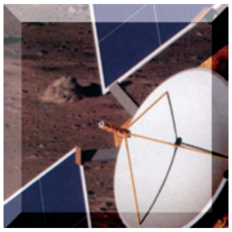

NEAR Mission Design

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The Near Earth Asteroid Rendezvous (NEAR) spacecraft took 4 years from launch until it became the first spacecraft to orbit an asteroid in February 2000. A month later, the spacecraft was re-christened NEAR Shoemaker to honor the late Eugene Shoemaker. To save launch costs, the mission used a special 2-year-period trajectory with an Earth gravity assist. On the way, the spacecraft imaged the asteroid 253 Mathilde. On 20 December 1998, NEAR's large engine misfired, failing to brake it for entry into orbit about 433 Eros. Another attempt 2 weeks later succeeded, but the spacecraft was almost a million kilometers away and took over a year to reach the asteroid. The mission was recovered thanks to a generous fuel supply and robust contingency planning. The implementation of the spacecraft's daring orbital maneuvers is described, including those used to land on Eros' surface in February 2001.

INTRODUCTION

Rendezvous missions to near-Earth asteroids, including one to (433) Eros, were proposed as early as 1963 but these were relatively expensive missions costing half a billion dollars or more.[1–4] With the Apollo program and demands for planetary exploration, this kind of funding was not available for an asteroid mission. In 1991, a less expensive "Discovery" Near Earth Asteroid Rendezvous (NEAR) mission was proposed,[5] and competitive proposals for it were prepared by APL and by the Jet Propulsion Laboratory (JPL). The APL proposal was selected and system definition studies were carried out in 1992–1993. The studies first concentrated on direct flight paths to small near-Earth asteroids, with a mission to (4660) Nereus that would launch in January 1998 adopted as a baseline.[6]

Some scientists were concerned that an intensive orbital survey of such a small asteroid might not be very productive. Eros would be a much better target since it has dimensions of about $14 \times 14 \times 33$ km, about 400 times the area and over 6000 times the volume of Nereus. Unfortunately, Eros' orbit is inclined 11° to the ecliptic (Earth's orbit plane), requiring, for direct transfers, high declination of launch asymptotes and launch energies that are too high for a reasonably sized spacecraft with the Discovery-baselined Delta-class launch vehicle. This problem was solved by using a 2-year ΔV-Earth Gravity Assist (ΔVEGA) trajectory. The spacecraft would be launched into an orbit with an approximately 2-year period in the ecliptic plane 23 months before the latest minimum-launch energy departure date on 22 or 23 January 1998. Near aphelion of this orbit, a ΔV maneuver would be performed to target an Earth swingby at the optimum date. At the Earth return, the spacecraft's velocity relative to the planet would be increased considerably, allowing a swingby low over the Northern Hemisphere that would bend the trajectory into Eros' orbit plane with its 11° inclination to the ecliptic.[6]

In mid-1993, the ΔVEGA trajectory to Eros was adopted as the baseline for the NEAR mission. At aphelion in early 1997, the spacecraft would be behind the Sun as seen from the Earth, so the deep space ΔV was moved to early March, several days after the NEAR spacecraft (re-christened NEAR Shoemaker in March 2000 to honor the late Eugene Shoemaker) left the solar exclusion zone within 3° of the Sun, where communications with the spacecraft would be difficult or impossible. This trajectory is shown in Fig. 1.

A Delta 7925-8 rocket was used to launch NEAR. This was the first time that a rocket as small as a Delta was used for an interplanetary mission. The required launch energy (C_3) was ≈26.0 km^2/s^2, giving a maximum spacecraft mass of 805 kg. Details for a 16-day launch window, from 16 February to 2 March 1996, were computed.[6] Both unfavorable high-altitude winds and a balky range computer forced postponement on the first day. A flawless launch was executed on 17 February 1996.

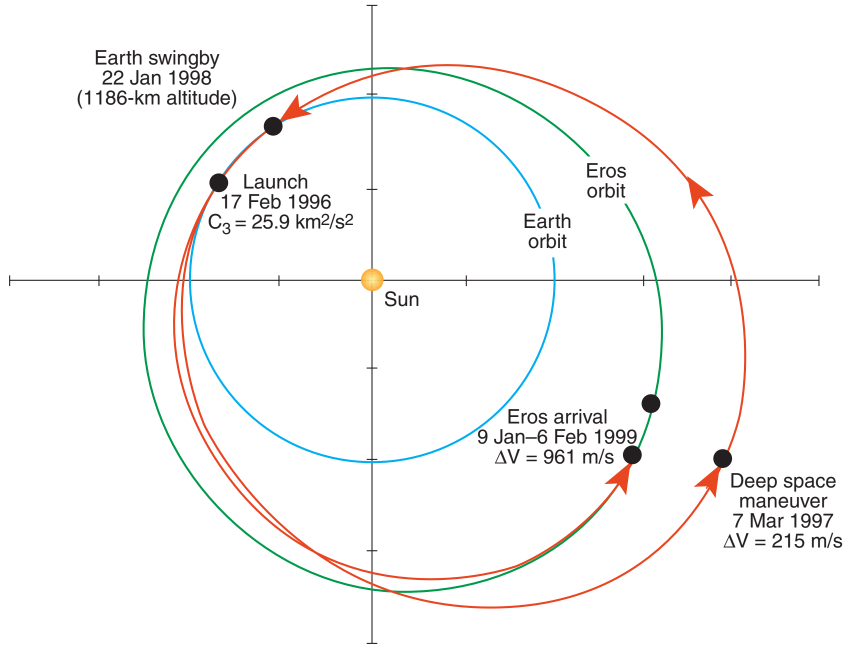


Figure 1. NEAR Shoemaker trajectory profile adopted in 1993 (C_3 = launch energy).

Figure 2 shows NEAR's launch trajectory. The spacecraft's injection burn was only 4 m/s less (less than the 1-sigma predicted velocity error) than the planned velocity. Just after NEAR exited Earth's shadow, both the optical observations and the early tracking data from Canberra, Australia, showed that no emergency correction maneuver was needed[7]; the first maneuver could wait for at least a week, allowing a relatively leisurely spacecraft checkout. Fortunately, an elaborate post-launch contingency strategy that could have accomplished NEAR's primary objectives even in case of injection shortfalls as great as 300 m/s was not needed.[8]

MANEUVER IMPLEMENTATION

Following launch, NEAR had to perform several deterministic and stochastic maneuvers of different sizes to accomplish its mission. Its propulsion system consisted of a 470-N (106-lbf) large-velocity adjust (LVA) bipropellant thruster for the large deterministic maneuvers; four 21-N (5-lbf) thrusters aligned with the LVA to steer the large engine and settle the fuel properly in the tanks for initiating LVA firings; and seven 3.5-N (0.8-lbf) thrusters for applying torques and ΔV maneuvers in other directions. The LVA used N_2O_2 oxidizer and the same hydrazine fuel that was used by the smaller monopropellant thrusters. NEAR's thruster arrangement and how they were used are described elsewhere.[9,10]

In principle, NEAR could apply a ΔV in any direction by appropriate selection of the thrusters described above. In practice, the selection of the orientation and thrusters was complicated by the desire to monitor the burns in real time and NEAR's immovable communication antennas shown in Fig. 3 of Ref. 11. Monitoring the burns not only permitted real-time Doppler measurement of the line-of-sight component of the actual ΔV but also allowed transmission of some basic engineering data about the burn performance. The highest data rates were obtained with the high-gain antenna (HGA). The fanbeam medium-gain antenna provided coverage overlapping the HGA and extending almost 40° from it toward the $+x'$ direction; the coverage width was about 5°. Finally, the two low-gain antennas provided omnidirectional coverage, but only when NEAR was within a few tenths of an astronomical unit (AU) from the Earth. If the Earth was put in the fanbeam pattern during the most distant parts of NEAR's trajectory, a low-rate link was established. After the maneuver was completed, the HGA was pointed at the Earth to download detailed accelerometer data and other information about the propulsion system performance.

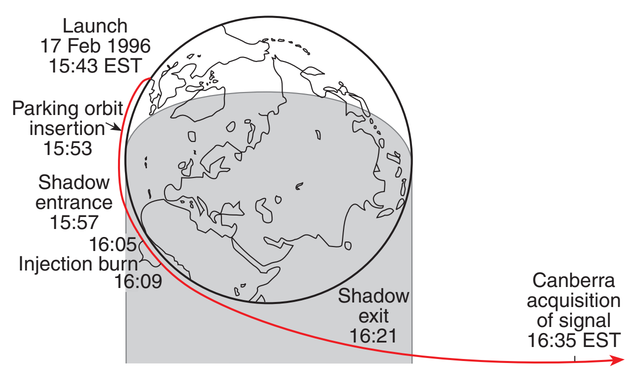


Figure 2. NEAR launch trajectory.

Besides communication, it was also desirable to align either the spacecraft z or x' axis (either plus or minus) with the ΔV vector to eliminate penalties that were incurred when burns were performed in components (i.e., using two burns perpendicular to each other to obtain the desired ΔV vector sum). Also, since the solar panels are perpendicular to the z axis, the angle that the direction to the Sun makes with the $+z$ axis, called the Sun angle, had to be small enough so that there was a comfortable power margin during both the preparation for and execution of the maneuver. These different factors were weighed for each maneuver by the mission design, operations, guidance and control, and spacecraft engineering teams to decide on the best spacecraft attitude.

