NEAR MISSION OVERVIEW AND TRAJECTORY DESIGN[1]

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The Near-Earth Asteroid Rendezvous (NEAR) mission will be the first launch in NASA's new series of low-cost planetary missions called the Discovery Program. In February 1996, a Delta-2 rocket will place NEAR into a two-year ΔVEGA trajectory that will eventually rendezvous with the large near-Earth asteroid, 433 Eros. The initial close pass at Eros (distance ~500 km) will occur on February 6, 1999. Later, as the spacecraft is maneuvered closer to Eros, NEAR will conduct science operations from orbits as low as 35 x 35 km. On its way to Eros, NEAR will perform a flyby of the main-belt asteroid 253 Mathilde on June 27, 1997. Among its many spaceflight "firsts," NEAR will be the first spacecraft to orbit a small body.

BACKGROUND

In 1983, NASA's Solar System Exploration Committee suggested that a rendezvous-class mission would be an ideal way to begin a program of spacecraft missions to near-Earth asteroids [1]. This was followed by a comprehensive assessment of a Near-Earth Asteroid Rendezvous (NEAR) mission by a distinguished Science Working Group (SWG) in 1986 [2]. The SWG found that the NEAR mission could be done with a Planetary Observer spacecraft, and also concluded that almost any dynamically accessible near-Earth asteroid would be a suitable target for the first mission.

Unfortunately, NASA's Planetary Observer Program was terminated after only one mission, the ill-fated Mars Observer. Therefore, plans for a NEAR mission remained in limbo after 1986. However, in 1990, NASA introduced a new program of low-cost planetary missions called "Discovery." A Discovery Science Working Group (DSWG) was established, and in October 1991, the DSWG recommended that "the first mission of the Discovery Program should be a rendezvous with a near-Earth asteroid" [3].

In 1991, competitive proposals for the NEAR mission were prepared by the Applied Physics Laboratory (APL) and the Jet Propulsion Laboratory (JPL). After a thorough review of the two proposals by a select panel of experienced project managers, NASA awarded primary management responsibility for the NEAR mission to the APL team. Following the selection, system definition studies were carried out at APL in 1992-93. The development phase for NEAR began in December 1993, and the spacecraft is scheduled to be launched in February 1996.

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NEAR MISSION OPPORTUNITIES

According to NASA instructions, Discovery missions must have well-focused scientific objectives as well as strict limits on project costs and development time. Mission costs through launch plus 30 days must not exceed $150 million in FY92 dollars, and development times cannot be longer than 35 months. In addition, Discovery missions must use launch vehicles of the Delta class or smaller. This last constraint drastically limits the number of potential mission opportunities for a rendezvous with a near-Earth asteroid.

In 1992, a search was conducted for admissible launch opportunities for a Discovery-class NEAR mission. The results of this survey are given in Table 1. These opportunities were determined by applying the following constraints:

- Launch dates in the interval 1996 to 2000.
- The orbit of the target asteroid should be well determined (i.e., a numbered asteroid).
- The aphelion of the target asteroid should be less than 2.5 AU.
- The post-launch ΔV requirements should not exceed 2.00 km/sec.
- The total ΔV requirement should be less than 6.00 km/sec. (Total ΔV is the sum of the ΔV needed to depart from a low circular Earth parking orbit and the deterministic post-launch ΔV that is needed to complete the rendezvous).

The third and fourth conditions relate to spacecraft cost and complexity (especially with respect to power, thermal, and propulsion subsystems), while the fifth condition ensures that the mission can be accomplished with a Delta-class launch vehicle. Although these conditions severely restrict the availability of suitable mission candidates, the limitations are consistent with Discovery program guidelines. Even with these restrictions, four acceptable mission opportunities were found during the five-year period.[3]

The original target for NEAR was 1943 Anteros, but early in 1992, programmatic considerations resulted in a switch to 4660 Nereus with a launch in January 1998. This mission opportunity was especially attractive because a number of extended-mission scenarios involving flybys of additional asteroids and comets were possible following the completion of the Nereus rendezvous mission [5]. However, as shown in Table 1, the total ΔV requirement is a little bit on the high side.

Table 2 lists some orbital and physical parameters for the target asteroids of Table 1, and compares them with the well known near-Earth asteroid 433 Eros [6]. Although Nereus satisfied all the requirements for a Discovery-class mission, some scientists were concerned that its small size could restrict the quantity and diversity of the science return (i.e., a long-duration mission to such a tiny object might become somewhat boring after the initial results were obtained). Responding to this concern, mission planners tried to find some way to reach the much larger target asteroid, Eros.

[3] Several opportunities also exist for the recently-discovered asteroid 1989 ML [4]. However, although this object has been observed during two separate appearances, it is still an unnumbered asteroid.

Table 1
NEAR Mission Opportunities: 1996 – 2000

Target Asteroid	Launch Date	Arrival Date	C3 (km^2/sec^2)	Post-Launch ΔV (km/sec)	Total ΔV (km/sec)
1943 Anteros	May 1997	Sep 1998	33	0.75	5.35
4660 Nereus*	Jan 1998	Jan 2000	31	1.20	5.74
3361 Orpheus	Mar 1998	May 1999	18	1.46	5.47
4660 Nereus	Jan 2000	Oct 2001	26	0.70	5.05

* With flyby of mainbelt asteroid 2019 Van Albada prior to rendezvous

Table 2
Orbital and Physical Parameters for Potential NEAR Target Asteroids

Asteroid	Spectral Class	Diameter (km)	Rotation Period (hours)	Perihelion (AU)	Aphelion (AU)	Inclination (degrees)
433 Eros	S	14x14x40	5.3	1.13	1.78	10.8
1943 Anteros	S	1.8	?	1.06	1.79	8.7
3361 Orpheus	S	0.8	3.6	0.82	1.60	2.7
4660 Nereus	C	1.0	?	0.95	2.03	1.4

EROS RENDEZVOUS OPPORTUNITY

In some of the earliest proposals for a mission to a near-Earth asteroid, Eros was frequently the “target of choice” [7-9]. However, as originally discussed in [9], rendezvous-class missions to Eros generally require large values of the declination of the launch asymptote (DLA), as well as a total ΔV greater than 6.00 km/sec. The high DLA values are especially troublesome because launch-vehicle performance from the Eastern Test Range (Cape Canaveral) is drastically reduced when the DLA exceeds 50 degrees. Using results from [10] with the addition of some corresponding DLA requirements, Table 3 lists some key parameters for Eros rendezvous opportunities over a 20-year period. Notice that the minimum total-ΔV opportunities (which occur every 7 years) are associated with an excessively high DLA requirement.

