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Postlaunch Contingency Trajectories for the Near-Earth Asteroid Rendezvous Mission

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The August 1995 Koreasat 1 Delta II launch vehicle failure pointed to the prudence of developing a postlaunch contingency strategy for varying levels of Delta II launch vehicle failure. The objective of this investigation is to define contingency strategies that maximize accomplishment of the Near-Earth Asteroid Rendezvous mission objectives. The baseline mission incorporates a trajectory correction maneuver at one week after launch, flyby of main belt asteroid (253) Mathilde in June 1997, and rendezvous with near-Earth asteroid (433) Eros in February 1999. After a partial launch vehicle failure for the Near-Earth Asteroid Rendezvous spacecraft, the need to reduce ΔV penalties associated with a delayed initial trajectory correction maneuver would require mission planners to quickly formulate a contingency trajectory design. Therefore, postlaunch contingency trajectories were designed prior to launch to avoid selection of a less-than-optimal alternative mission option resulting from emergency contingency planning after launch. Strategies were defined for how to perform the initial trajectory correction for launch vehicle failure approaching twice the velocity shortfall experienced by Koreasat 1. These strategies enable completion of most mission objectives with 1) rendezvous with Eros after an injection velocity shortfall up to 69 m/s and 2) rendezvous with near-Earth asteroid (4660) Nereus in 2003 after an injection velocity shortfall up to 300 m/s.

Nomenclature

A = semimajor axis of orbit
C_3 = launch energy
e = orbit eccentricity
i = orbit inclination
Q = orbit aphelion distance
q = orbit perihelion distance
V = velocity
W = orbit longitude of ascending node
w = orbit argument of periapsis

Introduction

THE Near-Earth Asteroid Rendezvous (NEAR) spacecraft, launched Feb. 17, 1996, on a McDonnell Douglas Delta II-7925 launch vehicle, was the first spacecraft launched in NASA's Discovery Program of low-cost planetary missions. The NEAR mission's 27-month development time and fiscal year 1992 (FY92) $108.4 million development cost through launch plus 30 days were well under Discovery Program limits of 35 months and FY92 $150 million, respectively. The NEAR spacecraft will fly by the main belt asteroid (253) Mathilde en route to a January 1999 rendezvous with near-Earth asteroid (433) Eros.[1]

Prior to launch of an interplanetary exploration mission, it is standard practice to identify backup launch opportunities that enable achievement of most or all mission objectives. The NEAR mission to (433) Eros had two such backup launch opportunities.[2]

Not only was it the first Discovery launch but NEAR also represented the first planetary mission for the Delta II launch vehicle.[3] This fact, when considered with the August 1995 Koreasat 1 Delta II launch vehicle failure, led to the initiation of the search for postlaunch contingency trajectories for NEAR. Investigators of the Koreasat 1 launch determined that a solid motor failed to jettison after burnout.[4] The net effect was a target velocity shortfall of about 500 ft/s (152.4 m/s). Conway and Chen[5] employed optimal control theory in 1996 to the August 1995 Koreasat 1 recovery and demonstrated stationkeeping fuel savings that would have provided nearly two additional years of on-orbit service. Unfortunately, the less efficient recovery maneuvers (planned after launch) consumed about 4.5 years of the spacecraft's 10-year lifetime onboard fuel supply. This paper will summarize NEAR contingency trajectories for transfer trajectory injection (TTI) shortfalls of less than this shortfall when Eros is the rendezvous target and greater than this shortfall for rendezvous with Nereus.

The NEAR spacecraft's dual mode (hydrazine and bipropellant) propulsion system and plans to utilize an Earth swingby combine to yield a versatile multilevel strategy for postlaunch contingency trajectories. Each level is identified by a contingency plan code (A–E) and is defined in Table 1. Research by Lau and Hulkower[6] indicated a favorable rendezvous launch opportunity to 1982 DB (later named Nereus) in January 1998, the same month planned for NEAR's Earth swingby. Knowledge of this launch opportunity led to discovery of a heliocentric transfer of type VI (nearly three orbits after Earth swingby) would yield the shortest trip time to Nereus that meets NEAR power, propulsion, and thermal constraints. A search for other contingency asteroid rendezvous candidates turned up no suitable targets for interplanetary trip times less than eight years.