Trajectory calculations for the Eros opportunity showed that only two large deterministic ΔVs would be needed during the mission, the deep space maneuver (DSM) near the apogee of the initial 2-year orbit and the Eros rendezvous. This information was known before the NEAR Shoemaker spacecraft was designed, so the LVA engine was placed on the $-x'$ side so that the ΔV imparted by it would be in the $+x'$ direction. This took advantage of the known geometry for these maneuvers, with the Sun approximately 90° from the ΔV direction. Also, for both maneuvers it was known that the Earth direction as seen from NEAR would be within about 20° of the Sun direction and about 60° from the ΔV direction. Then, by placing the fanbeam on the $+x'$ side of the spacecraft, the LVA thruster could be used for the two large maneuvers while ensuring a communication link and sufficient solar power during the burns. The angle that the direction to the Earth made with the $+z$ direction, called the Earth angle, was 32° for the DSM and 32° and 28° for the two large burns that were planned for the LVA thruster during the Eros rendezvous sequence, all within good coverage of the fanbeam antenna. Several attitude options, or "modes," for NEAR's maneuvers are described elsewhere.[12]

HELIOCENTRIC TRAJECTORY

Mathilde Flyby

In early December 1993, during a part of NEAR's Critical Design Review, R. Farquhar, the NEAR Mission Manager, scanned a list of close approaches of various asteroids to NEAR's trajectory and placed a checkmark next to an approach within 0.015 AU or about 2.25 million kilometers to the large main-belt object 253 Mathilde. New calculations made during the next couple of days showed that NEAR could encounter Mathilde for an additional ΔV cost of only 57 m/s, well within the spacecraft's generous margin. Since the spacecraft design was complete and fabrication of major components just beginning, the mission design team had to convince project and NASA management that the Mathilde flyby could be added without any change to the spacecraft design, without any significant risk, and with generous margins preserved for the Eros orbital phase. This was accomplished in early January 1994 with the Mathilde flyby trajectory adopted as the new baseline. At that time, little was known about Mathilde, but new astronomical observations showed it to be an interesting C-class object, none of which had previously been visited by a spacecraft. These asteroids with "carbonaceous" spectra are more typical in the outer asteroid belt, with NEAR encountering Mathilde near its perihelion. Mathilde was found to have a rotation period of 15 days, the third longest of all asteroids with measured rotation periods.[6]

After launch, five trajectory correction maneuvers (TCMs) were used to target the Mathilde flyby. But even before these, NEAR performed two autonomous attitude maneuvers that imparted tiny ΔVs. The first was a detumble maneuver that occurred shortly after launch to point NEAR's solar panels toward the Sun. The second maneuver, a week later, desaturated NEAR's momentum wheels when their rates exceeded programmed limits. After that, the NEAR mission operations team developed a scheme to tilt the spacecraft in ways that would allow solar radiation pressure on its large solar panels to desaturate the momentum wheels. Consequently, no further "momentum dump" propulsive maneuvers were needed during NEAR's heliocentric cruise phase.

Table 1 lists the B-plane coordinates at Mathilde achieved by each of the maneuvers. (A B-plane is a plane essentially perpendicular to the relative direction of the pre-flyby velocity that includes the center of Mathilde and the **b** parameter, a vector from the center of Mathilde to the intended point of closest approach.) TCM-1 removed the major part of the launch injection error. But the thrusters were not flight calibrated, so the maneuver was almost 10% too large. Better accuracies were achieved with TCM-2, performed in two parts with different thrusters half an hour apart. TCM-3 and TCM-4 were also performed as different components with different thrusters separated by 23 days to try to obtain enough tracking between maneuvers to separately calibrate the different thruster groups. Figure 3 shows NEAR's trajectory projected into the ecliptic plane, with the locations and dates of all TCMs and OCMs (orbit correction maneuvers, after insertion into orbit about Eros) indicated. The first point of Aries is to the right in this inertial frame view, so the Earth is directly to the right of the Sun on 23 September, directly above it on 21 December, etc. TCM-6, planned for a final targeting in Mathilde's B-plane only 12 h before the encounter, was canceled after NEAR's optical navigation images showed that the flyby would occur close enough to the planned target point. The resulting unperturbed (by propulsive maneuvers) trajectory

Table 1. Mathilde B-plane history (all distances in kilometers).

After	B·T	B·R	Distance from Mathilde	Distance from Target	June 27 UTC
Launch	−252527.0	+832105.0	869580.0	870733.0	1512:56.4
TCM-1	+23306.0	−78554.0	81938.0	80784.0	1400:27.3
TCM-2	−2265.0	+1438.0	2683.0	3487.0	1255:49.2
TCM-4	+152.9	−1199.8	1209.5	137.0	1256:00.9
TCM-5	−94.5	−1206.0	1209.7	110.6	1255:52.2
Flyby	−100.0	−1221.5	1255.6	117.9	1255:56.7
sigma	±5.7	±6.8	±6.8	±6.8	±3.6

Note: The target is at B·T = +15.9, B·R = −1199.0, or distance from Mathilde's center of 1200.0 km.

segment around the Mathilde encounter enabled a more accurate mass determination of the asteroid.[13]

On 3 July 1997, 6 days after the Mathilde flyby, NEAR's LVA engine was fired for nearly 11 min to accomplish the first deterministic maneuver, DSM-1, which is also known as TCM-7. The burn, guided by accelerometers, was nearly perfect, imparting a ΔV of 269 m/s. This put NEAR on course for the crucial Earth swingby in January 1998.[11] A contingency plan had been developed to perform DSM-1 as much as 2 months late, in case something went wrong and the 3 July maneuver could not be performed, but fortunately this was not needed.[14] The performance of all of NEAR's maneuvers is shown in Table 2.

Table 2 lists several parameters for each of the propulsive maneuvers performed by the NEAR Shoemaker spacecraft. In the last column, under "Mode," the table indicates the basic strategy for orienting the spacecraft according to the options listed in Ref. 12. Table 2 is a completion of the (partial) maneuver table in Ref. 12. The Sun and Earth angles given in the table are relative to NEAR's $+z$ axis. The antenna used for real-time communication is given for each event.

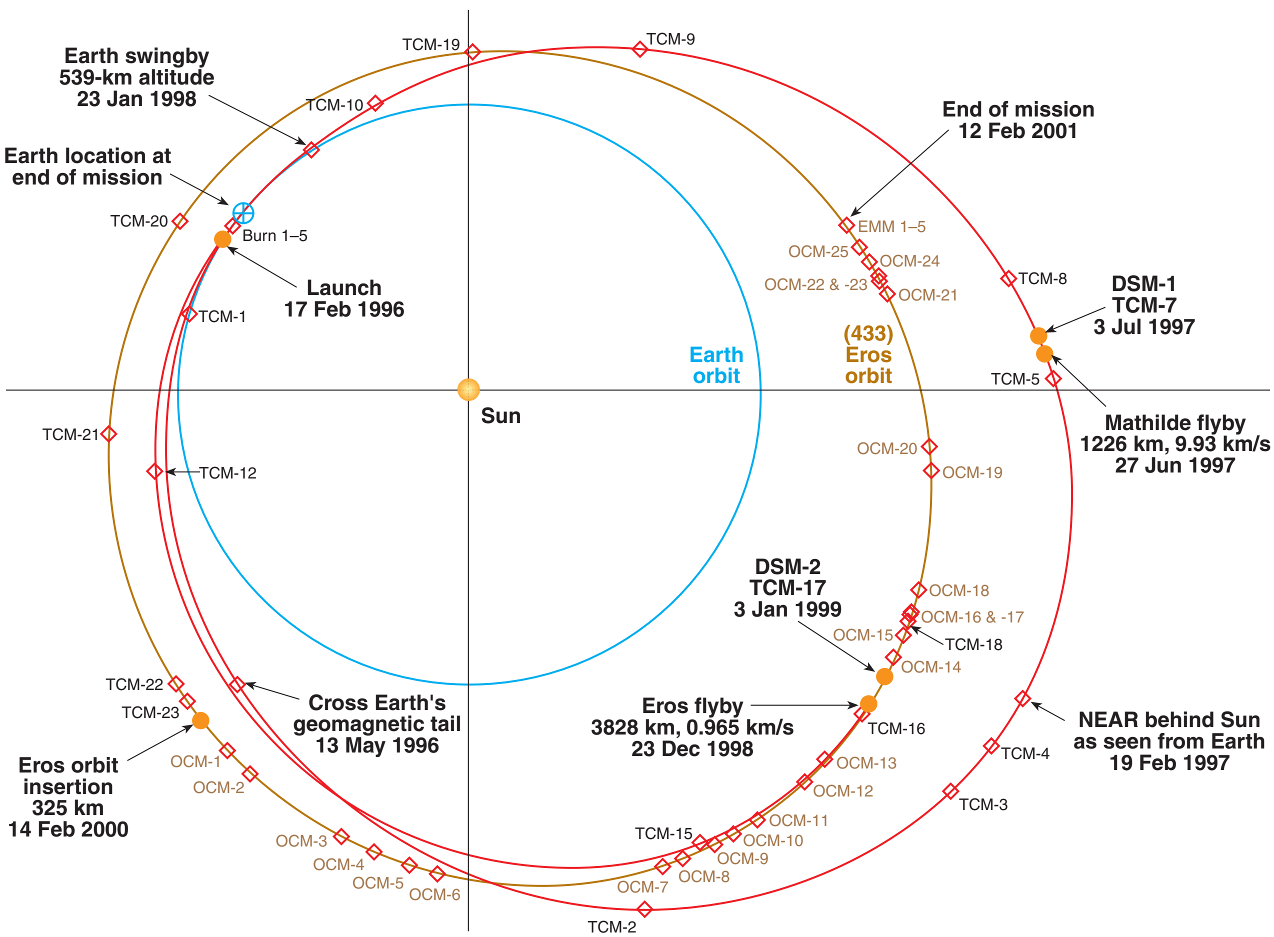


Figure 3. NEAR's heliocentric trajectory to Eros, inertial ecliptic plane projection, showing all TCMs and OCMs (EMM = end-of-mission maneuver).

Table 2. NEAR Shoemaker's propulsive maneuvers.