From the point of view of a mission designer trying to find an Eros rendezvous opportunity that satisfies the mission constraints given in the previous section, the numbers listed in Table 3 are not very encouraging. Ideally, for a Discovery-class NEAR mission, the total ΔV should be less than 5.80 km/sec with a DLA under 30 degrees. In [2] it was found that the DLA problem could be solved by using a one-year Earth-return trajectory followed by an Earth gravity-assist maneuver. Unfortunately, this technique did not lower the total ΔV requirement, and also had the undesirable effect of significantly increasing post-launch ΔV. However, in September 1992, NEAR mission designers utilized a 2-year ΔVEGA (ΔV and Earth Gravity Assist) trajectory technique [11, 12] with spectacular results. As shown in Table 4, the ΔVEGA technique produces acceptable numbers for both the DLA and total

Table 3
Eros Rendezvous Opportunities 1991-2010

Launch	Encounter Date	C3 (km^2/sec^2)	DLA (degrees)	Post-Launch ΔV (km/sec)	Total ΔV (km/sec)
Jan 1991	Sep 1992	36	-76	1.40	6.16
Jan 1993	Jun 1994	28	-68	2.55	6.98
Jan 1994	Mar 1996	45	-49	2.44	7.52
Jan 1996	Dec 1997	41	-49	1.78	6.72
Feb 1997	Jun 1999	48	-45	2.67	7.90
Jan 1998	Dec 1998	42	-71	1.12	6.10
Jan 2000	Jul 2001	30	-	2.32	6.80
Jan 2001	Apr 2003	45	-	2.55	7.65
Jan 2003	Jan 2005	42	-	1.91	6.88
Jan 2005	Nov 2005	38	-62	1.11	5.95
Jan 2007	Jul 2008	31	-	2.10	6.64
Jan 2008	Apr 2010	46	-	2.65	7.78
Jan 2010	Jan 2012	42	-	2.04	7.03

Table 4
Launch Options for an Eros Rendezvous in December 1998

Trajectory Type	Launch Date	C3 (km^2/sec^2)	DLA (degrees)	Post-Launch ΔV (km/sec)	TotalΔV (km/sec)
Direct	Jan 1998	42	-71	1.12	6.10
1- Yr. EGA*	Jan 1997	19	-12	2.08	6.12
2- Yr. ΔVEGA**	Feb 1996	26	-22	1.20	5.53

* ΔV at Earth Gravity Assist ~954 m/sec
** ΔV at First Aphelion ~239 m/sec

ΔV requirements. In mid-1993, the ΔVEGA mission to Eros became the baseline plan for NEAR. The change in targets from Nereus to Eros moved NEAR's launch date from January 1998 to February 1996.

NEAR's trajectory profile to Eros is shown in Fig. 1. It should be noted that this trajectory represents a new application of the ΔVEGA technique. Instead of using the Earth-swingby maneuver to increase the aphelion of the spacecraft trajectory, the maneuver actually decreases the aphelion distance while increasing the inclination from zero to about 10 degrees. The ΔVEGA maneuvers are still used to increase the C3 value at the Earth-swingby, but in this case the additional energy is used to effect an inclination change. Following the Earth-swingby maneuver in January 1998, the NEAR spacecraft will reach the vicinity of Eros in January 1999 where it will execute a series of rendezvous maneuvers over a four-week period.[4] The initial close pass at Eros will occur on February 6, 1999.

[4] In the profile shown in Fig. 1, the arrival time at Eros was delayed from December to January to minimize the total ΔV expenditure (ΔV savings ~25 m/sec).

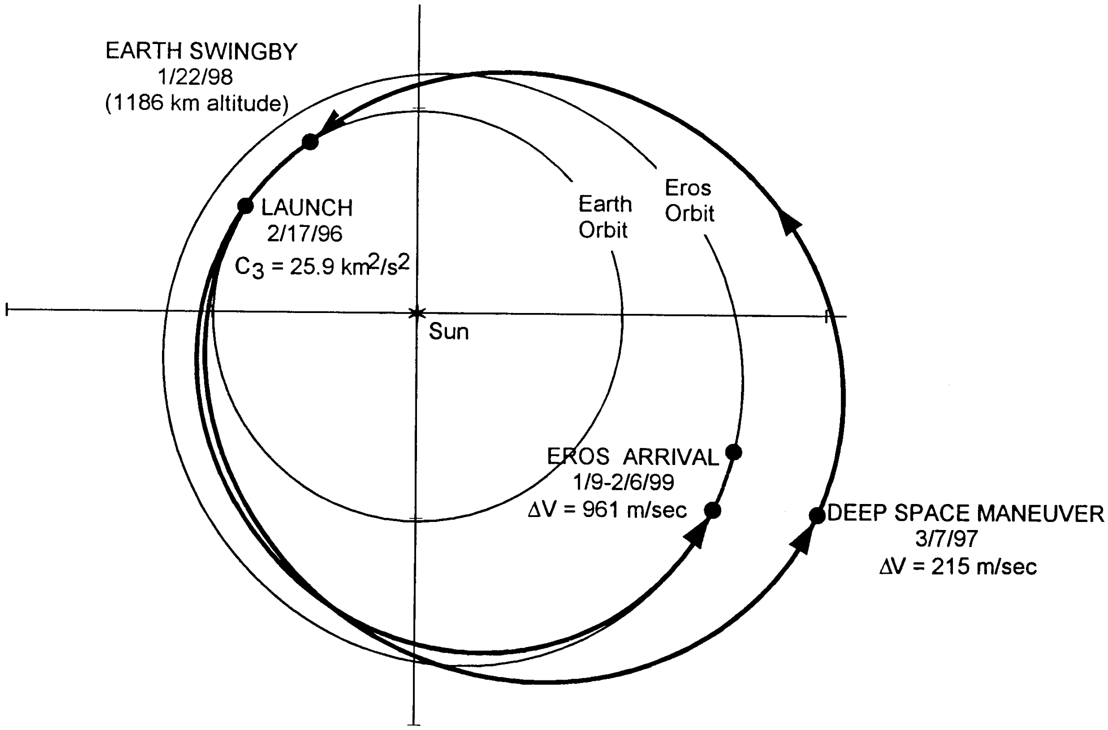

Fig. 1. NEAR Trajectory Profile

SCIENCE OBJECTIVES AND INSTRUMENTATION

The primary measurement objectives for an asteroid rendezvous mission can be summarized as follows [3]:

- To determine the gross physical properties of the asteroid, including size, shape, configuration, volume, mass, density, and spin state.
- To measure the asteroid's surface composition. Elemental abundances and abundance ratios are required at a precision of 0.5% for all elements present at greater than 1% of the mass of crust. In addition, spatially-resolved near-infrared measurements of surface mineralogy are required.
- To investigate surface morphology through comprehensive imaging under a variety of lighting conditions.

Secondary objectives include:

- To determine regolith properties and texture through imaging to sub-meter scales.
- To measure interactions with the solar wind and search for possible intrinsic magnetism.
- To search for evidence of current activity as indicated by dust or gas in the vicinity of the target.

- To investigate the internal mass distribution through measurements of the asteroid's gravity field and the time-variation of its spin state.

The NEAR instrumentation has been chosen to satisfy all of the primary science objectives, and most of the secondary ones. A listing of the NEAR science payload is given in Table 5. Brief descriptions of the individual instruments are contained in [13].

Imaging provides the primary means of determining the physical, geological, and morphological characteristics. The X-ray/gamma-ray spectrometer will determine the elemental composition of Eros to the required accuracy. The infrared spectrograph is the principal means of mapping the mineralogical composition. All three instruments work together to infer the heterogeneity of the surface. It is anticipated that the magnetometer will address the question of intrinsic magnetism, but it is not expected to characterize the solar wind interaction. Data from the laser altimeter will determine the shape and topography of Eros' surface to an accuracy of 10 meters. The mass of Eros will be determined to a high degree of accuracy by the radio science experiment (i.e., radiometric tracking of the spacecraft while in orbit around Eros).

