ratio of 2. That detection was confirmed in Opnav 3, but it was not until Opnav 5 that Mathilde was distinctly visible in individual frames. It appears that Mathilde was actually about 1.5 magnitudes fainter than expected, being 9.5 at Opnav 2 and brightening to 7.6 at Opnav 6.

We found one long-exposure science picture (at mission elapsed time 42827118 or about 12 minutes after the flyby) that contained four usable stars and most of Mathilde. This frame, using a centroid for Mathilde communicated to us by Peter Thomas, was added to the data set. The final data set included five co-added frames from Opnavs 2, 3, and 4, seven individual frames from Opnav 5, all 16 frames from Opnav 6, and the lone post-encounter science frame. These centroids were processed by one of the authors (WMO) using the Optical Navigation Program(8), and the residuals and partial derivatives were merged with the radio metric tracking data for orbit and mass determination.

By processing the optical navigation frames 2-7 in the solutions for the spacecraft and Mathilde orbits, the ***a priori*** ephemeris errors resulting from Mathilde's ground-based ephemeris were reduced from about 30 km to less than 10 km in the impact plane of the spacecraft (see Table 2). The position error in the time-of-flight direction (S) was not significantly affected since the optical navigation images provided very little information about the asteroid's posit ion in the spacecraft-asteroid direct ion,

Combined Orbit Determination Solution for the NEAR spacecraft and Mathilde

The combined orbit determination solutions for the NEAR spacecraft and Mathilde were carried out by D.J. Scheeres, then of the NEAR navigation team at JPL. The orbit determination solutions for the spacecraft were combined with the ground-based pre-encounter Mathilde ephemeris and with the optical navigation frames taken in the two days prior to the Mathilde flyby. The spacecraft orbit leading up to the Mathilde flyby was determined solely with radio metric data acquired by the Deep Space Network (DSN) during routine tracking of the spacecraft. The radio frequencies used for the Doppler tracking were X-band uplink and downlink (8510 MHz), and ranging measurements were routinely taken during each tracking pass. These radio-based solutions were combined with the ground-based ephemeris of Mathilde to produce solutions which predicted the spacecraft flyby conditions at Mathilde in the impact plane described above. Prior to the optical navigation frames, which imaged Mathilde with the NEAR Multi-Spectral Imager (MS I), the spacecraft and Mathilde solutions were uncorrelated with each other, and the flyby uncertainties in the impact plane were computed by adding the spacecraft and Mathilde uncertainties at the flyby time. Given the lack of correlation between the spacecraft and Mathilde measurements, there was a possibility for large systematic errors in the flyby solution, errors which the optical navigation frames can detect. Once Mathilde was identified in Opnavs 2 - 6 it became clear that the spacecraft orbit determination errors and the ground-based Mathilde ephemeris were consistent to well within 1-sigma of the combined orbit determination uncertainties. The optical navigation frames were then used to correct the relative positions of the spacecraft with respect to Mathilde (the correction involving changes to both the spacecraft and Mathilde orbit in inertial space) to provide the spacecraft an accurate Mathilde-centered ephemeris to use for driving its camera pointing during the flyby. After the flyby one usable optical navigation frame was identified (Opnav 7) and incorporated into the solution to provide an improved estimate of the flyby conditions and the time of the flyby. Doppler and range measurements of the spacecraft were available continuously from one week prior to the flyby to almost one week after the flyby with a gap of approximately 1 hour during the actual flyby when the imaging experiment took place. All these data were combined into one orbit determination solution to estimate the mass of Mathilde and corrections to its ephemeris.

The radio metric data arc used for the final mass solution spanned from 1997 March 24 (starting about one month after the NEAR solar conjunction) to 1997 July 3 when a deep space maneuver occurred (and which effectively ended the usable data arc for the Mathilde mass determination). The tracking schedule consisted of two to three 8-hour passes per week leading up to the execution of a trajectory correction maneuver which occurred on June 18, after which the tracking was continuous except for one hour near closest approach. During each pass, spacecraft Doppler was recorded and range measurements were taken. Most of the contacts were with the 34 meter HEF antenna at Goldstone, although passes with the Madrid and Canberra 34 meter HEF antennas were occasionally received as well.

