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Trajectory Options to Pluto via Gravity Assists from Venus, Mars, and Jupiter

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Analytic and numeric techniques are used to assess trajectory options for the Pluto Express sciencecraft for a launch early in the next decade. The constraints placed on the Pluto Express trajectory for this study are severe—total flight time to Pluto of 12 years or less using a Delta-class launch vehicle. In addition, no flybys of Earth are permitted. Suitable trajectories are found with launch windows before, near, and after the date of the baseline launch. All of these trajectories take advantage of a gravity assist with Jupiter, and all use two or three gravity assists with Venus before arriving at Jupiter. In two cases, a Mars gravity assist is used in conjunction with three Venus gravity assists. Several asteroid flyby opportunities are presented for the baseline mission and for a backup trajectory, which launch in March 2001 and July 2002, respectively. For example, a flyby of the asteroid Seraphina (which has a radius of 32 km) can be accommodated in the baseline mission for an additional deterministic delta-velocity of 0.12 km/s, well within the capability of the system.

Nomenclature

C_3	= V_∞^2, km²/s²
g	= standard gravitational acceleration on the Earth, km/s²
I_{sp}	= specific impulse, s
m_f	= total injected dry mass (final mass), kg
m_i	= total injected wet mass (initial mass), kg
m_p	= propellant mass, kg
$m_{s/c}$	= spacecraft mass (excluding propellant tanks), kg
R_J	= radius of Jupiter
r_{po}	= radius of circular parking orbit, km
$\boldsymbol{V}_V$	= velocity of Venus with respect to the sun, km/s
$\boldsymbol{V}_\infty$	= hyperbolic excess velocity vector, km/s
ΔV	= magnitude of a change in velocity, km/s or m/s
ΔV_{NAV}	= navigation ΔV, km/s or m/s
ΔV_{PL}	= deterministic postlaunch ΔV, km/s
ΔV_{TPL}	= total postlaunch ΔV, km/s
μ_E	= gravitational parameter of the Earth, km³/s²

Introduction

PLUTO is the only known planet in the solar system that has not been visited by an interplanetary spacecraft. For many years NASA has been studying mission concepts to explore this distant world. By 1993 the concept, known then as the Pluto Fast Flyby mission, was to launch a low-mass spacecraft (with a dry mass of approximately 100 kg) on a direct trajectory using a Titan IV or Proton launch vehicle with additional upper stages. In the prevailing budgetary climate, however, these launch configurations have been deemed too expensive.

The current concept, known as Pluto Express, evolved from a thorough trade study of various combinations of launch vehicles, upper stages, trajectory types, and spacecraft systems. The study shows that the most cost-effective and lowest-risk option (for a launch in 2001 or 2002) uses a Delta or Molniya launch vehicle to place the spacecraft on a trajectory with gravity assists at Venus and Jupiter.[1]

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The baseline trajectory launches in March 2001 and flies by Venus three times before using a Jupiter gravity assist to reach Pluto in about 12 years. [This type of trajectory is designated by VVVJGA to indicate three Venus gravity assists (VGAs) and one Jupiter gravity assist in that order.]

From a programmatic point of view, it is important to have a backup trajectory available with a launch date roughly a year from the baseline to allow for some schedule slips during spacecraft development. To minimize the effect on the design of the spacecraft, the backup trajectory should have substantially the same characteristics as the baseline. Similar direct trajectories from Earth to another planet occur every synodic period. However, when more than two planets are involved, the relative alignment of the planets does not repeat for a long time. The backup trajectory in this case will necessarily use a different combination of transfers to reach the final destination. The mission cannot wait until the original trajectory repeats. So a search is required to find a suitable backup to the VVVJGA trajectory for the Pluto Express mission.

In this paper, we search for trajectories to Pluto with the following characteristics: 1) launch date October 2001–December 2002, 2) postlaunch deterministic $\Delta V \leq 3500$ m/s, 3) launch C_3 such that propellant and payload can be launched on a Delta 7925, 4) flight time $\leq$ 12 years, and 5) no Earth flybys. The 3500-m/s postlaunch ΔV and 12-year flight time are not hard limits but serve as guidelines for examining and comparing trajectories. Although initially the flyby radius at Jupiter is not constrained, we use 5 Jupiter radii as a guideline for the minimum flyby radius to mitigate the radiation damage to the spacecraft. The spacecraft will likely use a radioisotope power source, so in order to essentially eliminate the possibility of an impact with Earth, no Earth flybys are allowed.

We describe the methods developed to search for trajectories with the characteristics given above, and present some trajectories resulting from our search. We apply these same methods to identify early launch opportunities (prebaseline) in late 2000 and to reexamine the options around the time of the baseline.

Approach

For this study we use a combination of analytic techniques and numeric software tools to find trajectories to Pluto satisfying the given constraints. The two primary mission design software tools that are used are Satellite Tour Design Program[2] (STOUR) and Mission Design and Analysis Software[3] (MIDAS). Both of these programs were originally developed at the Jet Propulsion Laboratory.