			ΔV	ΔV Errors (mag.)			Distances(AU)		Angles(deg)				
Event	Date	GMT	(m/s)	mm/s	%	deg.	Earth	Sun	Earth	Sun	Antenna	Thrusters	Mode
Detmb.	Feb. 17, 96	21:18	0.066	N/A	N/A	N/A	(382km)	0.988	N/A	shadow	none	-x'B,-zB	N/A
Desat-1	Feb. 24, 96	21:33	0.115	115.4	N/A	N/A	0.021	0.990	N/A	0.0	none	-x'B,-zB	N/A
TCM-1	Mar. 2, 96	20:00	9.398	920.3	9.79	1.55	0.041	0.997	67.9	22.5	LGA	+x'A	1
TCM-2A	Sep. 13, 96	17:00	2.120	52.6	2.54	0.47	1.685	1.892	0.0	32.0	HGA	+x'A	6
TCM-2B	Sep. 13, 96	17:30	0.155	12.5	8.78	1.88	1.685	1.893	0.0	32.0	HGA	+zA	6
TCM-3	Jan. 6, 97	13:00	0.057	0.9	1.57	0.20	3.030	2.163	0.0	10.4	HGA	-x'B	6
TCM-4	Jan. 29, 97	14:00	0.098	1.8	1.82	0.80	3.139	2.180	0.0	4.9	HGA	-zB	6
TCM-5	June 18, 97	18:30	0.620	9.7	1.59	0.25	2.311	2.015	0.0	26.0	HGA	-x'B	6
TCM-6	June 27, 97	1:00	cancelled										
DSM-1	July 3, 97	10:30	268.664	-534.2	-0.20	0.08	2.117	1.971	32.0	15.2	Fanbeam	LVA	3
TCM-8	July 23, 97	14:06	5.659	6.2	0.11	0.25	1.834	1.901	34.3	2.8	Fanbeam	+x'A	3
TCM-9	Nov. 17, 97	16:00	0.758	-1.7	-0.22	0.76	0.361	1.315	23.7	33.3	Fanbeam	+x'A	3
TCM-10	Jan. 9, 98	20:00	0.076	-2.9	-3.68	0.95	0.054	1.032	0.0	25.7	HGA	-x'B	6
TCM-11	Jan. 21, 98	19:00	cancelled										
CAL-1	Feb. 11, 98	14:00	0.013	2.7	26.71	N/A	0.075	0.990	90.0	4.7	LGA	-x'B	1
CAL-2	Feb. 11, 98	14:30	0.105	5.4	5.40	N/A	0.075	0.990	90.0	4.7	LGA	+x'A	1
CAL-3	Feb. 11, 98	15:00	0.094	0.1	3.73	N/A	0.075	0.990	90.0	4.7	LGA	-x'B	1
CAL-4	Feb. 11, 98	17:00	0.100	0.0	0.00	N/A	0.076	0.990	90.0	4.7	LGA	+x'A	1
CAL-5	Feb. 11, 98	17:30	0.100	0.0	0.00	N/A	0.076	0.990	90.0	4.7	LGA	-x'B	1
TCM-12	April 1, 98	16:00	1.656	31.1	1.91	1.63	0.225	1.128	19.3	40.8	Fanbeam	+zA	7
TCM-13	never scheduled												
TCM-14	Aug. 26, 98	17:00	cancelled										
TCM-15	Oct. 14, 98	17:00	0.369	7.6	2.11	0.77	1.927	1.753	0.0	31.0	HGA	-x'B,-zB	6
MCM-A	Oct. 28, 98	14:59	0.003	2.9	N/A	N/A	2.071	1.764	0.0	28.6	HGA	+zA,-zB	8
MCM-B	Nov. 18, 98	16:54	0.001	1.1	N/A	N/A	2.265	1.711	0.0	24.7	HGA	+zA,-zB	8
RND-1	Dec. 20, 98	22:00	14.96	*	-97.70	51.08	2.491	1.759	32.5	18.6	Fanbeam	+x'A	3
DSM-2	Jan. 3, 99	17:00	932.021	-6897.4	-0.74	1.30	2.556	1.745	22.3	10.7	Fanbeam	LVA	3
TCM-18	Jan. 20, 99	17:00	13.915	-34.3	-0.25	3.35	2.607	1.720	13.4	15.1	Fanbeam	+x'A	3
TCM-19	Aug. 12, 99	17:00	21.372	10.7	0.05	0.26	1.974	1.169	0.5	23.6	Fanbeam	+x'A	3
TCM-20	Oct. 20, 99	15:30	0.076	-50.3	-39.74	24.02	1.889	1.155	0.0	26.4	HGA	-x'B,+zA	6
TCM-21	Dec. 6, 99	15:30	0.129	-12.9	-8.98	1.14	1.880	1.264	0.0	28.9	HGA	-x'B,-zB	6
TCM-22	Feb. 3, 00	17:00	11.336	69.1	0.61	0.10	1.770	1.453	10.2	41.5	Fanbeam	+x'A	3
TCM-23	Feb. 8, 00	22:00	1.848	9.6	0.35	0.36	1.750	1.469	0.0	28.9	HGA	+x'A,-zB	6
OIM	Feb. 14, 00	15:33	9.996	-26.1	-0.26	0.11	1.726	1.487	10.9	42.5	Fanbeam	+x'A	3
OCM-1	Feb. 24, 00	17:00	0.135	-6.9	-4.88	0.37	1.679	1.518	0.0	35.6	HGA	-x'B,+zA	6
OCM-2	Mar. 3, 00	18:00	0.220	-12.3	-5.27	2.26	1.637	1.542	0.0	36.2	HGA	-x'B,-zB	6
MCM-1	Mar. 15, 00	20:00	0.002	2.5	N/A	N/A	1.565	1.576	0.0	36.9	HGA	+zA,-zB	8
MCM-2	Mar. 23, 00	15:20	0.002	1.9	N/A	N/A	1.514	1.597	0.0	37.3	HGA	+zA,-zB	8
OCM-3	Apr. 2, 00	2:03	0.501	-24.0	-4.57	1.31	1.448	1.621	26.0	22.0	Fanbeam	-zB	7
OCM-4	Apr. 11, 00	21:20	0.374	0.4	0.10	0.91	1.374	1.644	40.0	30.1	Fanbeam	+x'A,+zA	6
OCM-5	Apr. 22, 00	17:50	0.448	-0.1	-0.02	0.30	1.288	1.668	20.0	31.8	Fanbeam	+x'A,+zA	6
OCM-6	Apr. 30, 00	16:15	1.916	-46.4	-2.36	0.46	1.223	1.684	18.2	22.7	Fanbeam	-zB	7
MCM-3	May 10, 00	14:00	0.003	3.0	N/A	N/A	1.141	1.703	0.0	35.0	HGA	+zA,-zB	8
MCM-4	May 17, 00	13:00	0.001	1.4	N/A	N/A	1.083	1.715	0.0	33.7	HGA	+zA,-zB	8
MCM-5	May 24, 00	13:00	0.002	1.9	N/A	N/A	1.027	1.726	0.0	31.9	HGA	+zA,-zB	8
MCM-6	May 31, 00	16:00	0.002	2.2	N/A	N/A	0.971	1.736	0.0	29.7	HGA	+zA,-zB	8
MCM-7	June 7, 00	16:00	0.007	6.5	N/A	N/A	0.920	1.746	0.0	26.9	HGA	+zA,-zB	8
MCM-8	June 14, 00	16:00	0.003	2.7	N/A	N/A	0.874	1.734	0.0	23.6	HGA	+zA,-zB	8
MCM-9	June 21, 00	16:00	0.002	2.2	N/A	N/A	0.834	1.761	0.0	19.7	HGA	+zA,-zB	8
MCM-10	June 28, 00	16:00	0.002	2.1	N/A	N/A	0.801	1.767	0.0	15.3	HGA	+zA,-zB	8
OCM-7	July 7, 00	18:00	0.318	-0.0	0.00	0.32	0.773	1.774	7.8	14.8	Fanbeam	-xB	-3
OCM-8	July 14, 00	3:00	0.240	2.5	1.06	0.34	0.764	1.777	10.4	6.3	Fanbeam	-xB	-3
OCM-9	July 24, 00	17:00	0.341	4.6	1.35	0.70	0.771	1.781	0.0	5.2	HGA	-xB,+zA	-6
OCM-10	July 31, 00	20:00	0.500	2.3	0.46	0.46	0.791	1.783	10.2	7.4	Fanbeam	-xB	-3
OCM-11	Aug. 8, 00	23:00	1.009	-29.2	-2.82	0.67	0.827	1.783	11.5	12.1	Fanbeam	-zB	-7
OCM-12	Aug. 26, 00	23:25	1.397	-16.9	-1.24	0.78	0.947	1.779	30.0	22.8	HGA	-xB,+zA	-6
OCM-13	Sep. 5, 00	23:00	0.964	18.5	1.96	0.23	1.030	1.774	20.2	12.0	Fanbeam	-xB,+zA	11
MCM-12	Sep. 20, 00	17:00	0.004	4.4	N/A	N/A	1.166	1.763	0.0	32.7	Fanbeam	+zA,-zB	8
OCM-14	Oct. 13, 00	5:45	1.306	28.1	2.20	0.03	1.382	1.737	30.5	4.7	Fanbeam	+zA	7
OCM-15	Oct. 20, 00	21:27	0.577	-12.4	-2.10	1.56	1.454	1.726	0.0	35.2	HGA	-xB,-zB	-6
OCM-16	Oct. 25, 00	22:00	0.760	-1.9	-0.25	0.34	1.501	1.718	4.8	33.0	Fanbeam	+xA	3
OCM-17	Oct. 26, 00	17:40	1.658	13.1	0.80	1.72	1.508	1.716	10.0	35.8	Fanbeam	-xB,-zB	-6
OCM-18	Nov. 3, 00	3:00	0.539	1.6	0.29	0.56	1.574	1.704	28.6	36.3	Fanbeam	+xA	3
MCM-13	Nov. 15, 00	20:00	0.001	1.0	N/A	N/A	1.682	1.680	0.0	34.2	HGA	+zA,-zB	8
MCM-14	Nov. 29, 00	17:30	0.001	0.6	N/A	N/A	1.788	1.650	0.0	33.0	HGA	+zA,-zB	8
OCM-19	Dec. 7, 00	15:20	0.957	8.4	0.87	0.89	1.843	1.631	6.4	38.3	Fanbeam	-xB	-3
OCM-20	Dec. 13, 00	20:15	1.228	-17.4	-1.40	1.38	1.883	1.616	0.0	31.5	HGA	-xB,-zB	6
MCM-15	Dec. 27, 00	19:25	0.001	1.4	N/A	N/A	1.961	1.580	0.0	29.8	HGA	+zA,-zB	8
MCM-16	Jan. 9, 01	18:40	0.002	2.0	N/A	N/A	2.020	1.543	0.0	28.2	HGA	+zA,-zB	8
OCM-21	Jan. 24, 01	16:05	0.542	7.7	1.44	0.32	2.072	1.499	16.9	24.6	Fanbeam	+xA	3
OCM-22	Jan. 28, 01	01:25	0.559	-7.7	-1.36	0.53	2.082	1.488	0.0	25.8	HGA	+xA,-zB	6
OCM-23	Jan. 28, 01	18:05	0.677	5.2	0.77	0.39	2.083	1.486	28.0	9.3	Fanbeam	+xA	3
OCM-24	Feb. 2, 01	08:51	0.019	-7.6	-26.64	17.86	2.095	1.472	0.0	25.1	HGA	+xA,-zB	6
OCM-25	Feb. 6, 01	17:43.9	0.013	-0.1	-0.84	0.27	2.104	1.458	20.3	6.3	Fanbeam	-xB	-3
EMM-1	Feb. 12, 01	15:13.9	2.572	-1.3	-0.05	0.19	2.114	1.439	53.0	31.3	none	+xA	3
EMM-2	Feb. 12, 01	18:58.8	6.526	42.0	0.65	0.61	2.114	1.438	0.0	23.8	HGA	+xA,+zA	6
EMM-3	Feb. 12, 01	19:14.2	3.441	-34.5	-0.99	1.86	2.114	1.438	0.0	23.8	HGA	+xA,+zA	6
EMM-4	Feb. 12, 01	19:30.2	4.035	0.9	0.02	2.60	2.114	1.438	0.0	23.8	HGA	+xA,+zA	6
EMM-5	Feb. 12, 01	19:41.2	2.264	-464.0	-17.09	----	2.114	1.438	0.0	23.8	HGA	+xA,+zA	6