SPACECRAFT DESCRIPTION

Simplicity and low cost were the main drivers used in developing the NEAR spacecraft design [13]. Simplicity was achieved by requiring that three major components, the instruments, solar panels, and high-gain antenna, would be fixed and body mounted. Although this requirement will increase the complexity of spacecraft operations to some extent, it was an important factor in overall cost containment. NEAR's development cost totaled less than $125 million in real-year dollars, which was well under the Discovery cost cap of $150 million in FY92 dollars. The duration of the development phase was only 27 months, which compares favorably with the Discovery limit of 35 months.

Table 5
NEAR Science Payload

Investigation	Team Leader	Major Objective
Multispectral Imager	J. Veverka (Cornell)	Map morphology and color at 3m resolution
Near-Infrared Spectrometer	J. Veverka (Cornell)	Map mineralogy at 250 m resolution
X-ray Spectrometer Gamma-ray Spectrometer	J. Trombka (Goddard)	Measure abundances of key elements (Al, Mg, Fe, Ca, S, Th, K, etc.)
Laser Altimeter	M. Zuber (Johns Hopkins)	Measure topography to 5 m vertical resolution
Radio Science	D. Yeomans (JPL)	Determine mass and internal structure
Magnetometer	M. Acuna (Goddard)	Search for magnetic field

Figure 2 shows the NEAR spacecraft in its flight configuration. The spacecraft is three-axis stabilized with four reaction wheels for pointing control. It has four large gallium-arsenide solar panels that can provide 350 watts of power at NEAR's maximum solar distance of 2.2 AU. In addition to the 1.5 meter high-gain antenna, there are two low-gain antennas, and a medium-gain antenna with a fan-shaped radiation pattern. Data rates during the rendezvous phase are quite respectable, and can be as high as 17.7 kilobits/sec when using the 70-meter Deep Space Network (DSN) antennas. NEAR can also store as much as 1.7×10^9 bits of data on its two solid-state recorders. The dual-mode propulsion system uses a hydrazine/nitrogen-tetroxide combination for the large 450-Newton thruster (specific impulse: 313 seconds), and pure hydrazine for the 11 smaller monopropellant thrusters (specific impulse: 206 to 234 seconds). It is worth noting that the large bipropellant thruster will be fired during only two periods over the entire mission, the Deep-Space Maneuver and the first portion of the rendezvous ΔV maneuvers.

DETOUR TO MAIN-BELT ASTEROID 253 MATHILDE

One of the routine things that is done for a planetary mission is to examine the spacecraft's trajectory to see if it comes close to any interesting objects (e.g., asteroids or comets). This type of search was conducted for NEAR's original trajectory (to Nereus), but for one reason or another, a rigorous search with the new trajectory (to Eros) did not take place until late 1994. Initial data from this search produced the exciting and unexpected result that NEAR's trajectory would pass within 0.015 AU (~2.25 million km) of the large main-belt asteroid 253 Mathilde. Of course, a deviation of 0.015 AU from the baseline trajectory is not trivial, but further analysis revealed that the ΔV penalty associated with a trajectory change that would permit a close encounter Mathilde was only 57 m/sec.

NEAR's new trajectory profile that includes a flyby of Mathilde enroute to a rendezvous with Eros is illustrated in Fig. 3. Comparison with Fig. 1 shows a number of changes with the most important being the Mathilde flyby and the shift of the Deep-Space Maneuver form March to July of 1997. Notice that the arrival dates at Eros are unchanged.

- Three-axis stabilized
- Total weight: 800 kg
  - – Propellants: 320 kg
  - – Experiments: 60 kg
- ΔV capability: 1450 m/sec
- Solar array power @1.00 AU: 1800 watts
- Data rate @ Eros rendezvous (Earth distance: 2.63 AU)
  - – 34-meter DSN antenna: 4.4 kbps
  - – 70-meter DSN antenna: 17.7 kbps
- Two solid-state recorders: 1.7×10^9 bits