Numeric Software Tools

STOUR, originally an interactive program, was modified by Williams[4] to automatically find patched-conic gravity-assist trajectories. The user provides search parameters including a range (and step size) of launch dates and launch energies and the sequence of planets to be encountered. The user then executes STOUR to find all trajectories within the given constraints. Patel[5] incorporated the ability to include powered flybys and broken-plane maneuvers in the automated version. The algorithm he added approximates the local minimum ΔV for these maneuvers.

MIDAS minimizes total ΔV while using patched-conic trajectory simulation. The program is capable of shifting trajectory event times such as launch date, arrival date, and flyby dates and is able to add or delete deep-space maneuvers and powered flybys in order to find an optimal solution.

Analytic Techniques

A Jupiter gravity assist has enormous potential to reduce the launch energy, total ΔV, and flight time for trajectories to Pluto.[6–13] We note that Saturn, Uranus, and Neptune are not in good positions to provide a gravity assist to Pluto for the launch date range we are considering and for total flight times of 12 years or less. So our search focuses on trajectories that use a Jupiter gravity assist. In the time frame under consideration, a Delta 7925 cannot launch the Pluto Express spacecraft directly to Jupiter (keeping the flyby radius above 5 Jupiter radii) in such a way that it reaches Pluto in less than 12 years. Since we are searching for trajectories that do not use an Earth gravity assist, we use multiple Venus flybys as another way to increase the heliocentric energy of the trajectory to reach Jupiter at the appropriate time with a sufficient arrival V_∞.

Following an initial Venus flyby, trajectory legs that reencounter Venus can be either V_∞ turning or V_∞ leveraging. With V_∞ turning there are no maneuvers between the Venus encounters, and the V_∞ (magnitude) at Venus remains the same. The aphelion radius that can be achieved with V_∞ turning using one or more VGAs is shown in Fig. 1. We assume that the orbits of Earth and Venus are circular and coplanar and that the launch V_∞ is directed opposite to Earth's velocity. For the solid and dot–dash curves, total ΔV is simply the launch ΔV from an Earth parking orbit (circular, 185-km altitude). For the dashed lines, the total ΔV includes (in addition to the launch ΔV) a maneuver immediately following the final Venus flyby. These dashed lines originate from the point on each curve beyond which it is more efficient to add the maneuver. The minimum flyby altitude at Venus is assumed to be 250 km. The time-of-flight problem between VGAs is not taken into account for the multiple Venus flybys; consequently, many orbit revolutions may be required before the spacecraft reencounters Venus. Hence, portions of the curves are not realizable within a reasonable flight time.

As the Earth launch energy increases, the V_∞ at Venus increases. The thin solid line in Fig. 1 represents the final aphelion radius if the $\boldsymbol{V}_\infty$ can be turned parallel to the velocity of Venus, $\boldsymbol{V}_V$. However, a single gravity assist can turn the $\boldsymbol{V}_\infty$ only a limited amount. This turn angle decreases as V_∞ increases. As the launch energy increases and the corresponding V_∞ at Venus increases, a point is reached at which a single flyby can no longer turn the $\boldsymbol{V}_\infty$ parallel to $\boldsymbol{V}_V$, and the single-flyby curve (dot–dash curve labeled 1) in Fig. 1 diverges from the thin solid curve. The final aphelion radius then reaches a maximum and decreases. Multiple (n) Venus flybys increase the effective turn angle by a factor of n, and the curve shapes are similar to those for a single Venus flyby.

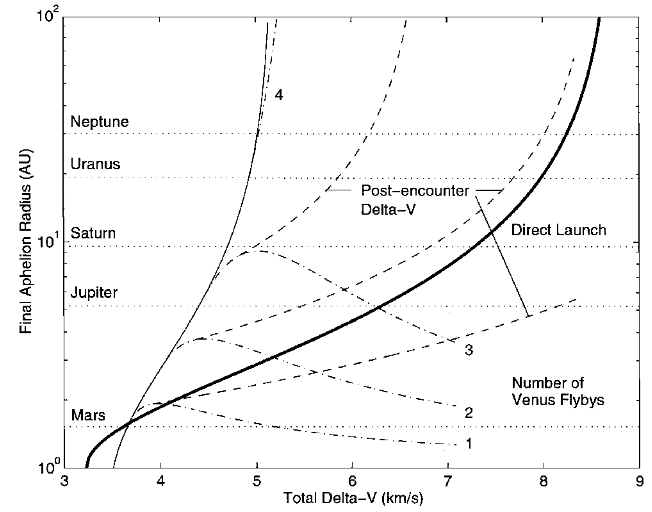

Fig. 1 VGA potential (V_∞ turning).