*RND-1 magnitude (mag.) error was –635.16 m/s.
EMM-3, EMM-4, and EMM-5 performance is based on G&C estimates since navigation solutions were not available for them.

Earth Swingby

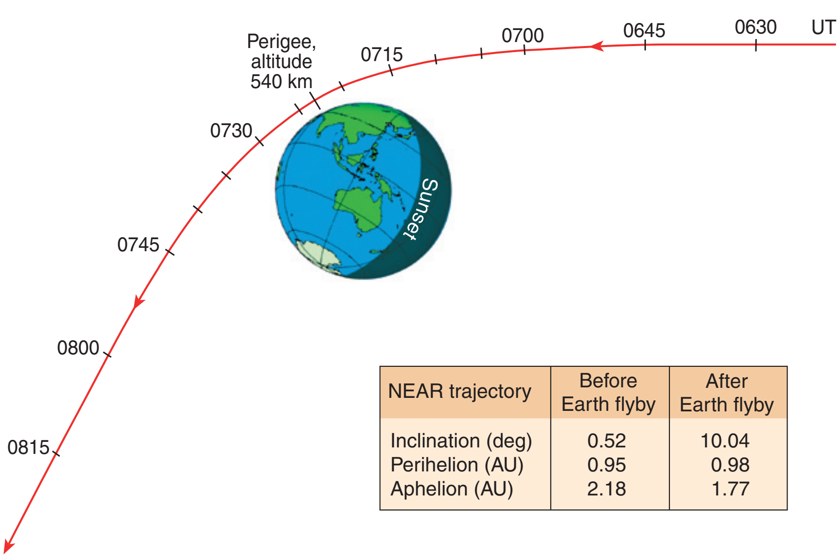
The main purpose of the Earth swingby on 23 January 1998 was to change NEAR's heliocentric orbital inclination to the ecliptic from 0° to 11° to match Eros' orbital plane. The swingby also decreased the aphelion distance to closely match that of Eros to enable the rendezvous at the end of 1998.

The Earth swingby provided an excellent opportunity for calibrating NEAR's instruments.[15] First, during the nightside approach, a test of the NEAR Laser Rangefinder was planned. The attempt was only partly successful because of cloudy weather at the ground station.[16] Magnetometer, spectrometer, and imager observations were all made on 23 January when NEAR passed closest to the Earth (Fig. 4). The perigee occurred at 0723 UT (Universal Time) 540 km over the southern Iran–Iraq border region. This altitude above the oblate Earth's surface was within a kilometer of the value needed for bending the trajectory toward the Eros target point.

From 0625 to 0648 UT, while NEAR was high above the northeastern Pacific Ocean, the spacecraft was rotated to reflect sunlight from its 10 m^2 of solar panels to different parts of the United States. The purpose of this test was to compare the predicted reflectance of NEAR's solar panels with the actual reflectance and to see if there was any offset from their intended pointing direction (tilt or warp of the panels). The resulting flashes of sunlight were expected to be as bright as a 1st-magnitude star that could easily be observed; it presented an unusual opportunity for thousands to see an interplanetary spacecraft. The predicted groundtrack of this "sunglint" is shown in Fig. 5. Glenn LeDrew, watching from a location northwest of Aylmer, Quebec (near Ottawa), saw NEAR brighten to 3rd magnitude at its expected location in Perseus just before 0626 UT. At the time, NEAR was about 28,000 km away, setting a distance record for an interplanetary spacecraft seen with the naked eye. Several photographs and videotapes were obtained in the southwestern United States. The NEAR sunglint was expected to be brighter, so many who attempted to see it did not. The observations showed that the sunglint occurred over a wider area than expected, indicating a probable misalignment of the individual solar cells in random directions by several tenths of a degree. That would have spread out the light enough to dim it to the observed 2.5-magnitude maximum brightness that was reported.

Careful analysis of NEAR's range and two-way Doppler radiometric measurements before and after the swingby showed that the spacecraft gained about 13 mm/s more velocity than expected during the swingby. Smaller anomalous gains were experienced by Galileo during its Earth swingbys. Some inadequacy of the gravitational geopotential model is probable, but an adequate explanation of the cause of this discrepancy remains elusive (see Antreasian, P. G., and Guinn, J. R., "Investigations into the Unexpected Delta-V Increases During the Earth Gravity Assists of Galileo and NEAR," AIAA Paper 98-4287, presented at the AIAA/AAS Astrodynamics Specialists Conference in Boston, MA, 10–12 August 1998; available from American Institute of Aeronautics and Astronautics at http://www.aiaa.org). Following the Earth swingby, tracking data showed that NEAR's trajectory would miss the target point at Eros by 14,000 km.

For about 1 month after the Earth swingby, the Sun–NEAR–Earth angle was near 90°, much higher than during all other phases of the mission. On 11 February, small ΔV maneuvers, designed to add vectorially to zero, were performed in different orientations and monitored in real time with Doppler measurements. The measurements were possible only because the Earth range was small enough to use the low-gain omnidirectional antennas. These burns, labeled CAL-1 to CAL-5 in Table 2, provided valuable calibration data for the thrusters and the accelerometer, which enabled more precise ΔV executions during the critical Eros orbital phase.



NEAR trajectory	Before Earth flyby	After Earth flyby
Inclination (deg)	0.52	10.04
Perihelion (AU)	0.95	0.98
Aphelion (AU)	2.18	1.77

Figure 4. NEAR's Earth swingby of 23 January 1998.

Rendezvous Burn Abort and Eros Flyby

From 20 December 1998 to 10 January 1999, NEAR was scheduled to perform four maneuvers of decreasing size and increasing precision to allow rendezvous with (433) Eros, the first-discovered and second-largest near-Earth asteroid.[17] The first of these rendezvous maneuvers (RND-1) was the largest

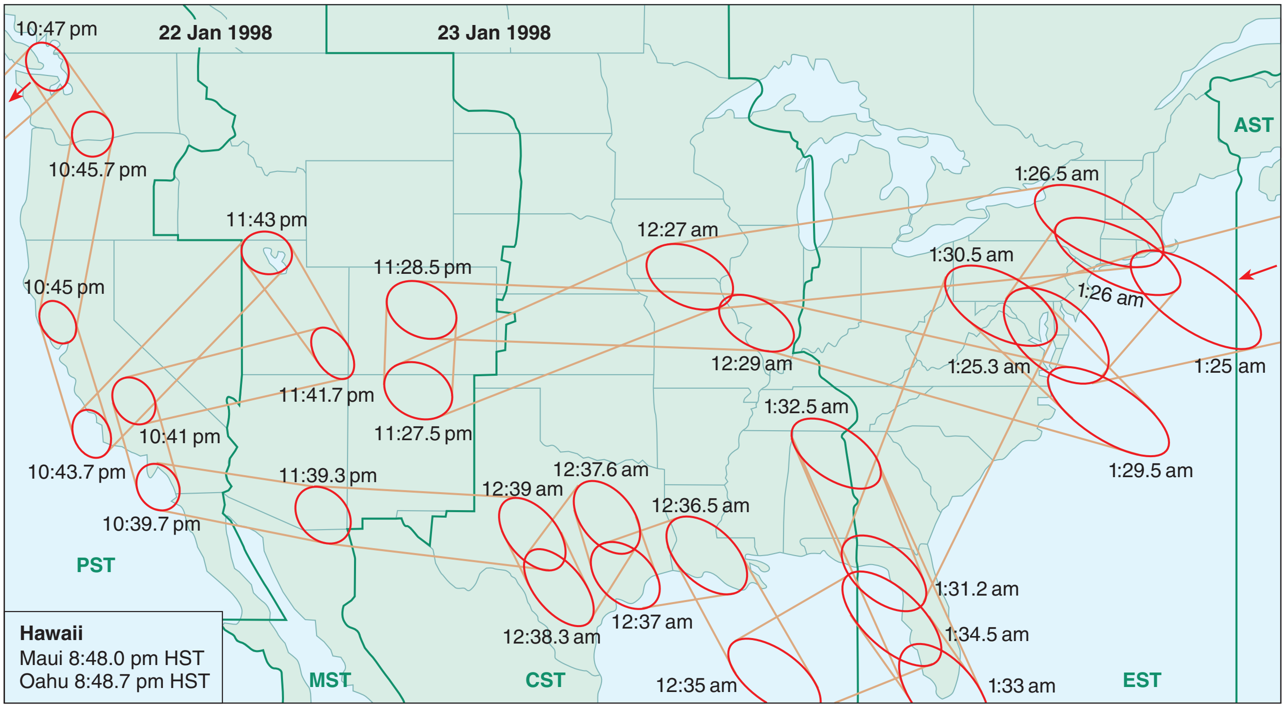


Figure 5. NEAR's sunglint path across North America. Local times are shown.