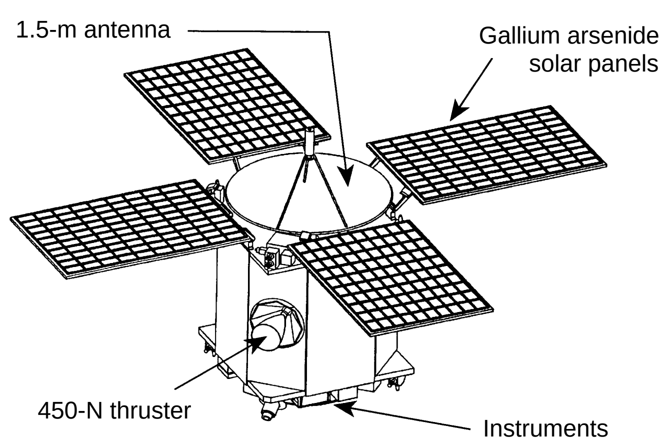

Fig. 2. NEAR Spacecraft Summary

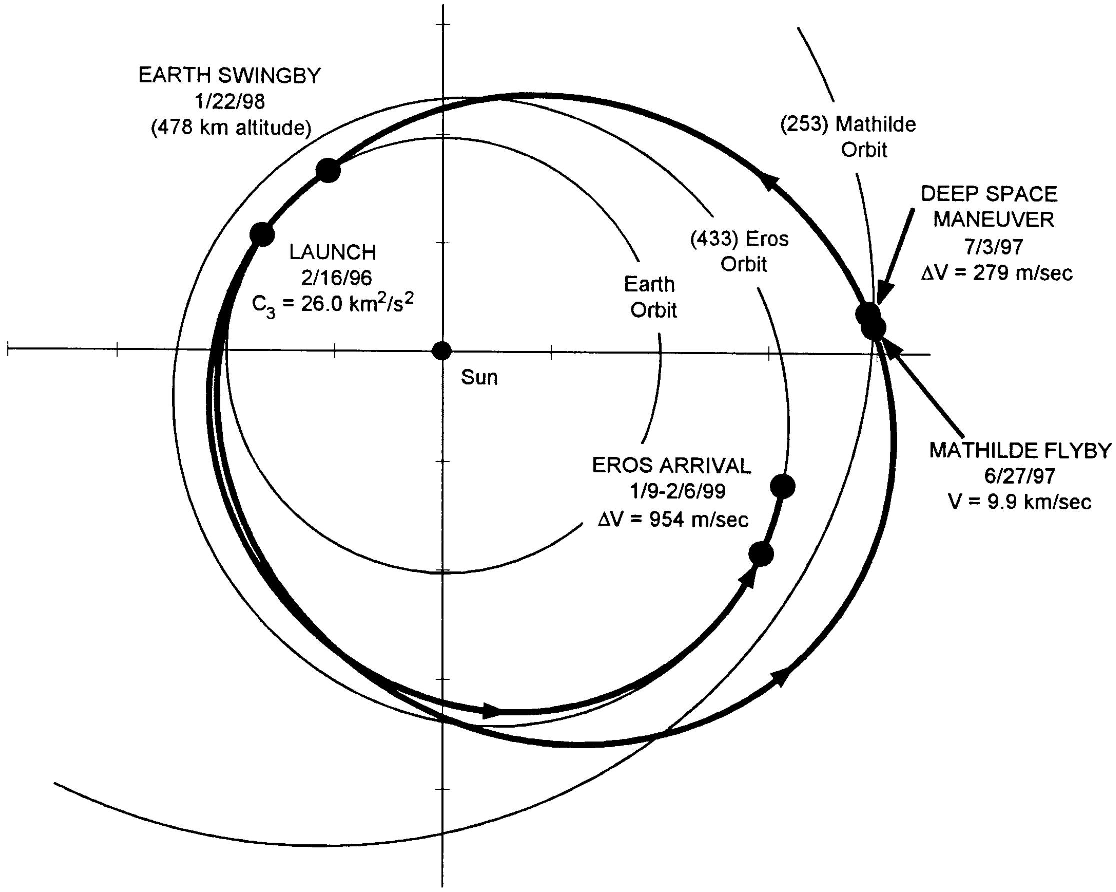

Fig. 3. NEAR Trajectory Profile with Mathilde Flyby

The principal encounter parameters for the Mathilde flyby, along with a few fascinating facts about Mathilde are listed in Table 6. Although Mathilde was discovered in 1885, it was not until early 1995 that it was observed to be a C-class asteroid. The 1995 observations also revealed that its rotation period is unusually long (~17 days). Data obtained by the Infrared Astronomical Satellite (IRAS) lists Mathilde's diameter at 61 km. This is substantially larger than either of the Galileo asteroids, 951 Gaspra (16 km) or 243 Ida (33 km). It should also be noted that Gaspra and Ida are S-class asteroids. Therefore, the NEAR encounter with Mathilde will produce the first close-up images of a C-class asteroid. Preliminary plans call for a closest approach distance of 1200 km[14].

Figures 4-6 give key trajectory parameters for the entire NEAR mission from launch to the nominal end of the mission on December 31, 1999. Movement of the Deep-Space Maneuver away from the aphelion location has provided two benefits. The power margin for this critical maneuver has improved by about 20%, and the communication distance to Earth is significantly shorter.

Table 6
Mathilde Flyby

• Main-Belt Asteroid 253 Mathilde – Discovered: November 12, 1885 – Estimated diameter: 61 km – C-class (carbon-rich) – Rotation period: 415 hours	• Encounter on June 27, 1997 – Closest approach: 1200 km – Flyby speed: 9.9 km/sec – Approach phase angle: 140° – Sun distance: 1.99 AU – Earth distance: 2.20 AU

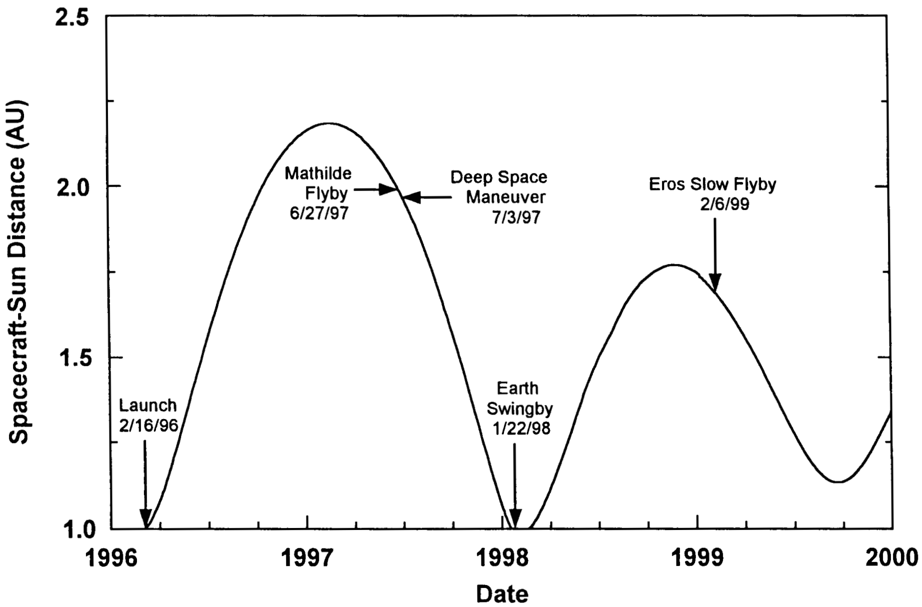

Fig. 4. Spacecraft-Sun Distance vs. Time

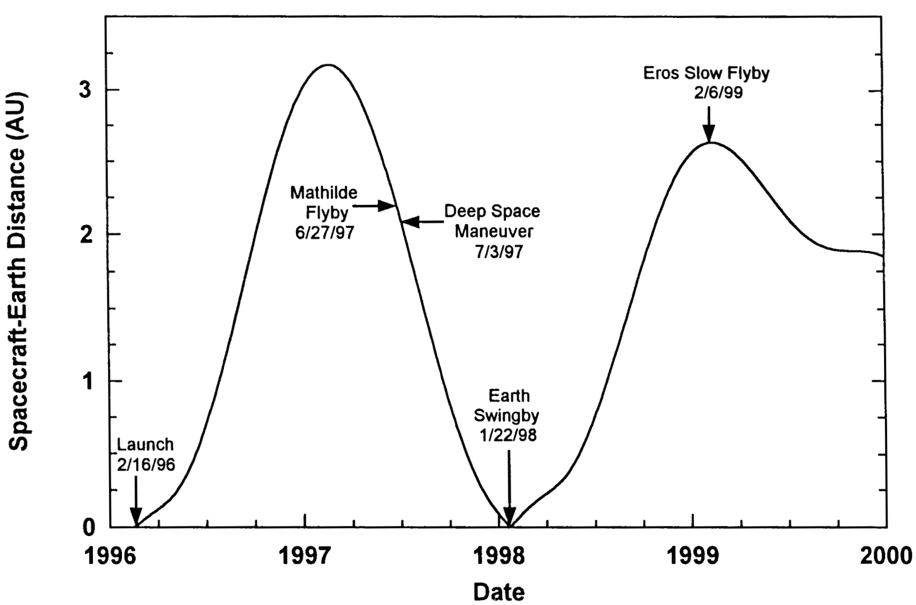

Fig. 5. Spacecraft-Earth Distance vs. Time

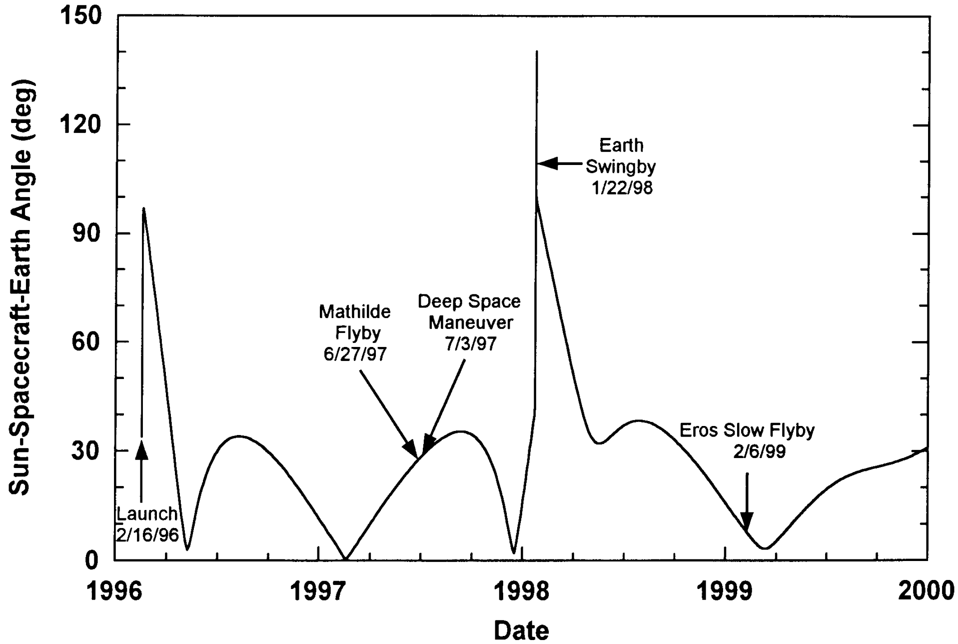

Fig. 6. Sun-Spacecraft-Earth Angle vs. Time

LAUNCH WINDOW AND ΔV BUDGET

A Delta-7925 launch vehicle will place the NEAR spacecraft into the required transfer trajectory. To maximize vehicle performance, a number of small but important modifications were made to the baseline Delta configuration. These modifications, which are listed in Table 7, include the use of high-performance nozzles, an 8-foot fairing, and a lightweight payload attach fitting. With these hardware modifications, and a slight reduction in the probability of command shutdown, the Delta rocket can deliver a spacecraft weight of 805 kg to the required C3 of 26.0 km^2/sec^2.