Baseline Mission

Before providing details of postlaunch contingency strategies and trajectories, it is necessary to review the baseline NEAR mission design. Selection of any alternate trajectory after a less than successful launch depends on the same mission design constraints that guided NEAR spacecraft design.

Key constraints such as minimum and maximum solar distance for NEAR are readily apparent in an ecliptic plane projection of the trajectory (Fig. 1). For NEAR, perihelion lies around 0.95 AU and aphelion reaches nearly 2.19 AU. A contingency trajectory with perihelion much below 0.95 AU will encounter thermal conditions that could endanger spacecraft functionality. In addition, contingency trajectories beyond 2.19 AU may lead to insufficient solar array power and a fully discharged battery.

Figure 1 also shows that the Feb. 16, 1996, first day of a 16-day launch period occurs at a heliocentric longitude of 147.5° longitude. For NEAR's $2^{-}\Delta V$ (Delta velocity) Earth gravity assist (EGA) trajectory, the sum of longitude of ascending node and argument of periapsis should be in the 113–133-deg range to align the line of apsides with the January Earth swingby. The Earth swingby lowers spacecraft aphelion and increases its orbital inclination to closely match these parameters for Eros. The Earth swingby altitude of 478 km exceeds the 300-km minimum altitude constraint. Figure 1 also identifies the date and location of the main belt asteroid (253)

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Mathilde flyby. Although not part of NEAR's primary mission objectives, a main belt asteroid flyby would enhance science return.

Table 2 summarizes onboard ΔV capability by listing expected ΔV and reserve ΔV for the Feb. 16, 1996, launch. When fully utilizing the advantages of NEAR's dual mode (monopropellant/bipropellant) propulsion system, a total postlaunch ΔV capability of about 1450 m/s is split between monopropellant hydrazine at about 250 m/s and bipropellant at nearly 1200 m/s. NEAR's 11 fine velocity control (FVC) thrusters deliver 1 or 5 lb thrust and are used for attitude control and smaller trajectory correction maneuvers (TCMs) (prelaunch unknown). When NEAR performs maneuvers with monopropellant, predicted values of specific impulse range from 206 to 235 s, depending on thrusting event type. NEAR's large velocity adjustment (LVA) 100-lb thruster is used only for larger deterministic (well defined prior to launch) maneuvers. The bipropellant (monomethyl hydrazine/nitrogen tetroxide) used with the LVA thruster has an average specific impulse of 313 s. The baseline plan is to perform TCM-1 and the fourth rendezvous maneuver (RND) at Eros arrival with FVC thrusters and the July 1997 deep-space maneuver (DSM) and first three Eros rendezvous maneuvers with the higher thrust LVA thruster.

This baseline mission overview demonstrates the NEAR spacecraft's limited flexibility to accommodate new asteroid rendezvous missions. Body-fixed antennas and solar panels, thermal management issues, and only a moderate postlaunch ΔV capability combine to eliminate most asteroids from being candidates for a postlaunch contingency rendezvous. However, the planned Earth swingby introduces additional flexibility in the search for a suitable rendezvous asteroid for TTI shortfalls large enough to prevent reaching Eros.

Table 1 Contingency plan strategy summary

Contingency plan code	Postlaunch ΔV allocation strategy/flyby/rendezvous targets
Nominal	TCM-1, RND 4 with FVC; DSM, RND 1-3 with LVA 253 Mathilde flyby, 433 Eros rendezvous (nominal orbit phase)
A	TCM-1, RND 4 with FVC; DSM, RND 1-3 with LVA 253 Mathilde flyby, 433 Eros rendezvous (nominal orbit phase)
B	RND 2B-4 with FVC; TCM-1, DSM, RND 1-2A with LVA 253 Mathilde flyby, 433 Eros rendezvous (nominal orbit phase)
C	RND 2B-4 with FVC; TCM-1, DSM, RND 1-2A with LVA 433 Eros rendezvous (shortened orbit phase)
D	RND 2-3 with FVC; TCM-1, DSM-1-4, RND 1 with LVA 306 Unitas flyby, 4660 Nereus rendezvous
E	TCM-1 with FVC; DSM (powered Earth swingby) with LVA Comet Tempel 2 flyby