(650 m/s), using the LVA bipropellant thruster. Recognizing the importance of this maneuver, we developed a preliminary contingency plan in case it failed or for any reason was delayed.[18] Two weeks before RND1, more comprehensive rendezvous contingency plans were developed.[19] The later study revealed a family of trajectories that was missed in 1997, with arrivals at Eros in May 2000. This is shown as the top curve in Fig. 6, depicting the amount of ΔV left for the Eros orbital phase after subtracting the RND-1 and Eros orbital insertion (performed at Eros arrival) ΔVs from the total ΔV available. For an execution of RND-1 for over 2 weeks after the missed date, the new family actually had better performance (that is, allowed more ΔV for the Eros orbital phase) than the nominal planned rendezvous. However, since NEAR had a generous fuel supply, trajectories that returned to Eros more quickly were preferred (the "recommended plan"; red line on the figure).

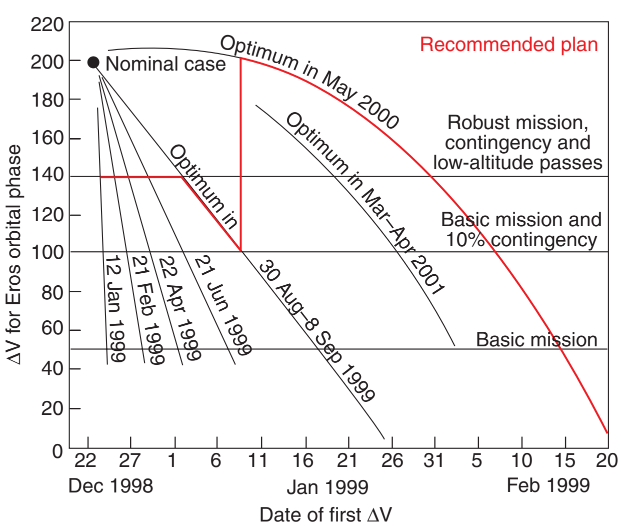


Figure 6. ΔV for the Eros orbital phase in case of RND-1 delays. Eros arrival dates are given along each curve.

RND-1 began on schedule at 2200 UT (5 p.m. local time) of Sunday afternoon, 20 December. The smaller hydrazine thrusters were fired to settle the liquid oxidizer over the tank outlets before starting the LVA engine. This settling burn worked as expected. The LVA engine fired on time, but then ceased within a second after it started. For 37 s, the Doppler signal received at NEAR's navigation center at JPL showed no motion; then the spacecraft's signal was lost. "Black Sunday" had begun. After 2 h, the navigation team produced a detailed plot (Fig. 7) of the Doppler residuals during the critical time and faxed it to the NEAR Mission Operations Center at APL. The navigation team concluded that the last few points on the right side of the figure after the straight portion were real, possibly indicating that the spacecraft started to turn, causing the signal loss.

A spacecraft emergency was declared. It is now known that NEAR tumbled slowly, pointing its solar panels away from the Sun, and discharged its battery to the preset low-voltage limit. Then, as planned, the spacecraft shut off its transmitter, finally pointed its solar panels at the Sun, and stayed in that configuration for 24 h to charge the battery. After the day-long wait,

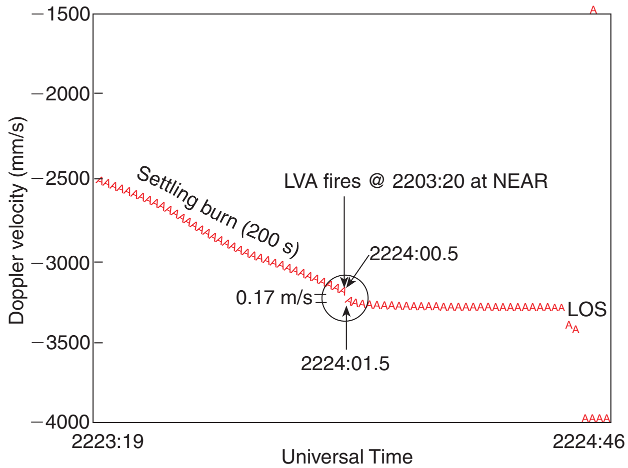


Figure 7. NEAR's Doppler signature, 20 December 1998. This is adapted from the original fax from the JPL NEAR navigation team, showing the aborted LVA burn followed by LOS (loss of signal) about 37 s later.

NEAR switched on its fanbeam transmitter. At 0101 UT of 22 December a clear signal was received from NEAR at the Canberra Deep Space Network tracking station. Several hours later, NEAR was returned to operational status, and telemetry showed that there was no damage to the spacecraft or the propulsion system. The cause of the LVA abort was found to be a larger-than-expected lateral acceleration that exceeded limits set in the onboard software.

While stopping the tumble and acquiring the Sun, the hydrazine thrusters fired thousands of times, using about 29 kg of precious fuel. This represented about 96 m/s in lost ΔV capability. Computer simulations have matched some features of NEAR's post-abort behavior, but the precise reason for the use of so much attitude control fuel is not known.[20] If another 15 kg of fuel had been used, NEAR would have lost all hope of a future rendezvous with Eros. Fortunately, NEAR had a resilient mission design that planned for adversity. The design included generous fuel margins and a large set of contingency options.

NEAR was moving toward Eros at almost a kilometer per second, its speed relative to the asteroid reduced by only a few meters per second by the RND-1 settling burn. Post-RND-1 tracking showed that NEAR would pass Eros at a distance of about 3800 km (rather than the 1000-km planned distance) on 23 December. In less than 24 h, the NEAR team updated the camera-observing sequence. At the distance of closest approach, 3827 km as determined from the tracking data, the best resolution was 400 m, good enough to show some craters and measure Eros' size and shape.[21] A density of 2.5 ± 0.8 g/cm^3 was obtained from the estimated volume and a mass determination from spacecraft tracking data.[22] These were the first close-up observations of any near-Earth asteroid, and they were of great help for redesign of NEAR's orbital phase trajectory.[23]

Recovery

The contingency plans shown in Fig. 6 had to be revised with the loss of 96 m/s of ΔV capacity. Engineers wanted more time to design a new LVA maneuver that would have a high chance for success. This new maneuver was called DSM-2; like DSM-1 in 1997, it would use the bipropellant system for a deterministic change in NEAR's heliocentric orbit. The maneuver had to be performed by 26 December in order for the spacecraft to return to Eros in early 1999, a deadline that could not be met under the circumstances.

A new version of Fig. 6 was prepared, concentrating on near-optimum arrivals at Eros in July–August 1999 and in early 2000, taking into account the current ΔV capacity of the spacecraft and the approximately 15 m/s uncertainty of that capability. The result is shown in Fig. 8, which plots the ΔV remaining for the Eros orbital phase and for heliocentric TCMs after subtracting DSM-2 and the Eros orbit insertion maneuver (OIM) from the remaining spacecraft ΔV capacity. For returns in 1999, the optimum rendezvous date would be near the end of August. But for only a 3 m/s penalty, the return could be on 20 July. Earlier arrivals were preferred because of the costs of operating NEAR during those extra months of heliocentric cruise. However, the calculations showed that the new maneuver had to be performed by 30 December. That date could not be met; the NEAR project wanted more time to try to figure out the best way to prevent a repeat of the 20 December failure.

Planning focused on returning to Eros in 2000 with a maneuver early in January 1999; Sunday, 3 January, was selected. The optimum arrival date was in the middle of May, but for less than 1 m/s penalty, NEAR could arrive

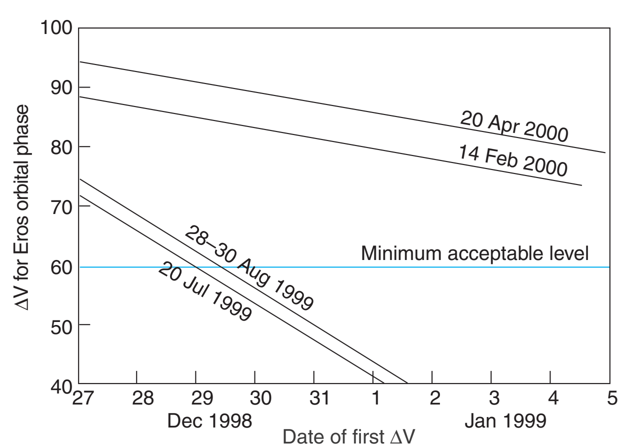


Figure 8. ΔV for the Eros orbital phase in case of DSM-2 delays, taking into account the lost capacity from the RND-1 maneuver abort.

at Eros on 20 April. However, for an additional cost of 5 m/s, the arrival could be moved up another 2 months, to February. Since the remaining total ΔV at Eros was still well above the acceptable level and 2 months of operations costs could be saved, 14 February was selected as the new arrival date. A Valentine's Day arrival seemed appropriate for Eros, named after the Greek god of love. January arrivals resulted in unacceptable penalties of 10–15 m/s more.

Another good reason for selecting a February 2000 arrival was deduced from Fig. 9, which shows the Sun's latitude on Eros. Eros' spin axis is nearly in its orbital plane, so its northern hemisphere is predominantly illuminated for half of its 1.7-year revolution around the Sun, and then its southern hemisphere is illuminated. The high operational costs during the intense orbital phase limited NEAR's science observations to about 1 year. When NEAR arrived at Eros in January 1999, according to the original plan, the time at Eros was nearly equally divided between the northern hemisphere and southern hemisphere illumination periods. But if the arrival had occurred in April 2000, nearly all of the coverage would be during the southern hemisphere "summer," with little time to study the northern hemisphere. In addition, it was desirable to spend the first 2 months at Eros in relatively high orbits, 100 km or more from the asteroid, to map its gravitational field in detail. Only after that information was obtained would it be safe to navigate the orbits of 50 km or less where most of the primary scientific observations were made. A February 2000 arrival gave enough time for NEAR to drop below 100 km in April, allowing more than 2 months of close observations while Eros' northern hemisphere was still reasonably well illuminated.