The dynamic model used in the orbit determination process incorporates the gravity (including relativistic effects) of all the planets (except Pluto), the moon and the sun. The solar radiation pressure acting on the spacecraft was accurately modeled by incorporating all known spacecraft attitude changes and recomputing the total radiation pressure acting on a detailed model of the NEAR spacecraft represented in the software. Also, stochastic accelerations were applied to the spacecraft with a correlation time of 1.5 days and 1-sigma magnitude of 5 X 10^{-13} km/sec^2. These accelerations model small non-gravitational forces that the software cannot account for, but are small enough so that the mass determination of Mathilde was not corrupted, Many different parameters were included in the actual orbit determination solution so that several potential systematic errors were removed, thus allowing the data measurements to be weighted at close to their actual noise values. Besides the spacecraft state at an epoch, these parameters include a scale factor applied to the solar radiation pressure model, the magnitude and direct ion of the trajectory correction maneuver performed on June 18, the coordinates of all participating DSN tracking stations, the Mathilde ephemeris, and Mathilde's mass(9). Also estimated were stochastic parameters describing the Earth orientation, troposphere and ionosphere delays for each pass, range biases for each pass, and camera pointing biases for each Opnav image. This orbit determination system had been refined and validated (as much as possible) during the months prior to the flyby. Consistency checks on the final solution values of all the parameters were made to ensure that they did not stray outside their expected uncertainty levels. This system allowed the data to be fit very accurately. Doppler data were weighted at 0.0056 Hz (O. 1 rnm/see) and were fit to an accuracy of 0.002 Hz (0.036 nm/see) over the entire arc, and to an accuracy of 0.0015 Hz (0.027 mm/sec) around the actual flyby. Range data were weighted at 1 meter and fit to an accuracy of several meters.

The reconstructed flyby location and uncertainties are given in Table 2. Shown in Figure 2 are the impact plane solutions and uncertainties prior to the Mathilde Opnavs, prior to the flyby (including, all pre-flyby Opnavs) and the reconstructed solution which included one additional post-flyby Opnav and all the post-flyby radio metric tracking. From this figure it is evident that the radio metric data, ground-based Mathilde observations and the spacecraft-based Mathilde observations were all consistent to within their expected uncertainties.

As is apparent from Table 2, the Opnav images reduced the Mathilde-spacecraft relative uncertainties to less than 10 km in the impact plane. Because the Opnavs are taken in the spacecraft's plane-of-sky (impact plane), they can do very little to reduce the uncertainties in the spacecraft-Mathi lde direct ion (S).

The Mass and Bulk Density of Mathilde

Accurate asteroid mass determinations (known to better than 30%) exist for only 1 Ceres, 2 Pallas, 4 Vesta, 11 Parthenope, 243 Ida, and now 253 Mathilde. The values for Ceres, Pallas, Vesta, and Parthenope were computed using their perturbations upon another asteroid or Mars while the mass of Ida was estimated by using the assumed orbital characteristics of its moon, Dactyl. Table 3 gives the mass determinant ion results for these five asteroids and rough estimates for some of their bulk densities.

Mathilde's gravitational perturbation upon the NEAR spacecraft during the flyby produced a shift in the spacecraft's Doppler data of 0.0128 Hz (0.23 mm/sec). By including Mathilde's value of GM (gravitational constant x mass of Mathilde) as one of the solution parameters in the combined orbit determination process, the observed Doppler shift implies a GM of 0.00683 +/- 0.00039 km^3/s^2 and a corresponding mass of 1.024 +/-0.058 x 10^{20} g. The corresponding deflection angle of the NEAR trajectory as a result of Mathilde's gravitational interaction was approximately 0.11 microradians, and the total heliocentric change in velocity was approximately 1.12 mm/sec. The Doppler shift due to

Mathilde's mass perturbation is clearly evident in the spacecraft tracking data, given the level of accuracy seen in the data residuals (see Figure 3).