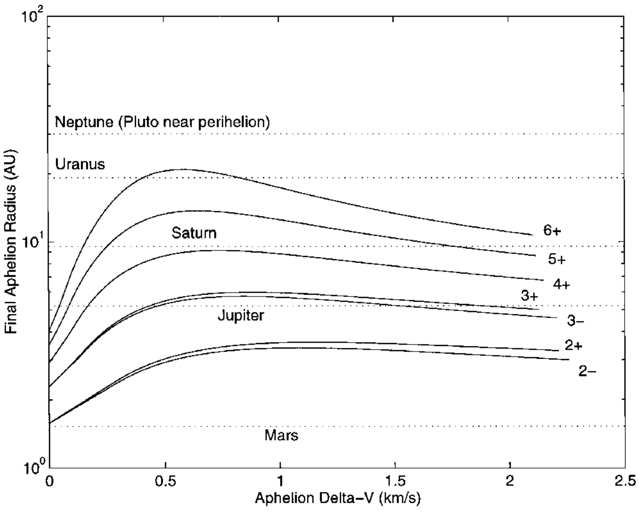

Fig. 2 ΔV–VGA performance vs aphelion ΔV (V_∞ leveraging).

The thick solid curve labeled "Direct Launch" indicates the aphelion that can be achieved by a launch directly from Earth with no Venus flyby. As can be seen, a single VGA and subsequent ΔV requires more total ΔV than a direct launch to reach the radius of Jupiter, but multiple VGAs have the potential to outperform a direct launch.

The transfer orbits between Venus encounters for Fig. 1 do not include any maneuvers. To increase the V_∞ at Venus in this case, we need to increase the Earth launch V_∞. Another way to increase the V_∞ at Venus is to use V_∞ leveraging. The term V_∞ leveraging refers to the use of a relatively small deep-space maneuver to modify the V_∞ at a body. For the purposes of this study, the maneuver occurs near aphelion of a near-resonant transfer between consecutive Venus flybys to increase the V_∞ at Venus. These trajectories are analogous to the ΔV–EGA trajectories introduced by Hollenbeck.[14] The potential of these ΔV–VGA trajectories is shown in Fig. 2, where we plot the final aphelion radius that can be achieved, without a propulsive maneuver at Venus, as a function of the aphelion ΔV. The numbers on the plot correspond to the number of Venus years between Venus flybys for the nominal resonant transfer. The $+$ $(-)$ indicates Venus encounter just after (before) the spacecraft passes through perihelion. (A more thorough analysis and explanation of V_∞ leveraging and V_∞ turning at Venus are presented in Refs. 15 and 16.)

The aphelion on the transfer leg of the $2^\pm$ ΔV–VGA is slightly larger than the semimajor axis of Mars. So given the appropriate phasing between Venus and Mars, a Mars flyby would occur near aphelion and could be used to offset or entirely replace the aphelion ΔV, thereby making these trajectories very efficient in terms of propellant usage.

Methods for Discovering Trajectories

We use three methods for discovering complete trajectories from launch to Pluto arrival. In the first method we use STOUR to analyze various segments of possible trajectories. We then patch together these segments and add Venus–Venus transfers as appropriate, based on our analytic techniques. In the second method we modify trajectories that we originally developed for a mission to Saturn. In the third method we run STOUR by specifying the entire sequence of flybys from launch to Pluto arrival. In each case we use MIDAS to optimize the trajectories to minimize the total ΔV.

Method 1

The arrival dates at Venus for trajectories launched from Earth are shown in Fig. 3. (This type of plot is known as a pork-chop plot.) The launch date for the STOUR run ranges from Oct. 1, 2001,