At 932 m/s, the 3 January DSM-2 maneuver almost stopped NEAR's motion relative to Eros, using up 54% of the spacecraft's pre-launch hydrazine fuel. With the lateral acceleration limits increased, the burn did not abort. Two TCMs, on 20 January 1999 and 12 August 1999, were designed to correct the 7 m/s magnitude and 1.3° pointing errors of DSM-2.[24] After DSM-2, NEAR and Eros were separated by less than a million kilometers, and under 300,000 km in distance from the Sun, so their paths are on top of each other at the scale of Fig. 3.

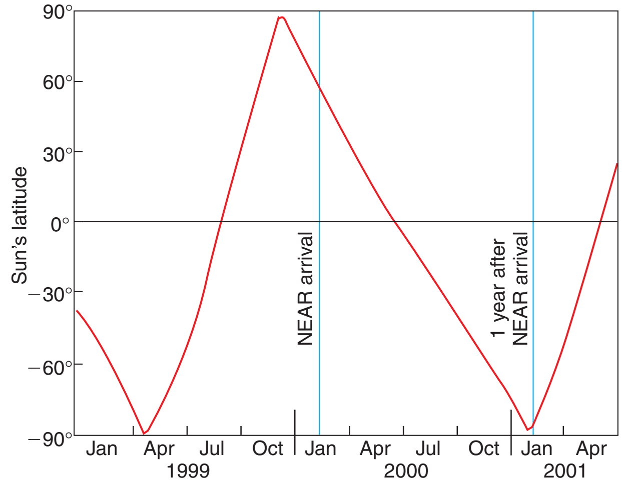


Figure 9. The Sun's latitude above Eros' equator.

NEAR's trajectory relative to Eros is shown in more detail in Fig. 10. It is a projection into Eros' orbit plane, with the horizontal Sun–Eros line fixed. Following the January DSM-2 and TCM-18 maneuvers, NEAR was in an orbit with a slightly smaller heliocentric semi-major axis than Eros and a slightly larger eccentricity. NEAR

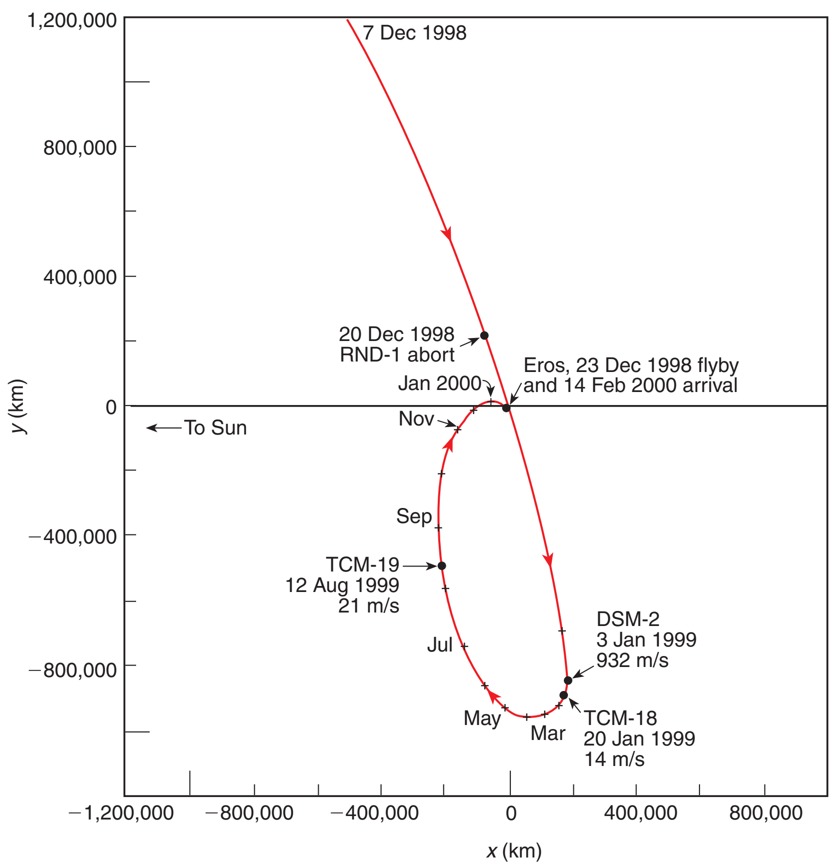


Figure 10. NEAR's U-turn trajectory back to Eros in a rotating Eros-orbit (*x*-*y*) reference frame.

first drifted a little farther from Eros, reaching a maximum distance just under a million kilometers in mid-March 1999. But NEAR was also traveling toward the Sun, causing its heliocentric speed to increase relative to Eros and allowing it to catch up to the asteroid and reach it in February 2000.

At the beginning of February 2000, NEAR was approaching Eros with a relative velocity of 20 m/s. A first maneuver of 9.5 m/s on 2 February would halve the relative velocity. It was compared with post-maneuver optical and radio navigation to determine calibration factors to improve the accuracy of the nearly identical (virtually the same geometry and size) and critical OIM on 14 February. The approach to Eros was designed to pass exactly between the Sun and Eros at a distance of 200 km. With a leisurely 10 m/s relative velocity, this would allow extensive observations of Eros with NEAR's infrared spectrometer at phase angles at and near 0°, ideal conditions for this instrument, which had a scan mirror to allow imaging at a wide range of phase angles. Ten hours after passing through the Eros–Sun line, called the "zero-phase flyby," NEAR would reach the desired orbit plane that is perpendicular to the Sun direction (the Sun plane of sky) and there, at a distance of about 330 km from Eros, it would perform the 10-m/s OIM. After failure of the 2 February burn, maneuvers (TCM-22 and TCM-23) were designed and successfully performed on 3 and 8 February, preserving the planned schedule and zero-phase flyby illustrated in Fig. 11.[12]

NEAR SHOEMAKER AT EROS

Orbit Insertion

On Valentine's Day 2000, the OIM started on schedule at 1533:06 UTC (10:33 a.m. EST), but controllers did not know it until 1547 UT, when the spacecraft signal reached Earth. The Doppler shift indicated a nearly perfect burn with an error of only about 0.1%. Controllers waited several more minutes to receive confirmation from NEAR's accelerometers that the maneuver had indeed been performed as planned. Two hours later, a spectacular image of the largest known crater on Eros gave a further confirmation of the orbit, the first of hundreds of optical navigation images that would be used for orbit determination. The crater, later named Psyche, was right in the center of the image as planned, giving final confirmation of NEAR's orbit about Eros.

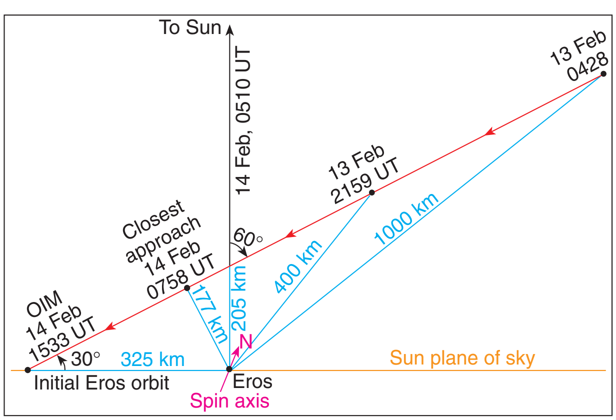


Figure 11. Geometry of NEAR's approach to Eros with zero-phase flyby before the orbit insertion.

The orbit about Eros that was achieved had a periapsis distance of 321 km (near the OIM point) and an apoapsis distance of 366 km, considerably less than the 500-km maximum distance originally planned. The shortfall was not caused by maneuver accuracy; the burns (TCM-22, TCM-23, and especially OIM) all had very small errors. Rather, the lower apoapsis was caused by uncertainty in Eros' mass, which could not be as well determined during the approach as expected because of the interruption of the tracking data by TCM-23 on 8 February. But the more nearly circular orbit had advantages for the initial imaging of Eros and also allowed entry into lower orbits about Eros a little earlier than planned.

Northern Hemisphere Coverage

On 24 February 2000, NEAR performed its first propulsive maneuver while in orbit about Eros. This OCM was the first of six OCMs that guided the spacecraft through various orbital distances and inclinations on the way to the first prime science orbit, an orbit close enough to the asteroid's surface to allow nearly every instrument to acquire valuable observations. Design of each OCM depended on adherence to many operational and science constraints and guidelines as well as to careful consideration of orbit stability and ever-improving knowledge of the asteroid's gravity model and time-dependent attitude (see articles by Williams, Domingue and Cheng, and Holdridge, this issue).