NEAR's launch trajectory is shown in Fig. 7. Notice that the coast period in the parking orbit is relatively short (~13 minutes). The injection burn, which will be accomplished mainly by Delta's third stage solid motor, is entirely inside the Earth's shadow. It is anticipated that the initial contact from the Canberra DSN station will occur about 14 minutes after the spacecraft exits the shadow region.

Details of NEAR's 16-day launch window are given in Table 8. Notice that the launch energy, C3, is fairly constant throughout the window. Although they are not listed in Table 8, DLA values are also quite acceptable with the largest angle at only 21 degrees.

One of the most important entries in Table 8 refers to the inclusion or exclusion of a Mathilde flyby in NEAR's trajectory profile. It is shown that a flyby is possible only for the first 11 days of the launch window. However, the post-launch ΔV requirement increases by 4 to 5 m/sec per day during this period. Therefore, it is highly desirable for NEAR to launch as early as possible. During the last 5 days of the launch window, the Mathilde flyby is no longer a possibility.

Table 7
Launch Summary

- Launch vehicle: Delta 7925-8
  - With extended air-lit nozzles
  - 8-foot fairing
  - 3712C payload attach fitting
  - 95% probability of command shutdown
- Required C3: 26.0 km2/sec2
  (max. S/C weight: 805 kg)
- Launch dates: February 16 to March 2, 1996 (16 days)
- Daily launch window: 20 seconds

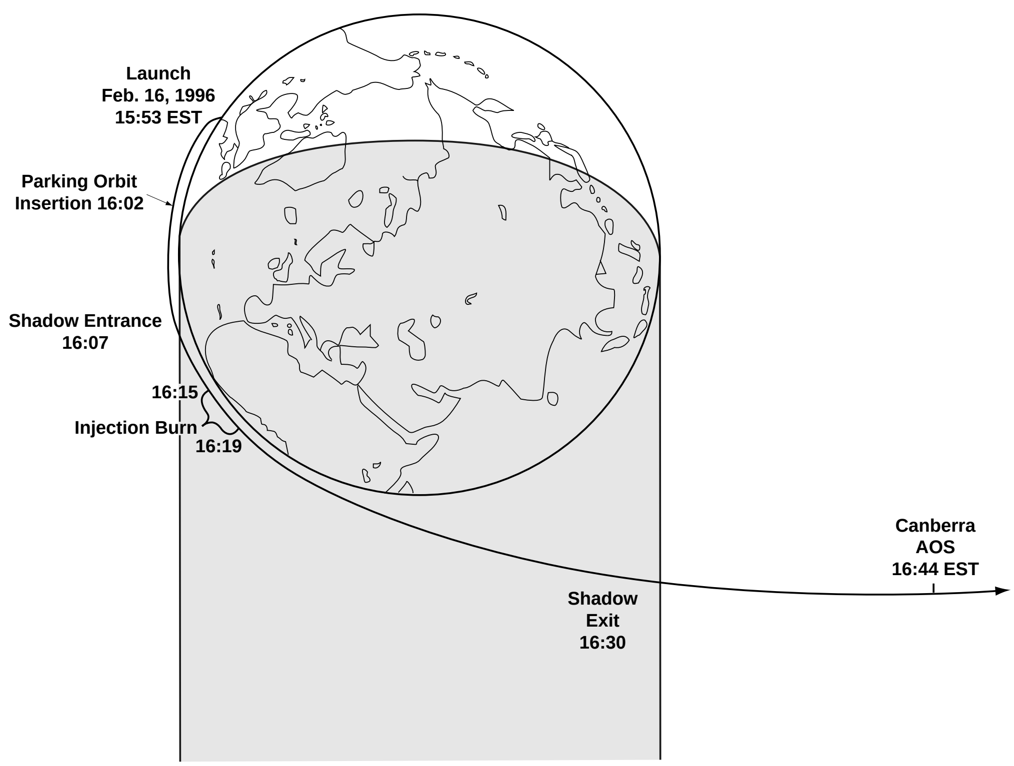

Fig. 7. NEAR Launch Trajectory

Table 8
NEAR Launch Window (Integrated Trajectories)

Launch Dates	C3	Mathilde Flyby	Deep-Space Maneuver			Earth Swingby	Post-Launch ΔV
(1996)	(km^2/sec^2)		Date (1997/6)	Sun Distance (AU)	ΔV (m/sec)	Altitude (km)	(m/sec)
Feb. 16	25.98	Yes	July 3	1.97	279	478	1233
Feb. 17	25.78	Yes	July 3	1.97	284	466	1237
Feb. 18	25.59	Yes	July 3	1.97	289	473	1242
Feb. 19	25.44	Yes	July 3	1.97	293	478	1247
Feb. 20	25.36	Yes	July 3	1.97	297	484	1251
Feb. 21	25.33	Yes	July 3	1.97	301	489	1255
Feb. 22	25.35	Yes	July 3	1.97	305	493	1259
Feb. 23	25.42	Yes	July 3	1.97	309	497	1263
Feb. 24	25.53	Yes	July 3	1.97	313	500	1267
Feb. 25	25.70	Yes	July 3	1.97	317	503	1272
Feb. 26	25.91	Yes	July 3	1.97	321	506	1276
Feb. 27	25.76	No	Jan. 9	2.17	249	479	1176
Feb. 28	25.76	No	Jan. 25	2.18	248	307	1170
Feb. 29	26.00	No	Feb. 12	2.19	232	654	1166
Mar. 1	26.00	No	Dec. 20	2.14	262	346	1181
Mar. 2	26.00	No	Nov. 26	2.09	306	320	1221

Is a 16-day window long enough to guarantee a launch to Eros in 1996? The history of prior Delta launches provides a high level of confidence that NEAR will be launched sometime during this window. Nevertheless, it is still prudent to have a contingency plan with backup launch opportunities. A brief summary of two additional launch opportunities for NEAR, one to Nereus in February 1997, and the other to Anteros in May 1997, is given in the Appendix.

The ΔV budget for the NEAR mission to Eros is tabulated in Table 9. Deterministic maneuvers during the cruise and rendezvous mission phases dominate this budget, and it should be noted that the 1275 m/sec number for this category represents a worst-case condition. A launch sometime during the first 3 days of the launch window (probability ~95%) will reduce this number to 1242 m/sec.

The ΔV penalty for launch vehicle and navigation errors was determined by using standard Monte Carlo analyses, and is a 99th percentile value. In computing the ΔV penalty for launch errors, it was assumed the first trajectory correction maneuver (TCM-1) would be performed at launch +7 days. It was further assumed that the encounter time at Mathilde would be unconstrained. A fixed encounter time at Mathilde would increase the ΔV cost by about 6 m/sec.