Prior to the Mathilde encounter, we had assumed that the effective radius of Mathilde was 30.5 km and its bulk density was 2.5 g/cm^3. Thus the pre-encounter estimate for Mathilde's GM was 0.0198 km^3/sec2. The preliminary GM determination above is only one third this ***a priori*** value. Based upon the NEAR images of Mathilde, Peter Thomas has provided an average radius of 26.5 +/- 1.3 km, a nominal volume estimate of 78,000 km^3 with lower and upper limits of 67,000 km^3 and 90,000 km^3 respect ivel y(3). The determined mass and volume estimates for Mathilde then suggest a preliminary bulk density estimate of 1.3 +/- 0.2 g/cm^3.

The estimated average radius and volume for Mathilde are relatively poorly known because the NEAR cameras viewed only about 60% of the solar illuminated surface as it flew past. This circumstance is due to the very long 17.4-day rotation period for Mathilde(10). Because Mathilde passes 1.3 AU from the Earth in early November 1997, Steve Ostro and his colleagues plan to use the Arecibo Planetary radar facility to "radar image" Mathilde for several weeks in an effort to determine the asteroid's spin characterist its, surface properties, shape, and volume(11). The radar observation campaign will take advantage of Mathilde's existing light curve to help determine the asteroid's rotation state. As a result of using the NEAR spacecraft images in conjunction with ground-based light curve analyses and radar observations, there is a good chance that the accuracy of Mathilde's volume estimate (and bulk density) can be improved to a level of about 10%.

The preliminary bulk density for Mathilde is lower than our expectations. However, we note that in the 1989 study of the effects of large numbers of asteroids upon the orbit of

Mars, Standish and Hellings concluded that the average bulk density for the C class asteroids was 1.7 +/- 0.5 g/cm^3. As part of an improved planetary ephemeris development effort, Standish found recently that this average value was 1.2 -t /- 0.1 g/cm^3 (12). While Standish notes that the given formal uncertainty on this latter value is likely to be optimistic, this result is consistent with Mathilde's preliminary bulk density determination. If we assume that Mathilde was formed of black chondritic material (13) with a density (D) of about 2.8 g/cm^3, Mathilde's bulk density (d) of 1.3 g/cm^3 suggests that the asteroid's porosity (p = I-d/D) is over 50%.

Summary

The terminal navigation of the NEAR spacecraft was extremely successful, thus allowing impressive images to be taken and an accurate mass to be determined for asteroid 253 Mathilde. From ground-based optical astrometric observations alone, the ephemeris error for Mathilde was less than 30 km in the spacecraft's impact plane. Optical navigation images of Mathilde taken onboard the NEAR spacecraft were used to further refine the impact plane positions of Mathilde to an accuracy of less than 10 km. A velocity perturbation on the NEAR spacecraft during the 1226 km flyby of Mathilde was obvious in the Doppler tracking data and allowed the mass of Mathilde to be determined to better than 6% --- the first asteroid mass determination using spacecraft tracking data. Although Mathilde's volume could not be determined to better than about the 20% level, it seems likely that the bulk density of Mathilde is a surprisingly low 1.3 g/cm^3 and that the porosity of this C-type asteroid is above 50%. This level of porosity suggests that either Mathilde formed from relatively loosely packed fragments or evolved into a "rubble pile" of material as a result of repeated impacts from other asteroids.

REFERENCES AND NOTES

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6. Positions for the three bright reference stars in the field were taken from the highly accurate Hipparcos catalog (M .A. C. Perryman, 1997. The Hipparcos Catalogue, European Space Agency). Although Hipparcos reference star positions had been made available in advance of publication for improving the orbit of asteroid Ida prior to the Galileo spacecraft flyby in August 1993 (W. M. Owen Jr. and D.K. Yeomans. Astron. J., 107, 2295, 1994), the Mathilde encounter marks the first operational use of the Hipparcos catalog by JPL navigation.

7. Our centroiding algorithm modeled the camera's point-spread function as an elliptical Gaussian with sigmas of 1.7 pixels in the sample direction and 1.0 pixel in the line direction. The DN value in each pixel was modeled by the integrated flux from the point source plus a constant background, with the integration extending over only the light-sensitive part of the pixel. An iterative linearized least-squares procedure then solved for the (x,y) coordinates of the centroid, the brightness of the point source, and the background. This procedure failed at the low signal-to-noise ratio typical of co-added Mathilde images, and we estimated Mathilde's center by eye and lowered the weight appropriately.