From late February through late April 2000 the NEAR Shoemaker spacecraft repeated a descend-circularize strategy with periodic inclination changes while maintaining orbit stability constraints. In March 2000, the name of the spacecraft was officially changed to NEAR Shoemaker in memory of Eugene Shoemaker. As the spacecraft descended through these early orbits (shown in Fig. 12), techniques such as optical navigation, landmark tracking, and laser radar data analysis refined knowledge of Eros' gravity, rotation, and pole, and the effect of perturbing forces such as solar gravity gradient.[25] In addition, thrust calibration data continued to be collected and used to refine the accelerometer scale factor error for various thruster pairs. This analysis led to the most accurate maneuvers, OCM-4 and -5, each having execution errors of less than 1-mm/s ΔV.[12]

When NEAR Shoemaker arrived at Eros, the asteroid's north pole was oriented toward the Sun and its southern hemisphere was dark. About 4 months

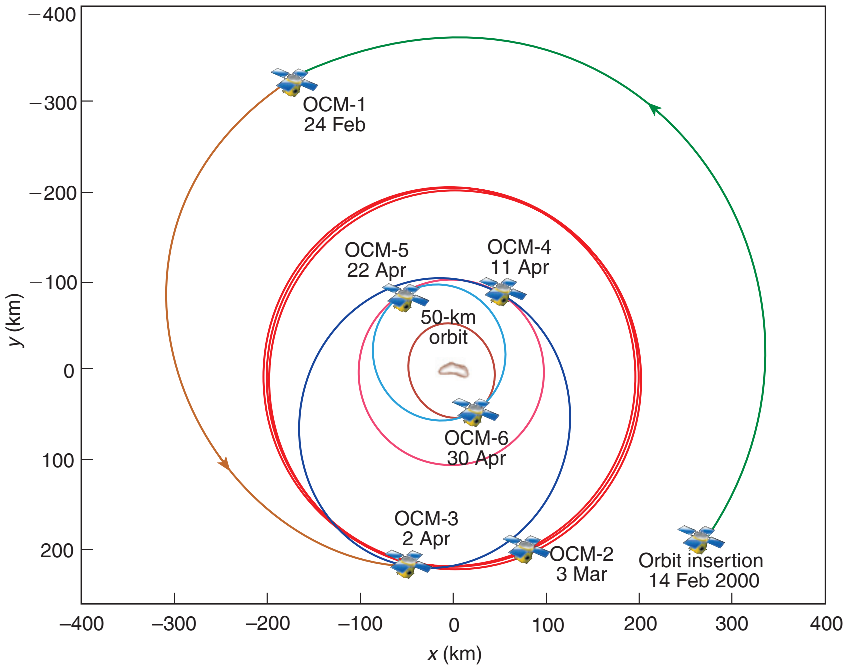


Figure 12. Early Eros orbit phase (view from the Sun).

later, as Eros traveled along its orbit around the Sun, its rotation axis was perpendicular to the Sun–Eros line. As can be seen from Fig. 9, the Sun was over Eros' equator. NEAR's orbital geometry at this time (June 2000) is shown in Fig. 13a. NEAR Shoemaker is shown in a 50-km circular orbit around Eros as viewed by an observer on the Sun. NEAR Shoemaker's orbit and Eros are drawn to scale, but obviously the spacecraft is not. This is a convenient reference frame to show the spacecraft's orbit because its orbital plane was controlled so that it was always within 30° of a plane that is normal to the Sun–Eros line. In this configuration, NEAR's fixed solar panels are oriented toward the Sun. The science instruments are pointed at Eros' surface by slowly

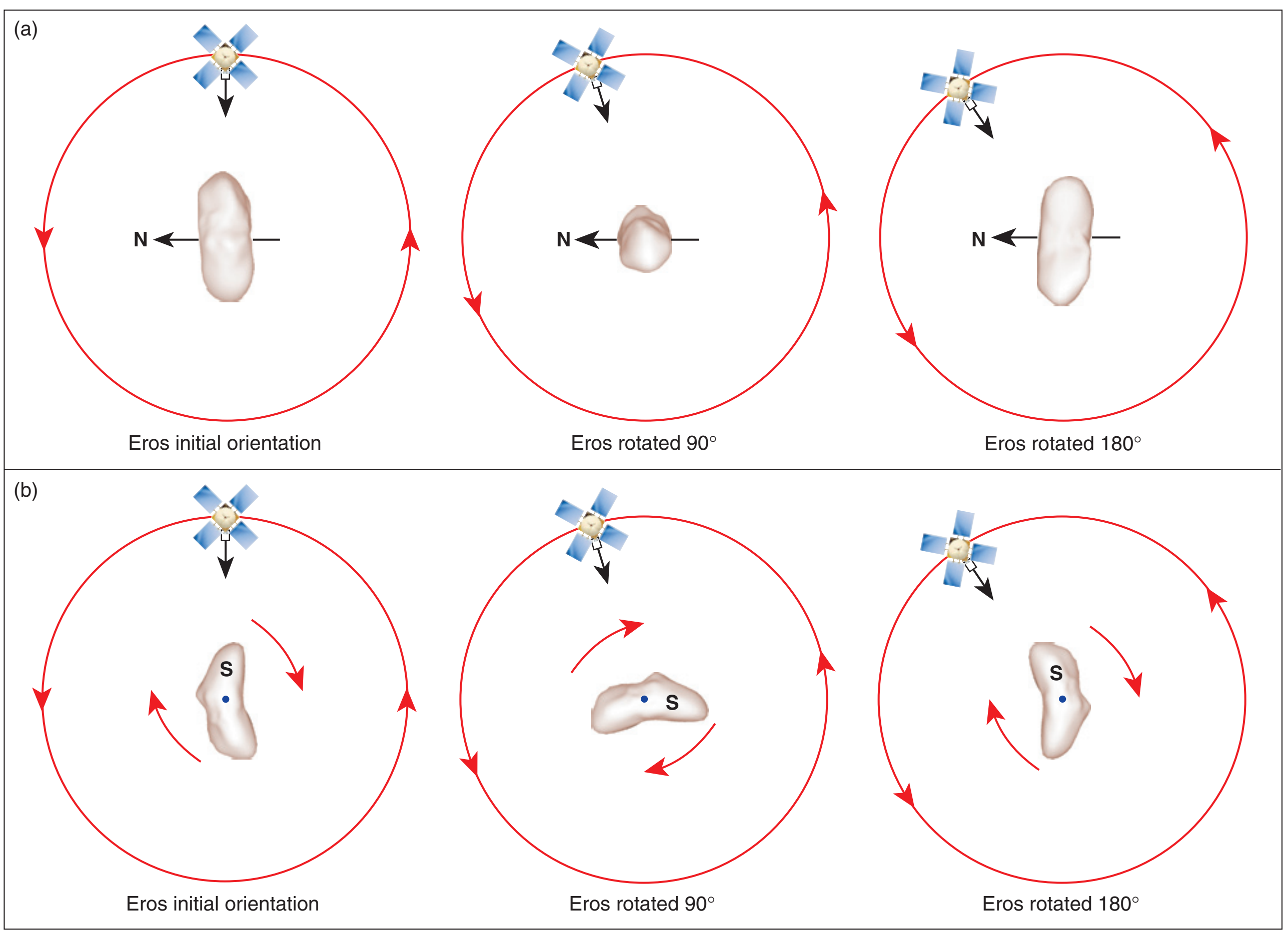


Figure 13. NEAR's orbital geometry at Eros in (a) June 2000 and (b) February 2001 (view from the Sun; orbit size: 50 × 50 km; orbital period: 1.2 days). Eros' rotation axis (a) perpendicular to the Sun–Eros line; (b) aligned with the Sun–Eros line.

rolling the spacecraft as it orbits Eros. The orbital geometry in February 2001 is shown in Fig. 13b. Here, Eros' south pole is directed at the Sun, and the northern hemisphere is in darkness.

During its initial high-orbit phase, NEAR obtained thousands of images of Eros' northern hemisphere at resolutions of about 25 m/pixel. Later, when the spacecraft reached its 50 × 50 km orbit, NEAR's camera mapped the surface at scales of 5–10 m. It was also necessary to get closer to Eros because the X-Ray/Gamma-Ray Spectrometer (XGRS) required long observation periods in orbits with radii of 50 km or less. However, the evolution of low-altitude orbits around Eros is strongly influenced by its irregular gravity field.[26] Orbits exist that are quite unstable, and safe operation in these low-altitude orbits required close coordination between the science, mission design, navigation, and mission operations teams.[27]

Equatorial and Southern Hemisphere Coverage

During the first low-orbit phase from 1 May to 26 August 2000, NEAR Shoemaker spent virtually all of its time in a 50 × 50 km orbit. The only exception was a brief 10-day interval in July when it operated in a 35 × 35 km orbit. Because this first operation in the 35 × 35 km orbit did not encounter any serious navigation problems, it was decided to go directly to this orbit during the second low-orbit phase. This decision allowed the XGRS instrument to operate for about 2 months in an orbit that regularly passed by Eros at altitudes under 20 km.

During the summer of 2000, the NEAR Shoemaker team was planning the end of the mission for February 2001; they wanted to know if good images could be taken during a maneuver. In order to access the quality of such images, OCM-13 on 5 September was performed in a unique way, using a new "mode 11." It was found that the Earth would be within the fanbeam antenna pattern (for real-time monitoring) if OCM-13 was performed in components with the +*x′* axis (with NEAR's Multi-Spectral Imager) pointed at the 3rd-magnitude star α Trianguli. The images of the star obtained during OCM-13 showed no smear.

In the original orbital plan, a second zero-phase trajectory was scheduled for September 2000 to allow Near Infrared Spectrometer (NIS) imaging of the southern hemisphere to complement the northern hemisphere NIS observations obtained during the flyby just before the OIM.[23] But the NIS failed in May 2000, and none of the other instruments were gimbaled to point toward the asteroid during such a flyby. Instead, a low-altitude pass over one of the ends of Eros was scheduled for 26 October 2000 (Fig. 14). This pass was executed without any problems and produced images from ranges to the surface of only 6 km.

The success of the 26 October low-altitude flyover led to a second set of low-altitude passes in late January 2001. This orbit was made elliptical for 4 days, allowing repeated close passes at the minimum-distance-to-center orbit point as the asteroid's ends rotated rapidly under the spacecraft (Fig. 15). The 28 January images during the lowest (2.74-km) altitude pass on that date revealed details of strange regolith "ponds" with resolutions under 0.5 m.

Twenty-three OCMs were carried out through the end of January 2001 with a total ΔV cost of only 17.2 m/s, as detailed in Table 2. At the beginning of February, NEAR's remaining ΔV capability was estimated to be 36.1 ± 6.8 m/s.