MATHILDE ENCOUNTER AND DEEP-SPACE MANEUVER

Following the launch and early operations phase in February-March 1996, NEAR will settle into a routine cruise mode until June-July 1997 when two critical mission events, the Mathilde flyby and the Deep-Space Maneuver, will take place (see Fig. 3). Both of these events are operations intensive, and will require higher staffing levels for the mission operations and navigation teams during this brief period. In support of the increased activity, the DSN will provide continuous coverage from its 34-meter network from June 20 to July 10. This will require 21 eight-hour passes per week from these antennas instead of the normal cruise coverage of 3 four-hour passes per week.

A timeline and selected encounter parameters for the Mathilde flyby are given in Tables 10 and 11. For planning purposes, a closest approach distance of 1200 km has been specified. Although the approach phase angle is almost 140 degrees, NEAR's imaging system should be able to obtain useful optical navigation (OpNav) images about 3 days before the encounter. OpNav sequences are scheduled at 4-hour intervals with each sequence consisting of about 4 pictures.

Expected values for the targeting errors at Mathilde with and without OpNav images are listed in Table 12. Notice the dramatic improvement in targeting accuracy in the impact plane (B-Plane) when OpNav measurements are employed. However, the down-track (along the line of flight) uncertainty is still quite large. Because of the rather large down-track uncertainty, it will be necessary to employ a mosaic technique to guarantee images at closest approach. For a more complete discussion of the navigation and imaging strategy at the Mathilde encounter see [14].

The primary science instrument during the flyby will be the camera, but measurements of magnetic fields and Mathilde's mass will also be made. The whole illuminated portion of the asteroid will be imaged in color at about one km resolution, with the best monochrome views at some 200-300 meters resolution. As the spacecraft recedes from Mathilde, a thorough search for possible satellites will be conducted.

The Deep-Space Maneuver will be executed about one week after the Mathilde flyby. It will be broken up into two segments to minimize the possibility of an overburn situation.

Table 9
NEAR ΔV Budget

	ΔV (m/sec)
Deterministic maneuvers (cruise, rendezvous)	1275
Launch vehicle, navigation errors (99%, cruise and rendezvous)	50
Attitude maneuvers (cruise)	10
Allocation for Eros orbit	50
Contingencies	65
Total	1450

Table 10
Timeline for Mathilde Flyby and Deep-Space Maneuver

E-15 days	Targeting maneuver #1
E-3 days	Begin OpNav sequence (one sequence every 4 hrs)
E-1.5 days	Targeting maneuver #2
E-0.5 days	End OpNav sequence (update encounter sequence)
E-8 minutes	Begin encounter sequence
E+20 minutes	End encounter sequence
E+1 day	Complete data playback
E+6 days (Jul 3)	Deep-Space Maneuver #1 (90% of required ΔV)
E+7 days (Jul 4)	Deep-Space Maneuver #2 (10% of required ΔV)

Table 11
Encounter Parameters for Mathilde Flyby

Time From Closest Approach	Mathilde As Seen From Spacecraft				Power Factor (Percent)
	Distance (Km)	Phase Angle (Degrees)	Magnitude	Angular Diam. (Degrees)	
-4.0 days	3,433,386	138.4	9.5	0.001	66.3
-3.0 days	2,574,959	138.8	8.9	0.001	65.9
-2.0 days	1,716,601	139.2	8.0	0.002	65.4
-1.0 days	858,289	139.5	6.5	0.004	64.9
-0.5 days	429,144	139.7	5.0	0.008	64.7
-8 minutes	4,916	134.5	-5.0	0.711	71.3
-5 minutes	3,212	130.3	-6.2	1.088	76.2
-2 minutes	1,691	114.9	-8.6	2.067	90.1
0	1,200	80.4	-11.0	2.914	98.6
+ 2 minutes	1,691	48.9	-11.2	2.067	75.4
+ 5 minutes	3,212	39.5	-10.1	1.088	63.6
+10 minutes	6,079	38.5	-8.7	0.575	62.2
+20 minutes	11,981	38.9	-7.2	0.292	62.9

Table 12
One-Sigma Targeting Errors for Mathilde Flyby

- OpNav interval: E - 3 days to E - 0.5 days
- One OpNav measurement every 4 hours
- Measurement accuracy: 40 microradians (one-sigma)

	B-Plane Uncertainty Ellipse		Down-Track Uncertainty (km)
	Semi-Major Axis (km)	Semi-Minor Axis (km)	
Without OpNav Measurements	190	46	135
With OpNav Measurements	21	19	89

The first segment, DSM-1, will provide 90% of the required ΔV. Accelerometer measurements of DSM-1 will then be used to update DSM-2 which will supply the remaining 10%.

EARTH SWINGBY

The next critical phase of NEAR's flight profile occurs in January 1998 when the spacecraft passes by the Earth at an altitude of only 478 km. This maneuver drastically alters NEAR's heliocentric trajectory, changing the inclination from 0.5 to 10.2 degrees and reducing the aphelion distance form 2.17 to 1.77 AU. An interesting consequence of the Earth flyby is that the post-swingby trajectory remains over the Earth's south polar region for a considerable time. It is hoped that this fortuitous situation will provide an opportunity for NEAR to obtain some unique images of the Antarctic continent.

Another consequence of the unusual geometry of NEAR's post-swingby trajectory is shown in Fig. 8. Because of NEAR's extreme southerly declination, the spacecraft can be viewed continuously from DSN's Canberra station for 71 days following the Earth flyby. However, the first visibility from the Goldstone and Madrid stations will not occur until 110 and 120 days, respectively.

EROS RENDEZVOUS AND ORBITAL OPERATIONS

Eros was discovered on August 13, 1898. Some 100 years later, in the fall of 1998, Eros will be seen by NEAR's imaging camera. Following this early observation, several clusters of optical navigation images will be obtained to reduce the size of Eros' ephemeris uncertainty. Then, beginning on January 9, 1999, a sequence of rendezvous maneuvers (see timeline in Table 13) will be used to decrease the relative velocity between the spacecraft and Eros to only 5 m/sec [15].

The initial close pass at Eros will occur on February 6, 1999. NEAR will fly by Eros on its sunward side at a distance of about 500 km. In addition to gathering important scientific data, this first pass is expected to provide improved estimates of Eros' physical parameters which are needed for navigation purposes. Goals for the first pass include a mass determination that is good to ±1% accuracy, identification of several hundred surface landmarks, and a vastly improved estimate of Eros' spin vector. As the spacecraft is maneuvered closer to Eros, estimates of the asteroid's mass, moments of inertia, gravity harmonics, spin state, landmark locations, etc., will be determined with increasing precision.