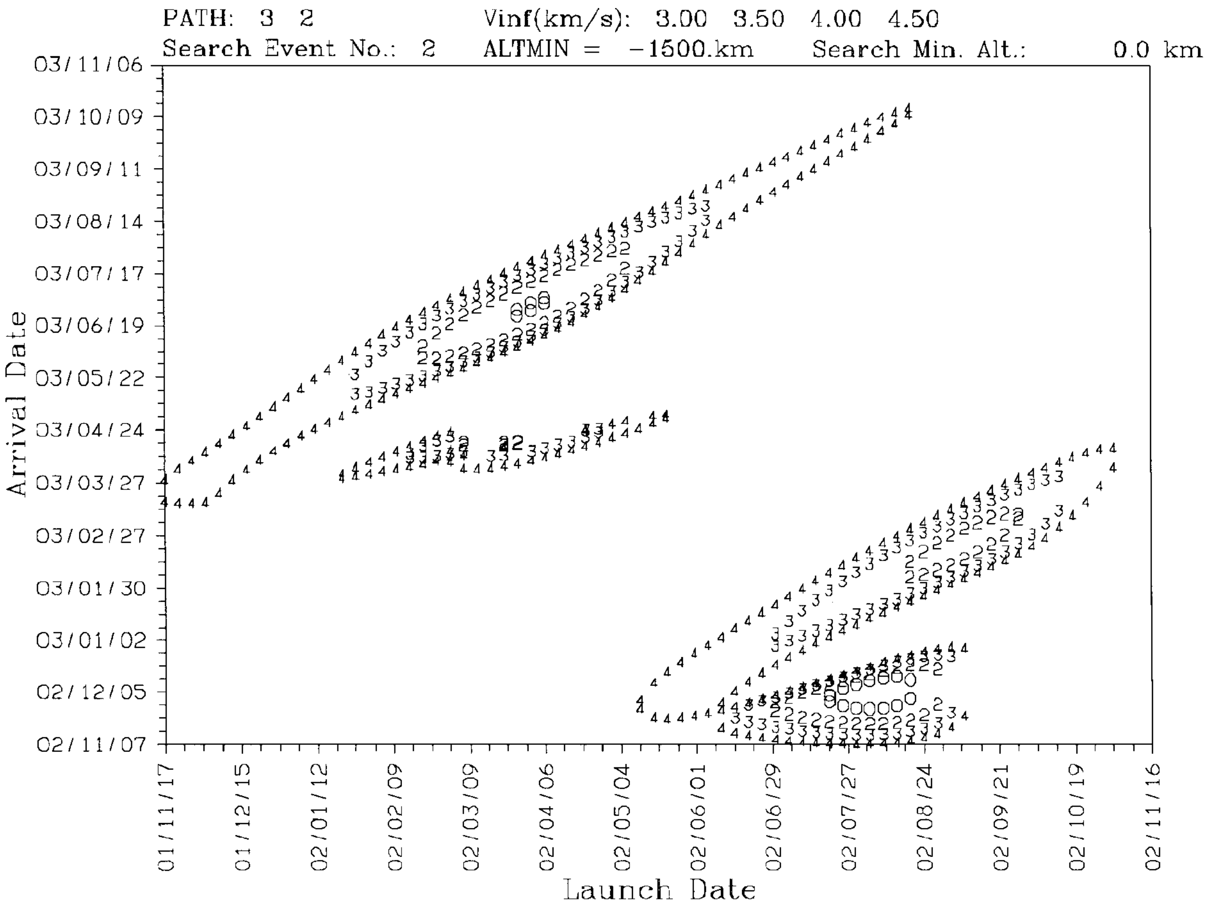

Fig. 3 Earth–Venus launch opportunities.

to Jan. 1, 2003, in steps of five days. The plotted numbers 0, 2, 3, and 4 correspond to the Earth launch V_∞ of 3.0, 3.5, 4.0, and 4.5 km/s, respectively. Type I and II trajectories (transfer angle less than 360 deg) are clearly distinguished from the type III and IV trajectories (transfer angle between 360 and 720 deg), which have longer flight times.

Figure 4 shows the time of flight (TOF) for trajectories from Venus to Pluto that fly by Jupiter. (The type of plot in Fig. 4 is a generalized pork-chop plot for trajectories that include a gravity assist.) The "Launch Date" would actually be the date of the final Venus flyby. The plotted numbers 0, 2, 3, and 4 correspond to V_∞ at Venus of 12, 14, 16, and 18 km/s, respectively.

The Venus–Jupiter–Pluto run provides dates on which the last Venus flyby should occur in order to use Jupiter on the way to Pluto. We mark these dates as arrival dates on the launch-date/arrival-date plots of the Earth–Venus trajectories. We can then pick out trajectories from Earth that arrive at Venus approximately an integer multiple of Venus years before the required Venus flyby dates for trajectories to Pluto via Jupiter. Additional Venus flybys are used with phasing such that the final Venus flyby occurs at the proper time. Using this process, we discovered several trajectories to Pluto with positive injection margins using the Delta 7925. Most of these trajectories include V_∞ leveraging between Venus flybys; that is, there are maneuvers near aphelion that increase the V_∞ at the following Venus flyby. With V_∞ leveraging, the flyby dates at Venus (on the Earth–Venus leg) are not exactly an integer number of Venus years from the final Venus flyby dates. This characteristic provides for greater flexibility in possible launch dates (than the V_∞ turning trajectories) and must be considered in the search for such trajectories.

Method 2

In the second method we find trajectories to Pluto by modifying a trajectory that we originally developed for a mission to Saturn. We discovered a trajectory to Saturn with four VGAs by starting with a complete analytic solution,[15,16] then using STOUR to determine the appropriate launch date, and finally optimizing with MIDAS. The trajectory had no Earth flybys and used V_∞ leveraging with Venus. Instead of encountering Saturn after the last Venus flyby, the trajectories are now targeted to fly by Jupiter on their way to Pluto. Because of the tight time constraints for the trajectories to Pluto, we remove the fourth Venus flyby and perform a powered flyby at the third Venus encounter to reach Jupiter, and hence Pluto, sooner. In one case, we use a Mars gravity assist to replace the V_∞ leveraging maneuver near aphelion on one of the Venus–Venus legs, resulting in a saving of more than 300 m/s of ΔV. In another case, we remove the third Venus flyby and proceed directly to Jupiter after the second Venus flyby.