Contingency Strategies for Eros Rendezvous

The first three postlaunch contingency plans (A, B, and C described in Table 1) share Eros as rendezvous asteroid. Before determining maximum contingency values for TCM-1, appropriate timing for TCM-1 was determined. Mission operations at Applied Physics Laboratory, Johns Hopkins University (APL/JHU) determined that 24 h after launch would be the earliest time for TCM-1 and 1 week after launch set as the nominal time for TCM-1. A trade study assuming 50-m/s TTI shortfall on these two TCM-1 times resulted in only a 3 m/s difference with less than 1 m/s difference in total postlaunch ΔV. Therefore, this study assumed that TCM-1 would occur at TTI plus 1 week. Key launch and early operations parameters for each contingency plan are summarized in Table 3.

The first contingency plan is identical to the baseline (or nominal) mission plan. Plan A assumes that TCM-1 and the fourth Eros RND

Table 2 ΔV summary for 3σ TTI shortfall Feb. 16, 1996, launch[a]

Date	Event	ΔV, m/s
Feb. 23, 1996	TCM-1	25.0
June 27, 1997	Mathilde flyby	0.0
July 3, 1997	DSM (90%)[b]	**247.1** + 4.4
July 4, 1997	DSM (10%)[b]	**24.6** + 3.3
Jan. 22, 1998	Earth swingby	0.0
Jan. 9, 1999	Rendezvous 1[b]	**696.1** + 7.4
Jan. 16, 1999	Rendezvous 2[b]	**194.8** + 5.2
Jan. 23, 1999	Rendezvous 3[b]	**35.5** + 4.5
Jan. 30, 1999	Rendezvous 4	5.0
Feb. 23, 1996–Jan. 30, 1999	Navigation	27.7
Feb. 6, 1999	Eros flyby	0.0
Feb. 8–Dec. 31, 1999	Eros orbital phase	66.0
End of mission	Hydrazine reserve	109.1
	Total ΔV	1452.7
	Hydrazine ΔV	254.6
	Bipropellant ΔV	**1198.1**

[a]Boldface type indicates maneuver utilizing LVA (bipropellant) thruster.
[b]ΔV includes settling burn and attitude control performed with hydrazine.