The prime science phase at Eros will begin around March 15, 1999. During this phase, NEAR will be operating in orbits which come as close as 15 km to Eros' surface. The evolution of low altitude orbits around Eros will be strongly influenced by Eros' irregular gravity field. Orbits exist which are quite unstable and could crash into the asteroid in a

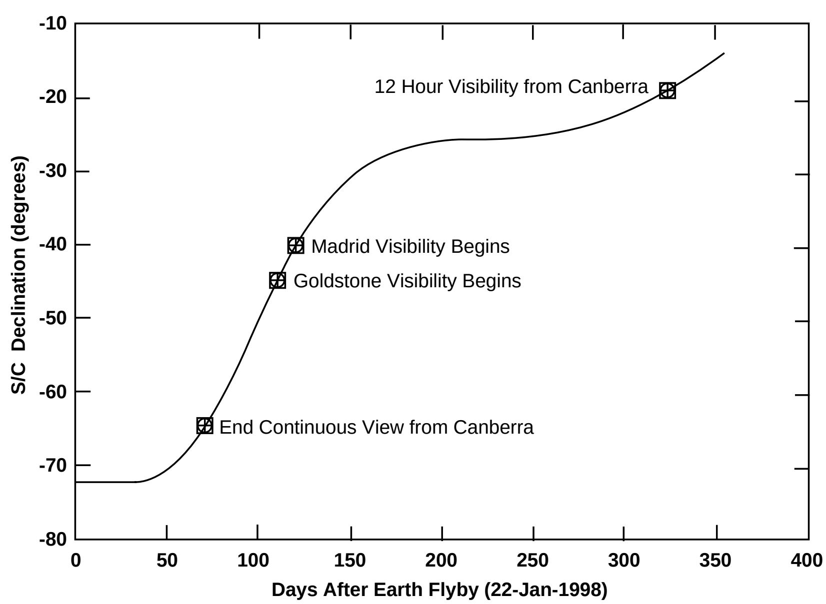

Fig. 8. DSN Station Visibility After Earth Flyby

Table 13
Rendezvous and Orbital Timeline at Eros

January 9, 1999	Rendezvous Maneuver #1 (704 m/sec)
January 16, 1999	Rendezvous Maneuver #2 (200 m/sec)
January 23, 1999	Fendezvous Maneuver #3 (40 m/sec)
January 30, 1999	Rendezvous Maneuver #4 (5 m/sec)
February 6, 1999	Initial Eros Flyby at V = 5 m/sec (500 Km distance on sunward side)
February 15, 1999	High-Orbit Phase (200 x 400 Km)
February 21, 1999	Intermediate Orbit (200 Km, circular)
March 15, 1999	Begin Prime Science Phase (Orbit Radius: 35→50 Km)
December 31,1999	End of Mission

matter of days [16]. Therefore, safe operation of the spacecraft during its 9-month prime science phase will require close coordination between the science, mission design, navigation, and mission operations teams.

Orbital velocities and periods for low altitude circular orbits around Eros are given in Table 14. In preparing this table, nominal values for Eros' size and density were utilized [6], and an idealized spherical gravity field was assumed.

Figure 9 depicts the NEAR spacecraft in a 35 km circular orbit around Eros as viewed by an observer on the Sun. The orbit and Eros are drawn to scale, but obviously the spacecraft is not. This is a convenient reference frame to show NEAR's orbit because the orbital plane will be controlled so that it is always within 30 degrees of a plane that is normal to the Sun-Eros line. In this configuration, NEAR's fixed solar panels are oriented towards the Sun. The science instruments are pointed at Eros' surface by slowly rolling the spacecraft as it orbits Eros.

Two fundamentally different orbital geometries are shown in Fig. 9. In the top frame, Eros' rotation axis is aligned with the Sun-Eros line.[5] The South Pole of Eros points towards the Sun which means that Eros' northern hemisphere is shadowed at this time. Approximately 4 months later, as Eros' orbital position around the Sun changes, Eros' rotation axis is perpendicular to the Sun-Eros line. Figure 9 shows that coverage of Eros' surface by NEAR's science instruments will vary considerably throughout the 9-month prime science phase. However, careful planning of the mission and science operations should produce satisfactory global coverage by all of NEAR's instruments [17].

A number of deterministic spacecraft maneuvers will be needed to control the orientation of NEAR's orbit plane, and also to effect changes in NEAR's orbital radius [15]. The ΔV cost for these deterministic maneuvers is approximately 37 m/sec, which is well within the allocation for Eros orbital operations (see Table 9).

[5] Fortuitously, Eros' rotation axis appears to lie within a degree or so of Eros' orbital plane [6].

Table 14
Circular Orbits Around Eros
(GM ~1.012 x 10^{-3} km^3/sec^2)

Orbit Radius (Km)	Period (hours)	Velocity (m/sec)
20	4.91	7.12
25	6.86	6.36
30	9.01	5.81
35	11.36	5.38
40	13.88	5.03
45	16.56	4.74
50	19.39	4.50
75	35.63	3.67
100	54.85	3.18

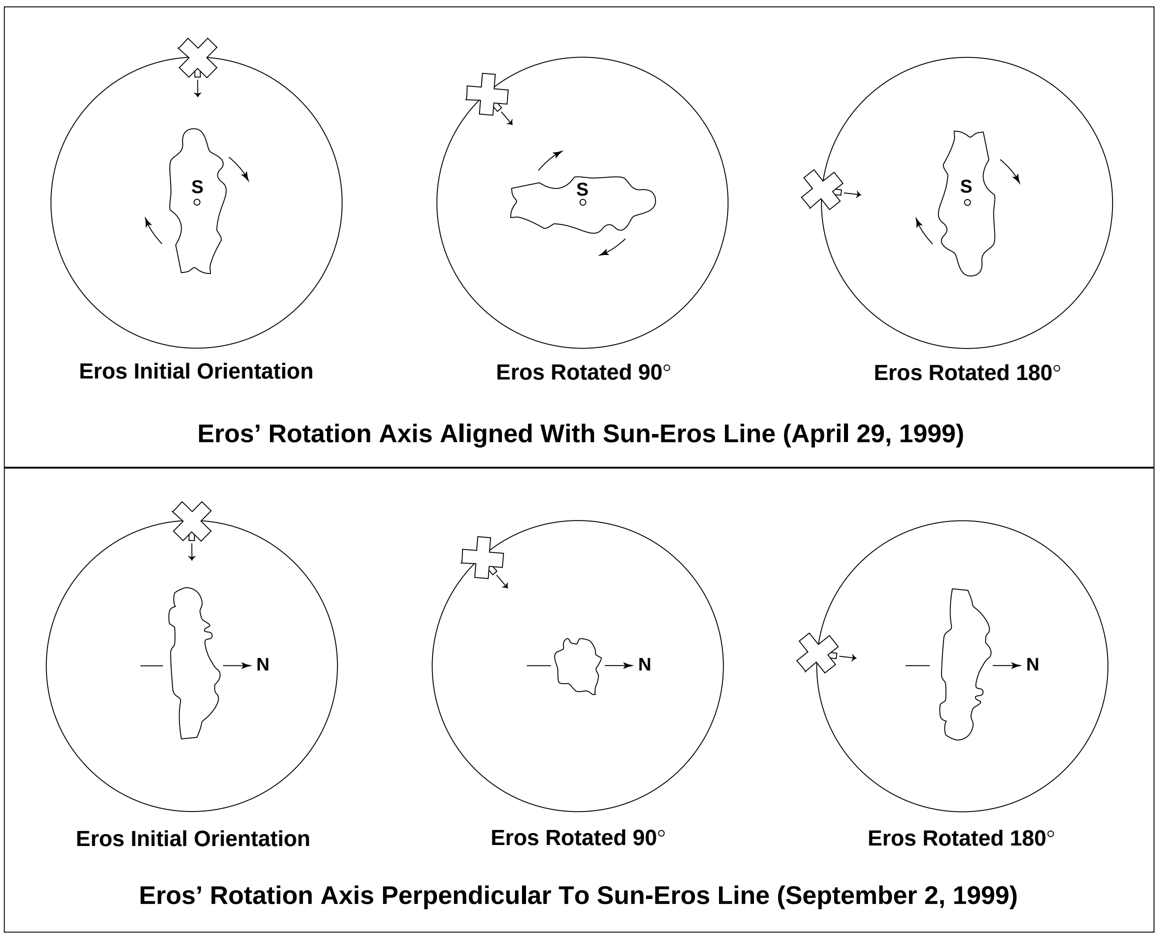

Fig. 9. NEAR Orbit Around Eros as seen from the Sun
(35 x 35 km Orbit, Period ~11.4 Hours)

Orbital operations at Eros will provide unprecedented and important information about asteroids. By mission end, surface detail will be mapped at scales of 3-5 meters and mineralogy delineated at scales of several hundred meters. The abundances of key elements will be measured on regional scales to compare the composition with those of major meteorite types. The asteroids' mean density and internal mass distribution will be determined and the topography charted with ± 5-10 meter accuracy.