Method 3

The latest version of the automated STOUR can include a single maneuver between one pair of flybys. This maneuver, which is locally optimized, is either a powered flyby or a broken-plane maneuver. Presently, STOUR cannot search directly for trajectories with a V_∞ leveraging maneuver (i.e., ΔV–VGA trajectories). Working within this limitation, we proceed as follows. In our STOUR runs, we specify the entire sequence of encounters, placing a maneuver after the final Venus flyby. In some cases, when optimizing the STOUR-generated trajectories, MIDAS will automatically add a maneuver near aphelion to create ΔV–VGA trajectories. In other cases, MIDAS will converge on a solution without leveraging. By specifically inserting a maneuver near aphelion (and possibly changing the Venus flyby dates slightly), we may be able to coax MIDAS into finding a trajectory with lower total ΔV using a ΔV–VGA. Following this procedure, we can find trajectories with powered flybys, broken-plane maneuvers, and V_∞ turning—and some trajectories that include V_∞ leveraging maneuvers.

We examine the following sequences using STOUR: 1) EVVV(ΔV)JP, 2) EVVV(ΔV)P, 3) EVV(ΔV)JP, 4) EVMVV(ΔV)JP, 5) EVMVV(ΔV)P, 6) EVMV(ΔV)JP, and 7) EVVMV(ΔV)JP.

A few new trajectories are identified using this approach, including an EVVVJP and an EVMVVJP with positive injection margins. Only one of the trajectories identified by methods 1 and 2 was

Table 1 Trajectories to Pluto using the Delta 7925 (flight time: 12 years)

Trajectory number	Gravity assists	Venus–Venus trajectory types	Launch date	C_3, km^2/s^2	ΔV_{PL}, km/s	ΔV_{NAV}, m/s	Injection margin, kg
I	VVJ	2^+ ΔV–VGA	4/3/2002	14.8	3.50	200	52.0
II	VVJ	3^+ ΔV–VGA	4/3/2002	13.2	3.60	200	54.4
III	VVJ	2^- ΔV–VGA	5/11/2002	12.9	3.61	200	55.5
IV	VVJ	3^- ΔV–VGA	5/13/2002	14.5	3.45	200	68.4
V	VVJ	2:1 Venus–Venus	7/17/2002	26.6	2.53	200	80.7
VI	VVVJ	2^+ ΔV–VGA, 3^- ΔV–VGA	7/20/2002	12.7	3.78	250	−1.1
VII	VVVJ	2^- ΔV–VGA, 2:1 Venus–Venus	7/29/2002	14.3	4.04	250	−106
VIII	VMVVJ	2^- M–VGA, 2:1 Venus–Venus	8/9/2002	18.2	3.34	300	10.2
IX	VMVVJ	2^+ M–VGA, 2.75 Venus–Venus	8/14/2002	20.2	3.11	300	33.0
X	VVVJ	1:1 Venus–Venus, 2:1 Venus–Venus	8/23/2002	16.9	3.16	250	87.0