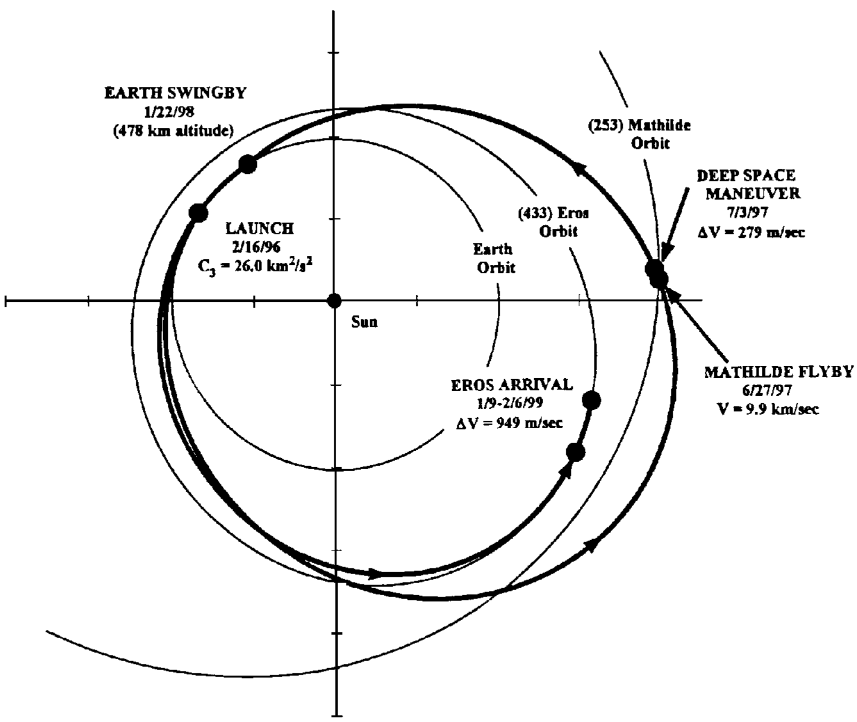

Fig. 1 NEAR trajectory profile for nominal Feb. 16, 1996, launch.

Table 3 Launch and early operations contingency plan summary[a]

Contigency plan code	Launch energy C_3, km^2/s^2	TTI shortfall ΔV, m/s	TCM-1 ΔV, m/s	Flyby target	Rendezvous target
Nominal	25.985	0.0	0.0	Mathilde	Eros
A	25.985–24.969	0.0–41.9	0.0–114.6	Mathilde	Eros
B	24.969–24.748	41.9–51.0	**114.6–137.2**	Mathilde	Eros
C	24.748–24.313	51.0–69.0	**137.2–185.0**	None	Eros
D	24.313–18.787	69.0–300.0[b]	**185.0–823.6**	Unitas	Nereus
E	11.156	626.6	197.1	Tempel 2	None

[a]Boldface type indicates maneuver utilizing LVA (bipropellant) thruster.
[b]August 1995 Delta II Koreasat launch target velocity shortfall was ~152.4 m/s.

Table 4 ΔV summary for worst-case contingency plan A[a]

Date	Event	ΔV, m/s
Feb. 23, 1996	TCM-1	114.6
June 27, 1997	Mathilde flyby	0.0
July 3, 1997	DSM (90%)[b]	**247.0** + 4.5
July 4, 1997	DSM (10%)[b]	**24.5** + 3.4
Jan. 22, 1998	Earth swingby	0.0
Jan. 9, 1999	Rendezvous 1[b]	**696.0** + 7.5
Jan. 16, 1999	Rendezvous 2[b]	**194.6** + 5.4
Jan. 23, 1999	Rendezvous 3[b]	**35.3** + 4.7
Jan. 30, 1999	Rendezvous 4	5.0
Feb. 23, 1996–Jan. 30, 1999	Navigation	24.7
Feb. 6, 1999	Eros flyby	0.0
Feb. 8–Dec. 31, 1999	Eros orbital phase	66.0
	Total ΔV	1433.2
	Hydrazine ΔV	235.8
	Bipropellant ΔV	**1197.4**

[a]Boldface type indicates maneuver utilizing LVA (bipropellant) thruster.
[b]ΔV includes settling burn and attitude control performed with hydrazine.

Table 5 ΔV summary for worst-case contingency plan B[a]

Date	Event	ΔV, m/s
Feb. 23, 1996	TCM-1[b]	**133.5** + 3.7
June 27, 1997	Mathilde flyby	0.0
July 3, 1997	DSM (90%)[b]	**260.7** + 4.6
July 4, 1997	DSM (10%)[b]	**26.1** + 3.4
Jan. 22, 1998	Earth swingby	0.0
Jan. 9, 1999	Rendezvous 1[b]	**692.2** + 7.5
Jan. 16, 1999	Rendezvous 2A[b]	**88.2** + 4.7
Jan. 16, 1999	Rendezvous 2B	107.1
Jan. 23, 1999	Rendezvous 3	40.0
Jan. 30 1999	Rendezvous 4	5.0
Feb. 23, 1996–Jan. 30, 1999	Navigation	29.0
Feb. 6, 1999	Eros flyby	0.0
Feb. 8–Dec. 31, 1999	Eros orbital phase	55.6
	Total ΔV	1461.3
	Hydrazine ΔV	260.6
	Bipropellant ΔV	**1200.7**