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14. A portion of this research was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract to NASA. We acknowledge the technical assistance and helpful discussions provided by P. W. Chodas, A.B. Chamberlin, J.G. Giorgini, M.S. Keesey, E.M. Standish, and R.N. Wimberly. Important ground-based astrometric observations of Mathilde were provided by several observers including M. Buontempo, D. Clowe, A. Galad, G .J. Garradd, E. Goffin, O. Hainaut, A.B. Monet, A. Mrkos, R. McNaught, P.J. Shelus, R. Stone, J. Surace, D. Tholen, J. Ticha, A. Whipple, and R.J. Whiteley. Pre-publication estimates of Mathilde's size and volume were kindly provided by the NEAR MSI team, in particular by Peter Thomas and the team chief, Joe Veverka. A large part of the success of the very difficult encounter with Mathilde was due to the tireless efforts of the NEAR Flight Team (both at APL and JPL). The outstanding leadership of NEAR's Systems Engineer, Andy Sante, deserves special recognition.

FIGURES

Figure 1. Spacecraft Trajectory Profile

Figure 2. Mathilde Impact Plane Uncertainties

After the trajectory course maneuver nine days prior to the encounter, the nominal aim point for the NEAR spacecraft was the center of the first ellipse - located about 1220 km sunward of Mathilde. This first ellipse represents the 1-sigma targeting uncertainty prior to the processing of on-board optical navigation data (Opnavs). The second ellipse represents the Mathilde targeting uncertainty after processing pre-encounter Opnavs 2-6 while the third ellipse represents the post-encounter knowledge of Mathilde after an additional post-encounter science image was used as Opnav 7.

Fig. 3. Doppler Tracking Residuals During Mathilde Flyby

Prior to the Mathilde close approach on June 27, 1997 at 12:55:57 UTC, the differences (residuals) between the observed and predicted spacecraft X-band Doppler measurements were centered upon zero. In this example, our predictions assumed a zero mass for Mathilde so that, after the flyby, the residuals shift off zero by an amount (-0.013 Hz = -0.23 mm/s) equal to that component of Mathilde's velocity perturbation on the NEAR spacecraft that acts along the Earth-spacecraft direction.
The residuals marked A, B, and C, represent observations from the Deep Space Network's 34 meter HEF antennas at Goldstone, CA, Canberra, Australia, and Madrid, Spain, respectively.

Table 1. NEAR Science Instruments

Science Investigation (Team Leader)	Scientific Objectives
Multispectral Imager Near-Infrared Spectrograph (Joseph Veverka, Cornell Univ.)	For target bodies, determine their size, shape, volume and surface morphology. Map distribution and abundance of minerals. Determine processes that affect their surfaces and internal structure and investigate compositional similarities to meteorites.
X-Ray/Gamma-Ray Spectrometer (Jacob I. Trornbka, NASA/GSFC)	Generate abundance maps of various elements including Mg, Al, Si, Ca, and Fe to determine heterogeneities in the surface.
Magnetometer (Mario H. Acuna, NASA/GSFC)	Detect whether or not a remnant magnetic field exists.

Laser Altimeter “ (Maria Zuber, M, I. T.)	Determine shape and detailed surface structure of Eros; study surface morphology and infer geological processes.
Radio Science (Donald K. Yeomans, NASA/JPL)	Determine masses and bulk densities for Eros and Mathilde. For Eros, determine gravity field and spin characteristics.

Table 2: NEAR Spacecraft Flyby of Asteroid Mathilde and Impact Plane Targeting Errors

Time of closest approach:	27-JUN-1997 12:55:56.7 (3.6 sec.) UTC	
Close approach distance:	1225.615 (5.753) km	
Flyby speed:	9.931556 (0.000002) km/sec	
Impact plane parameters		
	R (km)	T (km)
Coordinates:	-1221.5	-100.0

Joint Spacecraft-Mathilde flyby uncertainties
(includes pre- and post-encounter optical navigation images)