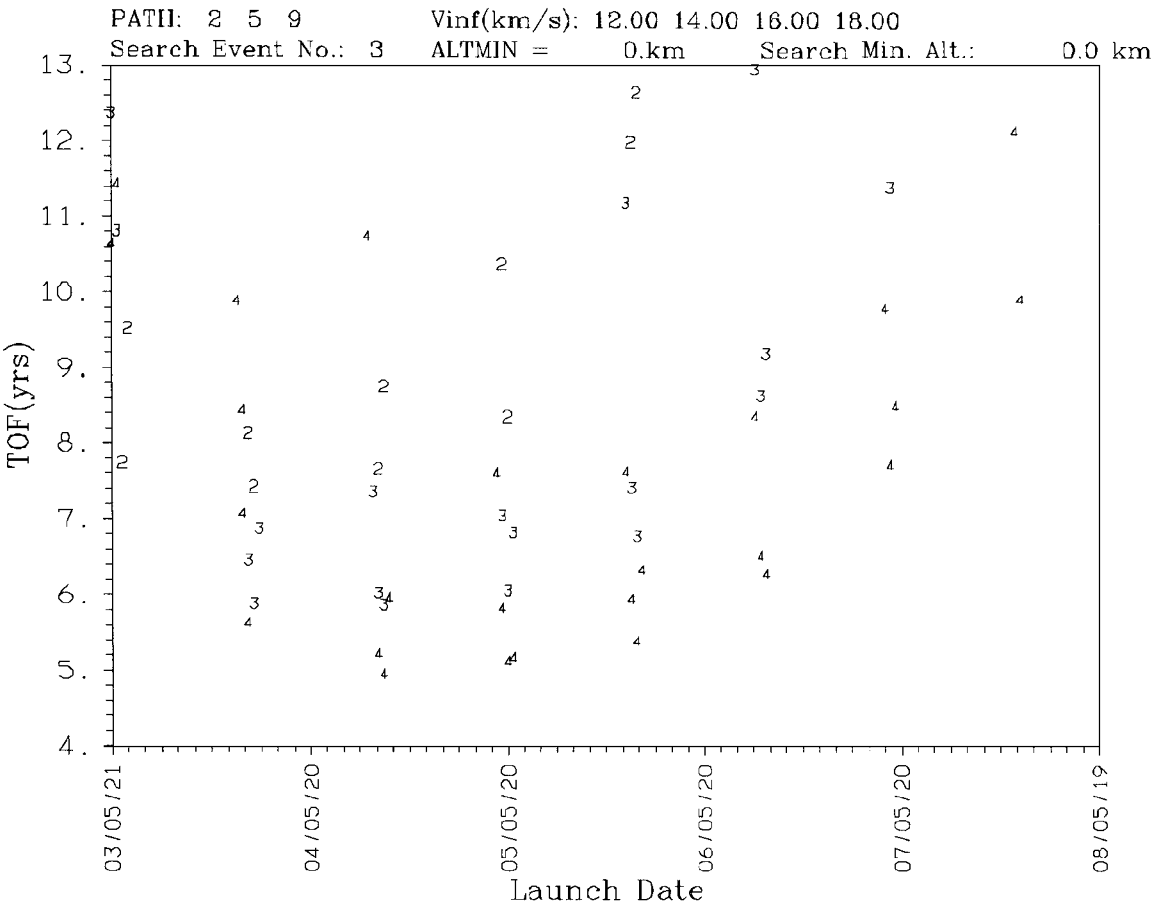

Fig. 4 Venus–Jupiter–Pluto trajectory opportunities.

rediscovered. The one trajectory that was rediscovered uses V_∞ turning and a powered flyby but has no V_∞ leveraging maneuver.

Results

Trajectories to Pluto

Characteristics of 10 of the trajectories, trajectories I–X, identified by the methods described are summarized in Table 1. Five of the trajectories listed are EVVJP, two are EVMVVJP, and the rest are EVVVJP. The launch dates range from April 3, 2002, to Aug. 23, 2002. (Recall that we are considering the time period from October 2001 to December 2002.) More details of trajectories IV, V, IX, and X are presented in Tables 2–5, respectively. Details for the other six trajectories are presented in Ref. 17.

STOUR was used with the sequence EVVV(ΔV)JP to help find trajectory X and with the sequence EVMVV(ΔV)JP to help find trajectory VIII. Following method 3, the output from STOUR was used as input to MIDAS. After several runs of MIDAS, with intervening manipulation of the flyby dates and maneuver locations, trajectories VIII and X in Tables 1 and 5 were found. STOUR also independently found a trajectory similar to trajectory V with the sequence EVV(ΔV)JP. MIDAS was used to manipulate the trajectory from STOUR and to eventually converge on the trajectory in Table 3, which we had already discovered by other means. STOUR has found no other comparable trajectories using the complete sequences of planetary flybys that we have examined. All of the other trajectories that are presented were discovered with MIDAS by patching together segments of the trajectories from STOUR (method 1) or by manipulating trajectories we had discovered previously (method 2).

If Mars is in the appropriate place to allow a flyby between Venus encounters, a Mars gravity assist can be used to replace the V_∞ leveraging maneuver. Examples of this can be seen in Table 1 by comparing trajectory IX with trajectory VI and trajectory VIII with trajectory VII. Trajectory VI uses a maneuver of 254 m/s between the first two Venus encounters to increase the V_∞ from 6.04 to 8.14 km/s and uses a maneuver of 465 m/s before the final Venus flyby to increase the V_∞ to 12.5 km/s. Trajectory IX uses a Mars gravity assist between the first two Venus encounters to increase the V_∞ from 6.73 to 13.4 km/s, resulting in a saving of 350 m/s in total deterministic

Table 2 Trajectory IV characteristics: EVVJP (3^- ΔV–VGA)

Launch	5/13/2002	$C_3 = 14.5$ km^2/s^2
Maneuver	9/29/2002	$\Delta V = 142$ m/s, 0.63 AU
Perihelion	10/2/2002	0.626 AU (min)
Perihelion	7/4/2003	0.626 AU (min)
Venus 1	8/7/2003	$V_\infty = 7.94$ km/s, $\Delta V = 721$ m/s
Maneuver	7/1/2004	$\Delta V = 365$ m/s, 2.30 AU
Venus 2	5/7/2005	$V_\infty = 12.3$ km/s, $\Delta V = 2.22$ km/s
Perihelion	5/15/2005	0.706 AU
Jupiter	8/1/2006	$V_\infty = 16.1$ km/s, flyby radius $= 12.5 R_J$
Pluto	5/13/2014	$V_\infty = 15.2$ km/s
Total deterministic postlaunch $\Delta V = 3.45$ km/s		

Table 3 Trajectory V characteristics: EVVJP (2:1 Venus–Venus)