[a]Boldface type indicates maneuver utilizing LVA (bipropellant) thruster.
[b]ΔV includes settling burn and attitude control performed with hydrazine.

are performed with hydrazine through selected FVC thrusters and the DSM and first three Eros RNDs are performed using bipropellant through the LVA thruster. The NEAR spacecraft, like Galileo, is expected to experience a Sterer check valve stuck open upon initial use of the LVA thruster. As a result, NEAR management chose to minimize risk by depleting end-of-mission hydrazine reserves before switching to use the LVA thruster for TCM-1. The 109.1 m/s end-of-mission hydrazine reserve transfers to the beginning of the mission (TCM-1) as an extra 89.6 m/s because the same propellant weight imparts less ΔV to the larger spacecraft mass. This plan A maximum TCM-1 ΔV of 114.6 m/s (Table 4) corresponds to a launch energy (C_3) of 24.969 km^2/s^2 and a TTI underburn of 41.9 m/s. The actual TTI shortfall experienced by the NEAR spacecraft was estimated at 4 m/s (Ref. 7). To complete this study within allocated resources, the TTI underburn was assumed to reduce ΔV magnitude, not direction.

The second contingency plan requires that TCM-1 utilizes the LVA thruster while preserving the main belt asteroid (253) Mathilde

Table 6 ΔV summary for worst-case contingency plan C[a]

Date	Event	ΔV, m/s
Feb. 23, 1996	TCM-1[b]	**181.1** + 3.9
March 6, 1997	DSM (90%)[b]	**238.5** + 4.5
March 17, 1997	DSM (10%)[b]	**23.6** + 3.4
Jan. 22, 1998	Earth swingby	0.0
Jan. 9, 1999	Rendezvous 1[b]	**709.4** + 7.6
Jan. 16, 1999	Rendezvous 2A[b]	**44.5** + 4.5
Jan. 16, 1999	Rendezvous 2B	151.0
Jan. 23, 1999	Rendezvous 3	40.0
Jan. 30, 1999	Rendezvous 4	5.0
Feb. 23, 1996–Jan. 30, 1999	Navigation	24.0
Feb. 6, 1999	Eros flyby	0.0
Feb. 8–Dec. 31, 1999	Eros orbital phase	24.2
	Total ΔV	1465.1
	Hydrazine ΔV	268.1
	Bipropellant ΔV	**1197.0**

[a]Boldface type indicates maneuver utilizing LVA (bipropellant) thruster.
[b]ΔV includes settling burn and attitude control performed with hydrazine.

flyby and a full Eros orbital phase. The end-of-mission hydrazine reserve, 25-m/s nominal TCM-1 allotment, and Eros orbital phase excess ΔV (about 10 m/s) were shifted to the second and third Eros RNDs. Bipropellant ΔV, nominally performed at Eros RNDs 2 and 3, was transferred to TCM-1, and a larger DSM was required for the reoptimized NEAR trajectory. This plan B maximum TCM-1 ΔV of 137.2 m/s (Table 5) corresponds to a launch energy of 24.748 km^2/s^2 and a TTI shortfall of 51.0 m/s.

Contingency plan C differs from plan B in that the spacecraft would not be targeted to fly by asteroid (253) Mathilde. For the worst-case plan C scenario NEAR would resort to a minimum Eros orbital phase about half as long as the 11 month full orbital phase. This shortened Eros orbital phase requires just under 25 m/s ΔV. For plan C more of the second Eros RND is performed with FVC thrusters freeing up additional bipropellant ΔV capability for TCM-1. The plan C maximum TCM-1 ΔV of 185.0 m/s (Table 6) corresponds to a launch energy of 24.313 km^2/s^2 and a TTI shortfall of 69.0 m/s.