Descent and Landing

A question that existed even before NEAR's launch was: What should be done with the spacecraft when its primary mission is completed? The NEAR team decided to attempt a slow descent and landing, even though NEAR was not designed for such a feat. During the descent, the spacecraft would point its HGA at Earth to transmit images and other science data as fast as possible. Because the images would be returned during the descent, success would not depend on the spacecraft surviving the landing impact, and NASA

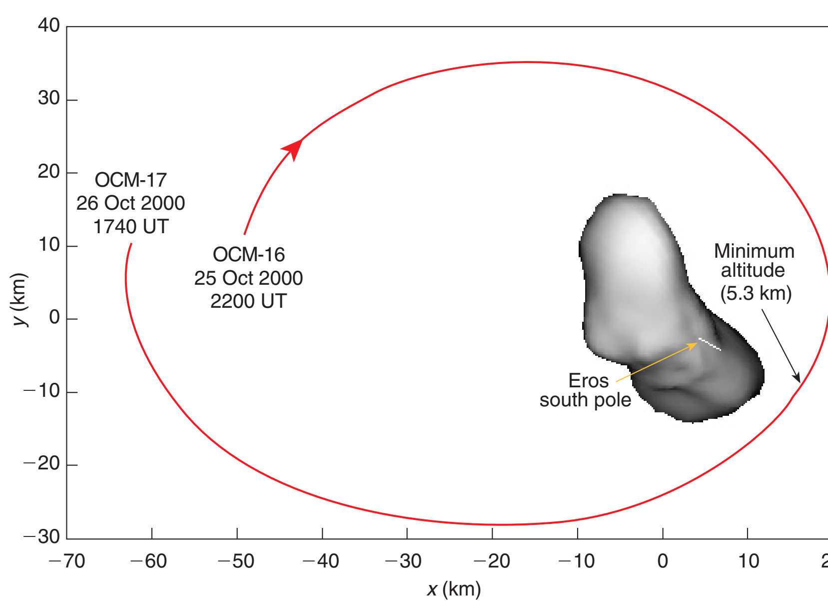


Figure 14. NEAR Shoemaker's low-altitude flyover of Eros on 26 October 2000 (view from the Sun).

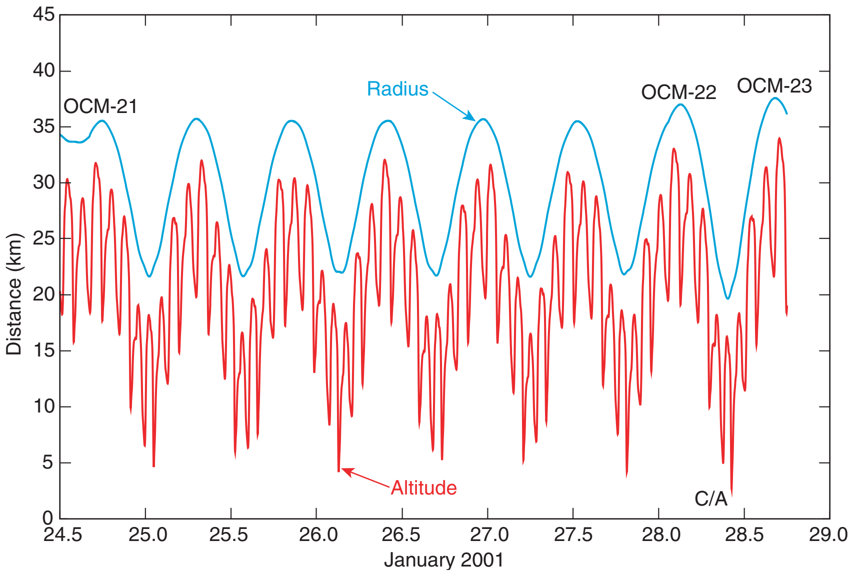


Figure 15. NEAR Shoemaker's low-altitude flyovers of Eros in late January 2001 (C/A = closest approach).

accepted the proposal. A secondary goal was to achieve a soft landing, as first stated by Farquhar et al.[28]

The controlled descent to Eros' surface was planned for 12 February 2001, just 2 days before the formal end of the mission. This plan[29] allowed time to contact the spacecraft after it had set down on Eros. A de-orbit maneuver at about 10:30 a.m. EST on 12 February began NEAR Shoemaker's descent. Approximately 3 h and 45 min later, the first of four braking maneuvers was initiated. This maneuver occurred at an altitude of roughly 5 km and slowed NEAR Shoemaker's rate of descent by about 6 m/s. A profile of the planned descent to the surface is shown in Fig. 16; it includes the steeper trajectories that the spacecraft would take (with harder impacts) if the later braking maneuvers, called "end-of-mission maneuvers" or EMMs, failed. The actual descent determined from the spacecraft's laser altimeter compared very well with the planned descent.

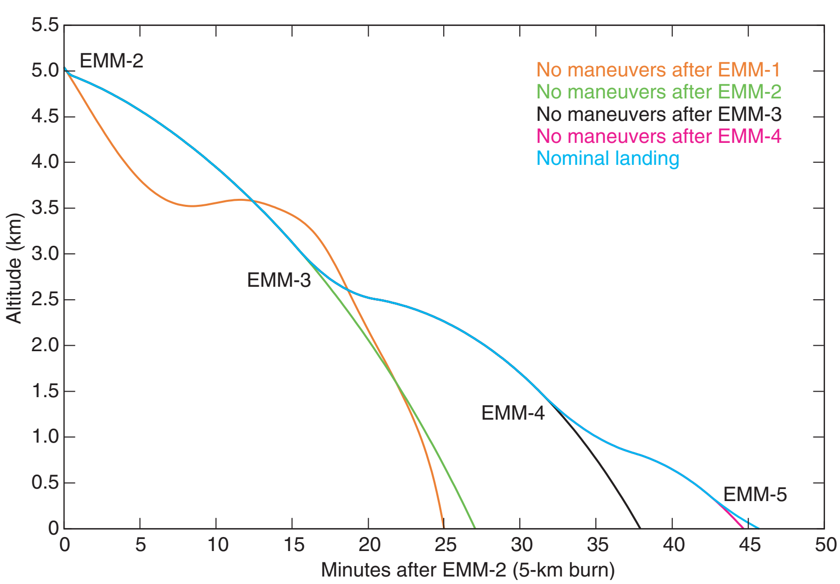


Figure 16. Planned landing descent.

NEAR Shoemaker touched down on the surface of Eros at 3:01:51 p.m. EST (2001:51 UT), as determined from Doppler tracking of its signal shown in Fig. 17. The phenomenon of increasing velocity during the last brake maneuver is explained by the spacecraft's acceleration toward the surface exceeding the weak thrusters' ability to slow the spacecraft. A weak signal continued to be received even after the landing. The touchdown occurred a little earlier than expected, actually during the last brake maneuver (EMM-5). Residual velocity after surface touchdown is evidence of the spacecraft bouncing off the surface prior to the end of its motion. The solar panels remained pointed in the general direction of the Sun after the landing, allowing adequate power, and low bit-rate communication was possible with NEAR Shoemaker's forward low-gain antenna.[30,31]

NASA extended NEAR Shoemaker's mission by 14 days to collect γ-ray spectrometer data.[32] On 28 February commands were sent to place the spacecraft into a deep sleep. As shown in Table 3, NEAR Shoemaker will be in continuous sunlight from 23 August 2002 to 4 January 2003. If the spacecraft survived an unprecedented 3-month period of total darkness from 8 August 2001 to 18 November 2001, it could be asked to provide additional engineering data from Eros' surface. The effects of extremely cold temperatures on NEAR Shoemaker's instruments and other spacecraft hardware would be particularly interesting. An attempt at revival will be made on 10 December 2002, when NEAR Shoemaker will receive nearly maximum sunlight and will be 0.93 AU from Earth, less than half the distance during the descent and landing in February 2001.

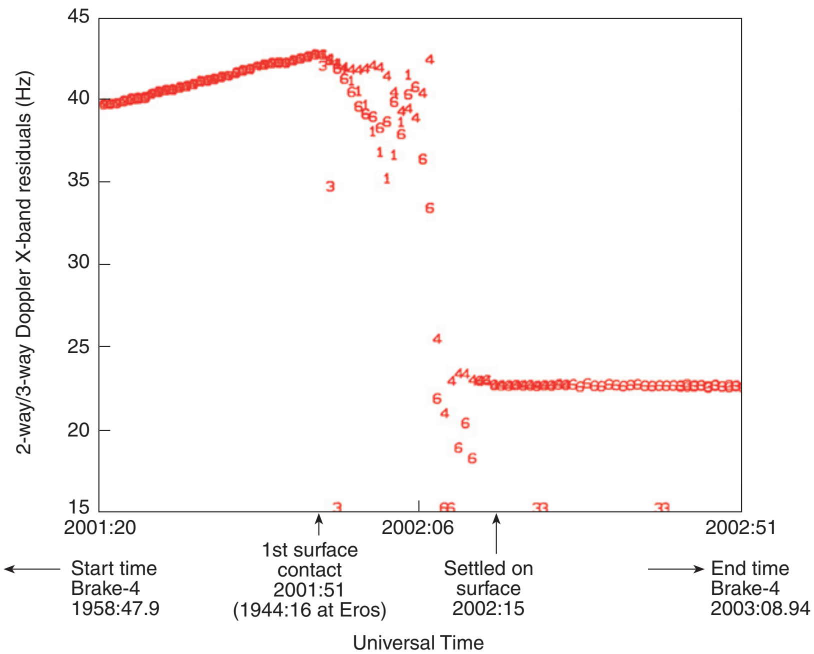


Figure 17. Doppler record of NEAR Shoemaker's landing on Eros on 12 February 2001 (10 Hz = 0.177 m/s).

Table 3. Lighting conditions at NEAR Shoemaker's landing site on Eros.

Date			Condition
12	Feb	2001	Full sunlight
1	Apr	2001	Start of sunsets
7	Jun	2001	Vernal equinox[a]
7	Aug	2001	Total darkness starts
19	Nov	2001	Total darkness ends
31	Mar	2002	Autumnal equinox[a]
22	Aug	2002	Full sunlight starts
7	Nov	2002	Midnight Sun highest
5	Jan	2003	Start of sunsets

[a]At the equinoxes, the lengths of day and night are equal.

CONCLUSIONS

NEAR was the first mission in NASA's Discovery Program of low-cost planetary missions. During its 5-year mission, NEAR used innovative trajectory techniques to accomplish its daring mission. It was the first use of a ΔVEGA trajectory to enable an orbital rendezvous with another Solar System body. A generous fuel supply and a clever preplanned recovery strategy enabled the mission to accomplish more than its planned goals in spite of the failure of its initial attempt to achieve orbit in December 1998.

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