Launch	7/17/2002	$C_3 = 26.6$ km^2/s^2
Venus 1	11/1/2002	$V_\infty = 10.1$ km/s
Perihelion	11/20/2002	0.682 AU (min)
Venus 2	1/25/2004	$V_\infty = 10.1$ km/s, $\Delta V = 2.53$ km/s
Perihelion	1/29/2004	0.719 AU
Jupiter	8/16/2005	$V_\infty = 11.3$ km/s, flyby radius $= 6.9 R_J$
Pluto	7/17/2014	$V_\infty = 13.8$ km/s
Total deterministic postlaunch $\Delta V = 2.53$ km/s		

Table 4 Trajectory IX characteristics: EVMVVJP (2^+ M–VGA, 2.75 Venus–Venus)

Launch	8/14/2002	$C_3 = 20.2$ km^2/s^2
Venus 1	12/22/2002	$V_\infty = 6.73$ km/s, $\Delta V = 163$ m/s
Perihelion	12/26/2002	0.717 AU
Mars	5/3/2003	$V_\infty = 12.2$ km/s
Perihelion	3/24/2004	0.604 AU (min)
Venus 2	4/19/2004	$V_\infty = 13.4$ km/s
Venus 3	12/28/2005	$V_\infty = 13.4$ km/s, $\Delta V = 2.95$ km/s
Jupiter	2/1/2007	$V_\infty = 19.1$ km/s, flyby radius $= 19.2 R_J$
Pluto	8/11/2014	$V_\infty = 15.5$ km/s
Total deterministic postlaunch $\Delta V = 3.11$ km/s		

Table 5 Trajectory X characteristics: EVVVJP (1:1 Venus–Venus, 2:1 Venus–Venus)

Launch	8/23/2002	$C_3 = 16.9$ km^2/s^2
Venus 1	11/14/2002	$V_\infty = 8.98$ km/s
Perihelion	1/2/2003	0.598 AU (min)
Venus 2	6/27/2003	$V_\infty = 8.98$ km/s
Perihelion	7/10/2003	0.701 AU
Venus 3	9/18/2004	$V_\infty = 8.98$ km/s, $\Delta V = 3.16$ km/s
Perihelion	9/22/2004	0.718 AU
Jupiter	2/13/2006	$V_\infty = 13.2$ km/s, flyby radius $= 10.0 R_J$
Pluto	8/24/2014	$V_\infty = 14.1$ km/s
Total deterministic postlaunch $\Delta V = 3.16$ km/s		

ΔV. A similar comparison can be made between trajectories VIII and VII, where the saving in total ΔV is more than 500 m/s.

Injection Margin

An important parameter in mission design is the injection margin—the difference between the mass the launch vehicle can inject on a given trajectory and the total mass of the spacecraft and propellants that is to be launched on that trajectory. The injection margins, using a Delta 7925 launch vehicle, for trajectories I–X are shown in Table 1 (Ref. 18). In determining the injection margin, we use the same spacecraft characteristics and launch vehicle capability as those used by mission designers at JPL for the Pluto Express mission. That is, we assume a launch vehicle contingency of 10% and an adapter mass that is 5% of the injected mass. We use the rocket equation to determine the propellant mass:

$$\Delta V_{\mathrm{TPL}} = I_{\mathrm{sp}} g \ln(m_i/m_f) \tag{1}$$

where

$$\Delta V_{\mathrm{TPL}} = \Delta V_{\mathrm{PL}} + \Delta V_{\mathrm{NAV}} \tag{2}$$

The mass of the propellant tanks is assumed to be 15% of the propellant mass, so we have

$$m_i = m_{\mathrm{s/c}} + m_p + 0.15 m_p \tag{3}$$

and

$$m_f = m_{\mathrm{s/c}} + 0.15 m_p \tag{4}$$

We assume an I_{sp} of 320 s and the total injected dry mass (spacecraft and propellant tanks) to be 235 kg. The navigation ΔV is a rough estimate based on the number of flybys and ranges from 200 to 300 m/s. The injection margin is then the injected mass capability (minus the 10% contingency) of the Delta 7925 for the given C_3 minus the mass of the spacecraft, propellant tanks, propellant, and adapter.

We use MIDAS to minimize the total deterministic ΔV (launch $\Delta V + \Delta V_{\mathrm{PL}}$). The relationship between launch ΔV and launch C_3, which specifies the launch vehicle capability, is given by

$$\Delta V = \sqrt{(2\mu_E/r_{\mathrm{po}}) + C_3} - \sqrt{\mu_E/r_{\mathrm{po}}} \tag{5}$$

where the parking orbit altitude is assumed to be 240 km. Although there is a correlation between total deterministic ΔV and injection margin, the trajectories are not optimized to maximize injection margin. The propellant system on the spacecraft has an effect similar to an upper stage on the launch vehicle such that for a given total deterministic ΔV, a larger ΔV_{PL} results in a larger injection margin. Spacecraft design considerations, however, dictate an upper limit on ΔV_{PL} and actually favor a smaller ΔV_{PL}. The final mission design must take into account these tradeoffs between trajectory design and spacecraft design.