Contingency Strategies for Alternative Rendezvous/Flyby Targets

For launch vehicle error resulting in TTI shortfall in excess of 69 m/s, an alternative near-Earth asteroid rendezvous opportunity was discovered. Research in the mid-1980s by Lau and Hulkower[6] revealed a January 1998 launch opportunity rendezvous with 1982 DB (Nereus) having low launch energy and postlaunch ΔV requirement. To meet NEAR's mission design constraints, the Nereus rendezvous required a type VI (nearly three heliocentric orbits) transfer after a late January/early February 1998 Earth swingby. After initial optimization of this trajectory an asteroid/comet flyby search revealed the potential for a low relative velocity (8.1 km/s) flyby of main belt asteroid (306) Unitas. The flyby of this 49-km-diam asteroid has a 131-deg approach phase angle, offering slightly better asteroid illumination than NEAR's 136-deg approach phase angle at (253) Mathilde.

Picking up where contingency plan C left off is the best-case plan D results (Table 7) requiring a postlaunch ΔV of only 802 m/s. Note that only half the Eros orbital phase ΔV budget is allotted for orbital operations at the much smaller Nereus. The worst-case plan D option leaves no end-of-mission ΔV reserve (Table 8). For this trajectory the required TCM-1 ΔV is 824 m/s following an 18.787 km^2/s^2 launch energy and a TTI shortfall of 300 m/s (refer to Table 8). Figure 2 presents an ecliptic plane projection of the worst-case Unitas flyby/Nereus rendezvous trajectory, which was optimized with two independent patched conic solution computer programs. Note also from Fig. 2 that both Earth and the sun are about 1 AU away from the spacecraft at Nereus rendezvous.

For TTI shortfalls in excess of 300 m/s, search criteria were defined to identify potential asteroid rendezvous candidates. The following search criteria were applied to an August 1995 version of the Jet Propulsion Laboratory's DASTCOM3 asteroids and comets data file: $0 < i < 10$ deg, $0 < e < 0.35$, $1.00 < A < 1.65$ AU, $0.8 < q < 1.2$ AU, $1.2 < Q < 2.1$ AU, $87 < W + w < 207$ deg, and $\Delta V_{PL/R} < 1.25$ km/s. The last quantity, $\Delta V_{PL/R}$, is the ΔV required at the spacecraft aphelion to lower or raise spacecraft perihelion (PL/R) (0.988 AU at launch) to the asteroid perihelion. Maximum postlaunch ΔV capability is about 1.45 km/s. Table 9 lists the asteroids meeting the search criteria. The Earth return years in Table 9 come from Table 10, which shows the spacecraft orbit period, Earth/spacecraft orbital resonance, and corresponding perihelion and aphelion distances assuming departure from a 1.0-AU circular orbit.

A thorough search was then conducted to find postlaunch contingency ΔV-EGA trajectories leading to rendezvous with any asteroids identified in Table 9. Total mission time was extended from about four years to nine years to increase opportunity of finding an acceptable rendezvous opportunity. Research recently conducted at Purdue University included a discussion of a V_∞ leveraging technique with application to multirevolution ΔV-EGA trajectories.[8] Application of V_∞ leveraging to search for postlaunch contingency asteroid rendezvous trajectories yielded no solutions meeting NEAR mission design constraints. This technique is best applied to flyby missions or less constrained rendezvous missions. Mars gravity assist did not prove helpful toward enabling an asteroid rendezvous.

The search for ΔV-EGA rendezvous opportunities included launch energies from about 18 km^2/s^2 down to 6 km^2/s^2. Included

Table 7 ΔV summary of best-case contingency plan D[a]

Date	Event	ΔV, m/s
Feb. 23, 1996	TCM-1[b]	**160.2** + 3.8
Feb. 9, 1997	DSM-1[b]	**28.8** + 3.2
Aug. 7, 1997	DSM-2[b]	**88.4** + 3.6
Feb. 2, 1998	Earth swingby	0.0
April 10, 2002	Unitas flyby	0.0
Jan. 16, 2002	DSM-3[b]	**112.1** + 3.8
Nov. 2, 2002	DSM-4[b]	**65.3** + 3.7
Oct. 18, 2003	Rendezvous 1[b]	**207.4** + 4.6
Oct. 25, 2003	Rendezvous 2	40.0
Nov. 1, 2003	Rendezvous 3	5.0
Feb. 23, 1996–Nov. 1, 2003	Navigation	39.0
Nov. 8, 2003	Nereus flyby	0.0
Nov. 10, 2003–Nov. 9, 2004	Nereus orbital phase	33.0
End of mission	Hydrazine reserve	329.4
	Total ΔV	1131.3
	Hydrazine ΔV	469.1
	Bipropellant ΔV	**662.2**

[a]Boldface type indicates maneuver utilizing LVA (bipropellant) thruster.
[b]ΔV includes settling burn and attitude control performed with hydrazine.