Uncertainties: (1-sigma)	R (km)	T (km)	S (km)
	5.7	6.8	36.0

Table 3. Asteroid Mass and Density Determinations

Asteroid	Mass (10^{22} g)		Bulk Density (g/cm^3)		Reference
1 Ceres	117	(6)	2.3	(1.1)	Schubart & Matson (1979)
	103	(6)			Landgraf (1988)
	99	(4)	2.3		Standish & Hellings (1989)
	93	(6)			Goffin (1991)
	91	(4)			Williams (1991)
	99	(4)			Viateau & Rapaport (1995)
	94	(4)			Standish (1997)
2 Pallas	21	(4)	2.6	(0.6)	Schubart and Matson (1979)
	28	(4)	3.4		Standish & Hellings (1989)
	20	(2)			Standish (1997)
4 Vesta	27	(2)	3.3	(1.5)	Schubart and Matson (1979)
	30	(6)	3.9		Standish & Hellings (1989)
	26	(2)			Standish (1997)
11 Parthenope					
	0.51	(0.02)			Viateau & Rapaport (1997)
243 Ida	0.0042	(0.0006)	2.6	(0.5)	Belton et al. (1995)
253 Mathilde					
	0.0102	(0.0006)	1.3	(0.2)	Present study

Table 3 references

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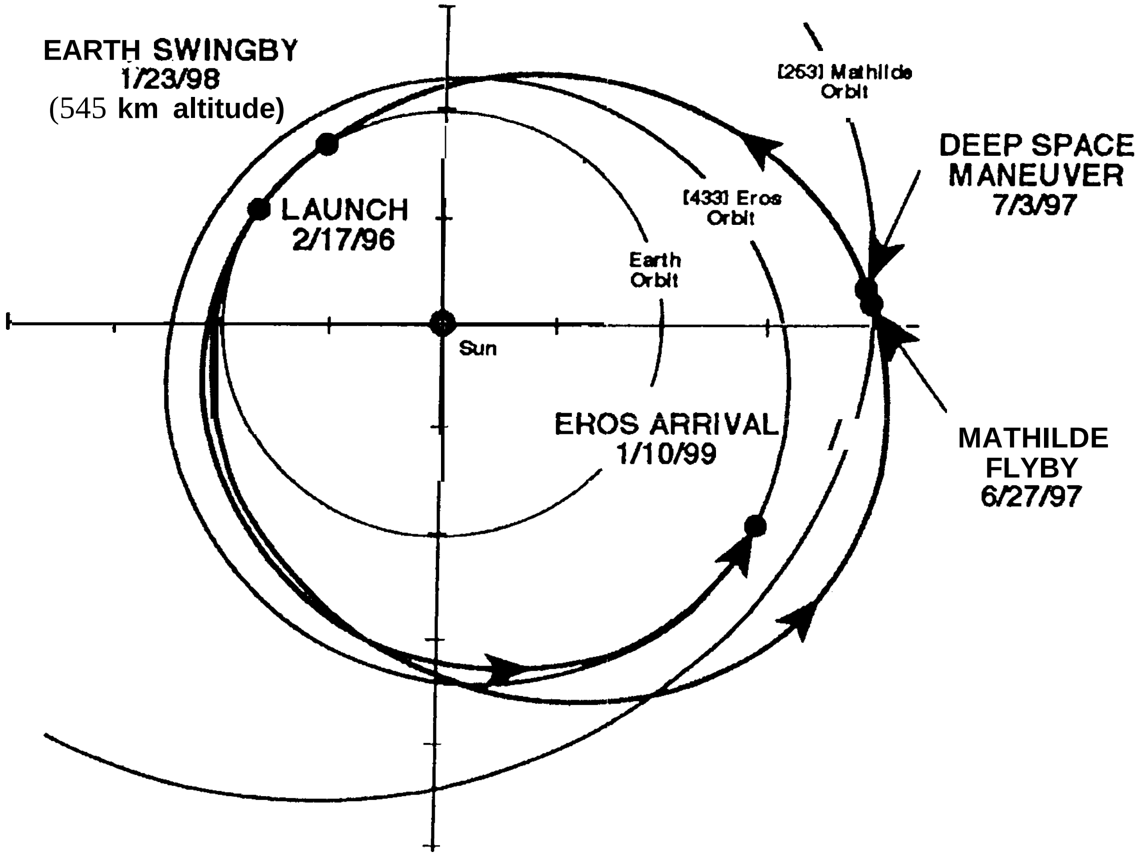