CONCLUDING REMARKS

NEAR will provide the first test of the "faster, cheaper, better" philosophy in the planetary mission arena. If everything goes as planned, it will accomplish a number of important firsts in space exploration including:

- First spacecraft to orbit a small body.
- First in-depth exploration of a near-Earth asteroid (433 Eros).
- First reconnaissance of a C-class asteroid (253 Mathilde).

Other mission features that should be mentioned include the following:

- This will be the first planetary mission for the Delta launch vehicle.
- This will be the first time that a spacecraft powered by solar cells has operated beyond Mars' orbit.
- The main-belt asteroid 253 Mathilde will be the largest asteroid visited by a spacecraft thus far.

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APPENDIX

Backup Launch Opportunities

In the unlikely event that NEAR is not launched to Eros in 1996, two backup launch opportunities have been identified for 1997. Basic facts concerning these 1997 opportunities are given in Table A-1. To satisfy the slightly higher C3 requirement, it will be necessary to offload about 20 kg of propellants. Even so, this still leaves a ΔV capability of 1400 m/sec which is more than adequate to accommodate both opportunities. Except for the fuel offload, no changes are needed in the NEAR spacecraft design to carry out the 1997 missions.

Trajectory profiles for the 1997 missions to Nereus and Anteros are shown in Figs. A-1 and A-2. Notice that the arrival date for the Anteros mission is about 8 months earlier than the planned arrival date at Eros. However, from a scientific viewpoint, Eros is a more desirable target.

Table A-1
NEAR Backup Launch Opportunities

- Maximum launch energy (C3): 27.5 km^2/sec^2
- Total spacecraft weight: 780 kg (propellants: 300 kg)
- ΔV capability: 1400 m/sec
- Nereus opportunity
  - Launch dates: February 11-17, 1997 (7 days)
  - Arrival dates: March 13-27, 2000
  - Maximum post-launch ΔV: 1030 m/sec
- Anteros opportunity
  - Launch dates: May 17-23, 1997 (7 days)
  - Arrival dates: May 17 to June 20, 1998
  - Maximum post-launch ΔV: 1100 m/sec

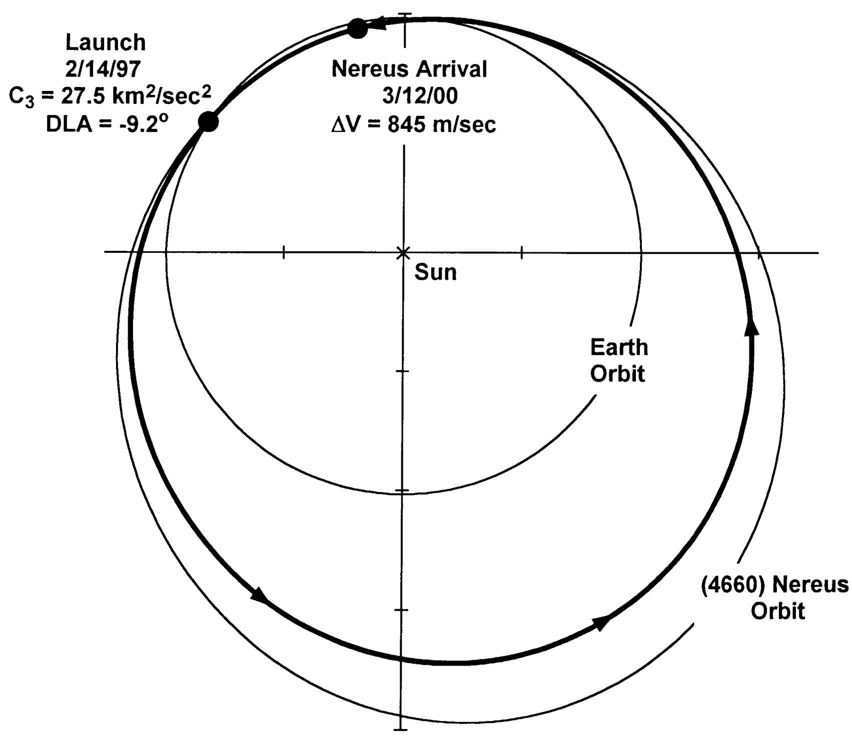

Fig. A-1. Trajectory Profile for Backup Opportunity to 4660 Nereus

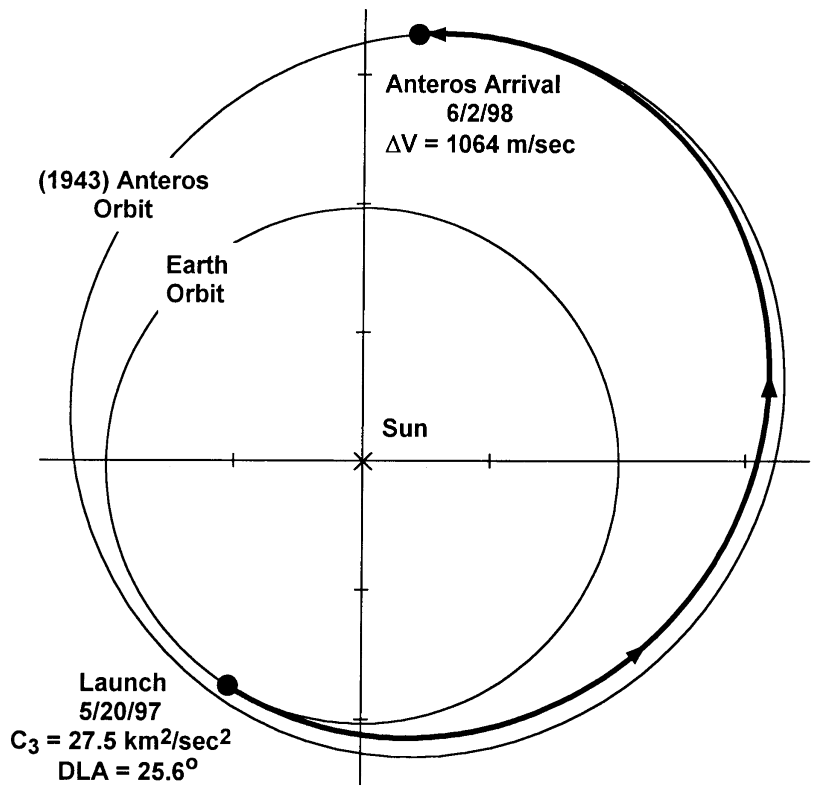

Fig. A-2. Trajectory Profile for Backup Opportunity to 1943 Anteros