Table 8 ΔV summary for worst-case contingency plan D[a]

Date	Event	ΔV, m/s
Feb. 23, 1996	TCM-1[b]	**817.4** + 6.8
Feb. 8, 1997	DSM-1[b]	**23.1** + 3.9
Aug. 7, 1997	DSM-2[b]	**89.7** + 4.3
Feb. 3, 1998	Earth swingby	0.0
April 10, 2002	Unitas flyby	0.0
Jan. 16, 2002	DSM-3[b]	**112.4** + 4.6
Nov. 2, 2002	DSM-4[b]	**58.5** + 4.5
Oct. 18, 2003	Rendezvous 1[b]	**87.2** + 4.7
Oct. 25, 2003	Rendezvous 2	159.7
Nov. 1, 2003	Rendezvous 3	5.0
Feb. 23, 1996–Nov. 1, 2003	Navigation	39.0
Nov. 8, 2003	Nereus flyby	0.0
Nov. 10, 2003–Nov. 9, 2004	Nereus orbital phase	34.4
	Total ΔV	1455.2
	Hydrazine ΔV	266.9
	Bipropellant ΔV	**1188.3**

[a]Boldface type indicates maneuver utilizing LVA (bipropellant) thruster.
[b]ΔV includes settling burn and attitude control performed with hydrazine.

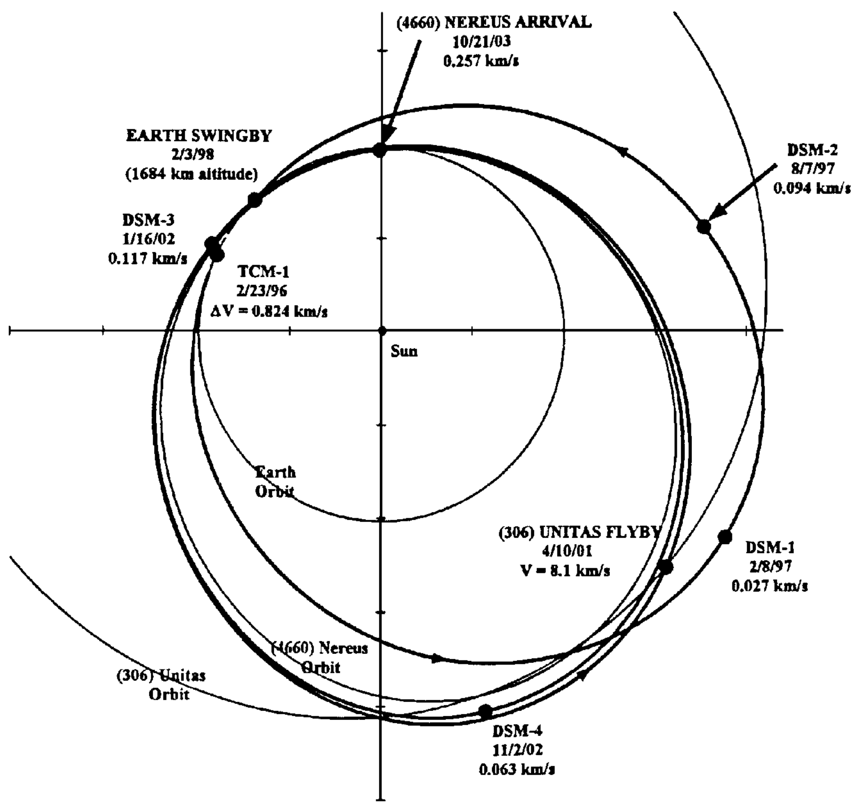

Fig. 2 NEAR trajectory profile to (4660) Nereus: 300 m/s TTI shortfall.