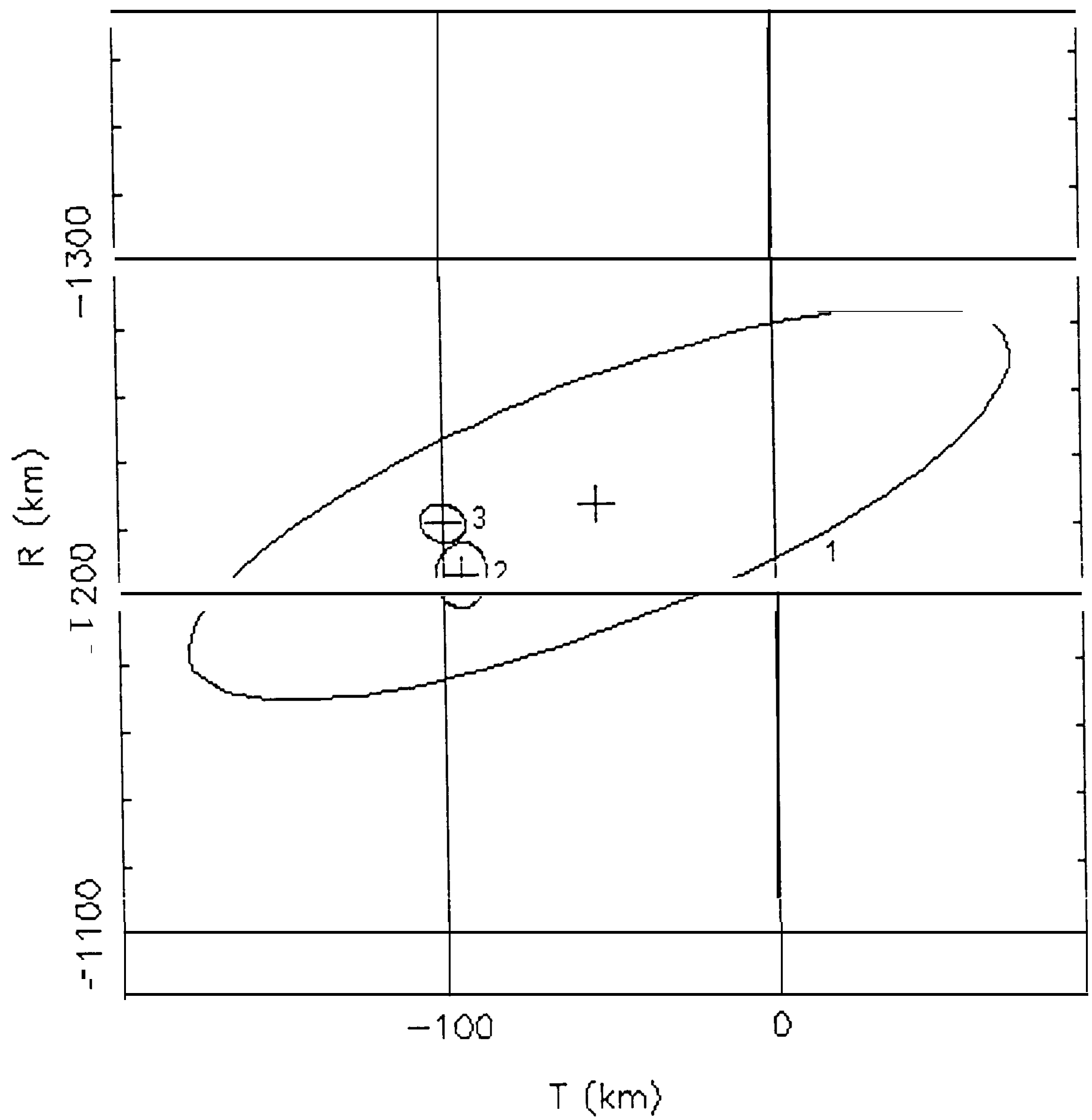
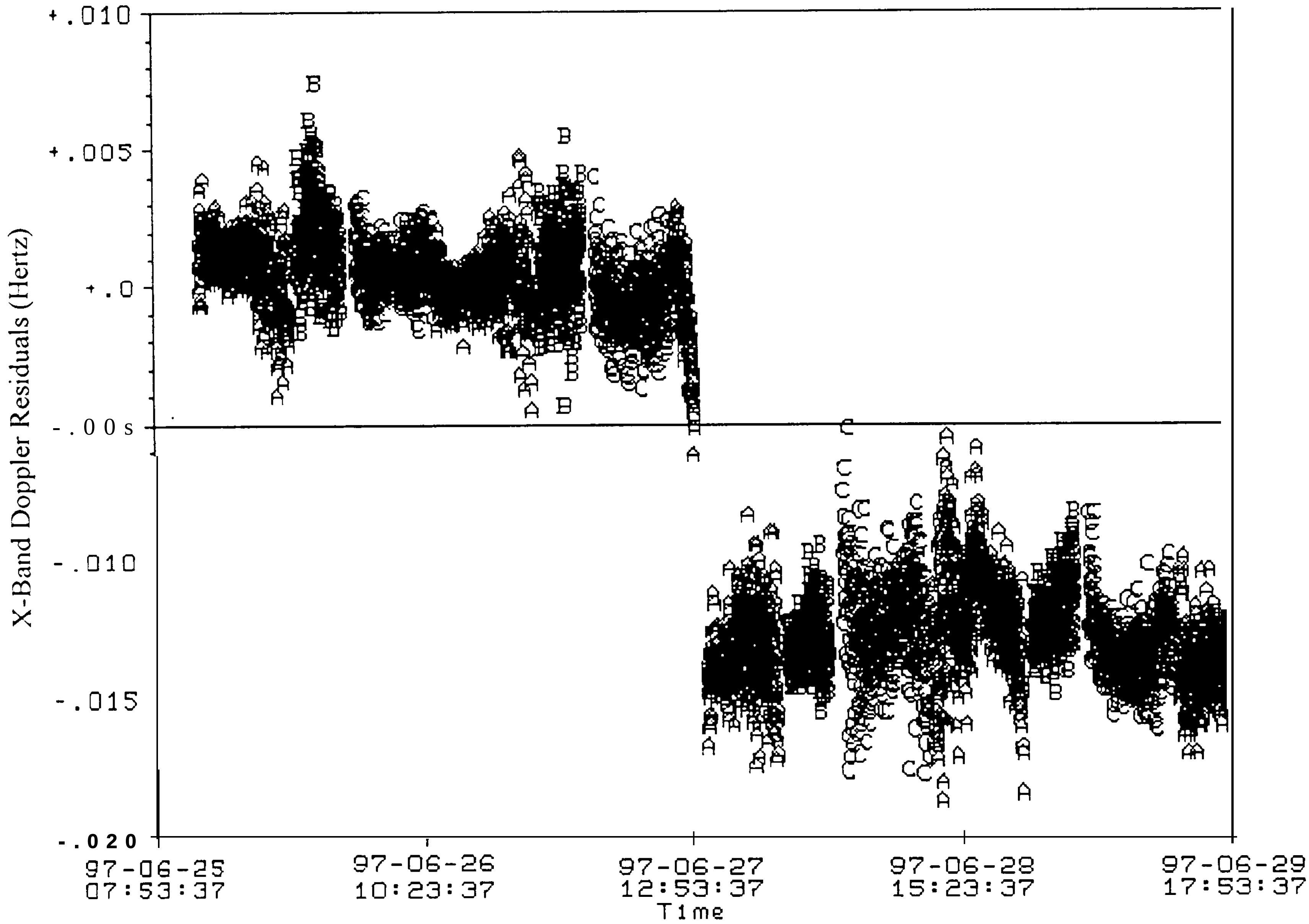

EARTH SWINGBY
1/23/98
(545 km altitude)
LAUNCH
2/17/96
[253] Mathilde
Orbit
DEEP SPACE
MANEUVER
7/3/97
[433] Eros
Orbit
Earth
Orbit
Sun
EROS ARRIVAL
1/10/99
MATHILDE
FLYBY
6/27/97


-1300
-1200
-1100
R (km)
-100
0
T (km)
1
2
3



+.010
+.005
+.0
-.00s
-.010
-.015
-.020
X-Band Doppler Residuals (Hertz)
97-06-25
07:53:37
97-06-26
10:23:37
97-06-27
12:53:37
97-06-28
15:23:37
97-06-29
17:53:37
Time