Table 9 Asteroid rendezvous candidates for extreme[a] contingency

Asteroid number	Asteroid name	C_3,[b] km^2/s^2	$\Delta V_{PL/R}$,[c] km/s	A, AU	Eccentricity	Incl., deg	q, AU	Q, AU	$\Omega + \omega$, deg	Earth return, year(s)
13489	1993 VA	18.3	1.063	1.356	0.3912	7.3	0.825	1.886	109.7	2003
14670	1993 BX3	15.6	0.091	1.395	0.2811	2.8	1.003	1.787	105.5	2001
3361	Orpheus	10.6	1.200	1.209	0.3226	2.7	0.819	1.599	131.4	1999, 2002
14675	1993 HA	7.2	0.669	1.278	0.1443	7.7	1.094	1.463	86.9	2000, 2003

[a]Transfer trajectory injection deficiency exceeding 300 m/s.
[b]Approximate launch enrgy to match spacecraft and asteroid aphelions.
[c]ΔV required at aphelion to lower or raise spacecraft perihelion (0.988 AU) to asteroid perihelion.

Table 10 Earth–spacecraft orbit resonance for contingency Earth swingby targeting

Period, days	Years/ orbits	A, AU	q, AU	Q, AU	C_3, km^2/s^2
730.514	2/1	1.587	1.000	2.175	25.785
639.200	7/4	1.452	1.000	1.904	18.693
608.762	5/3	1.406	1.000	1.811	16.210
547.885	3/2	1.310	1.000	1.621	11.156
511.360	7/5	1.251	1.000	1.503	8.154
487.009	4/3	1.211	1.000	1.423	6.223

in this range were 1) 7:4 and 5:3 Earth:spacecraft orbital resonance for asteroids 1993 VA and 1993 BX3 utilizing an Earth swingby in early 2003 and early 2001, 2) 3:2 resonance for (3361) Orpheus utilizing an Earth swingby in early 1999 and early 2002, and 3) 7:5 and 4:3 resonance for 1993 HA with Earth swingbys in early 2003 and early 2000. Multirevolution (types III–VI or 360–1080 deg) transfers were considered after Earth swingby for Earth swingbys in 1999 and 2000. Once again, no suitable asteroid rendezvous opportunities were found for TTI shortfalls beyond 300 m/s.

As an illustration of ΔV-EGA trajectory type for an extreme contingency case, the Tempel 2 comet flyby in 1999 was designed utilizing 3:2 Earth:spacecraft orbital resonance with an early 1999 Earth swingby. This plan E trajectory (Table 3) was known to exist based on research performed at APL/JHU for the Comet Nucleus Tour Discovery Mission proposal. A 445-m/s powered Earth swingby was required for this 626.6 m/s TTI shortfall case. Many other comet and asteroid flyby opportunities exist utilizing the ΔV-EGA trajectory type and meeting NEAR's mission design constraints.

Conclusions

As of Feb. 16, 1996, day 1 of a 16-day launch period for NEAR, a postlaunch contingency plan was ready in the event of deficient performance for the Delta II launch vehicle. Preparation of such a contingency plan represents the first known prelaunch optimization for recovery from a partial launch vehicle failure for a spacecraft departing Earth's gravitational influence. The baseline Eros rendezvous mission remains viable for shortfalls up to 69 m/s in the target spacecraft (injection) velocity at launch vehicle upper stage burnout. Alternate flyby and rendezvous asteroids [(306) Unitas and (4660) Nereus, respectively] served as optional targets when onboard propulsive capability prevented reaching baseline targets (253) Mathilde and (433) Eros. Beyond the 300-m/s injection velocity shortfall limit for these alternates, no asteroid rendezvous opportunities were identified. This multilevel contingency plan arose from a comprehensive, optimal approach to maximizing fulfillment of mission objectives.

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