Flight-Time Analysis

During our initial search, we looked for trajectories that could yield adequate performance. Generally, a shorter flight time requires a larger total ΔV, so the trajectories presented in Table 1 have flight times of approximately 12 years, the longest flight time that was considered reasonable. After the initial search, we performed a preliminary analysis of the effect of shorter flight times for some of the trajectories (Table 6). The results indicate that flight times shorter than 12 years are possible while maintaining a positive injection margin for launch on a Delta 7925. For example, the injection margin of trajectory V decreases from 80.7 to 51.2 kg as the flight time to Pluto decreases from 12.0 to 11.0 years. In general, as the flight time decreases, the ΔV immediately following the final Venus flyby increases and the Jupiter flyby radius decreases. The initial legs of the trajectories remain approximately the same.

Table 6 Examination of flight time to Pluto

Trajectory number	Launch date	TOF, yr	C_3, km^2/s^2	ΔV_{PL}, km/s	Rad.,[a] R_J	Injection margin, kg
IV	5/13/02	12.0	14.5	3.45	12.5	68.4
	5/14/02	11.0	14.6	3.85	9.7	−38.9
	5/15/02	10.0	14.7	4.48	7.1	−240
V	7/17/02	12.0	26.6	2.53	6.9	80.7
	7/19/02	11.0	26.2	2.73	5.3	51.2
	7/20/02	10.0	26.0	3.04	3.8	−11.7
	7/19/02	10.0	25.8	4.03	5.0	−267
IX	8/14/02	12.0	20.2	3.11	19.2	33.0
	8/14/02	11.0	20.4	3.61	15.0	−94.2
	8/14/02	10.0	20.5	4.43	11.0	−351

[a]Flyby radius at Jupiter.

Table 7 Launch window for trajectory V

Launch date[a]	C_3, km^2/s^2	ΔV_{PL}, km/s	Total ΔV, km/s	Injection margin, kg
7/7/2002	25.2	2.82	7.13	44.8
7/9/2002	25.5	2.74	7.06	57.8
7/11/2002	25.4	2.68	7.00	70.8
7/13/2002	26.1	2.61	6.95	75.4
7/15/2002	25.8	2.58	6.91	84.5
7/17/2002	26.8	2.53	6.91	80.0
7/19/2002	26.7	2.52	6.89	83.0
7/21/2002	27.1	2.56	6.94	71.0
7/23/2002	27.2	2.57	6.96	67.3
7/25/2002	25.6	2.69	7.01	67.4
7/27/2002	24.7	2.77	7.06	63.0
7/29/2002	23.9	2.86	7.11	56.3

[a]In all cases, the arrival date is 7/17/2014 (for a flight time of 12.0 years) and the flyby radius at Jupiter is 6.9 Jupiter radii.

Table 8 Baseline trajectory characteristics: EVVVJP ($2^+ \Delta V$–VGA, $4^+ \Delta V$–VGA)

Launch	3/9/2001	$C_3 = 15.9$ km^2/s^2
Perihelion	7/21/2001	0.605 AU (min)
Venus 1	8/29/2001	$V_\infty = 8.72$ km/s
Maneuver	3/20/2002	$\Delta V = 150$ m/s, 1.62 AU
Perihelion	11/6/2002	0.672 AU
Venus 2	11/25/2002	$V_\infty = 9.70$ km/s
Maneuver	1/23/2004	$\Delta V = 430$ m/s, 2.97 AU
Perihelion	5/14/2005	0.649 AU
Venus 3	6/1/2005	$V_\infty = 14.4$ km/s, $\Delta V = 1.67$ km/s
Jupiter	7/11/2006	$V_\infty = 17.8$ km/s, flyby radius $= 9.3 R_J$
Pluto	3/10/2013	$V_\infty = 18.1$ km/s
Total deterministic postlaunch $\Delta V = 2.25$ km/s		
Navigation ΔV, $\Delta V_{NAV} = 250$ m/s		
Injection margin, 284 kg		

Launch-Window Analysis

We also briefly examined the launch window for trajectory V, which has been selected as a backup to the baseline trajectory.[1] Some characteristics of the trajectory for a 23-day range of launch dates and a fixed arrival date are given in Table 7. The effect on the injection margin in this case is relatively small. For a 10-day window the injection margin is over 70 kg, and it is about 60 kg for a 20-day window.

Earlier Launch Dates

Having found trajectories satisfying our initial constraints, we extend our search to include launch dates as early as late 2000. The synodic period between Earth and Venus is 1.6 years, so Earth–Venus trajectories similar to those represented in Fig. 3 are available with launch dates approximately 1.6 years (2.6 Venus years) earlier. Following the procedure in method 1, we can determine the Venus arrival dates that are approximately an integer multiple of Venus years before the required Venus flyby dates for trajectories to Pluto via Jupiter. (Figure 4 is again used for these earlier launch dates.) This procedure indicates that there are type I and II Earth–Venus transfer legs with low C_3 that are five or six Venus years from the best Venus–Jupiter–Pluto legs. Our approach suggests that the most efficient trajectories to Pluto via Jupiter would use these Earth–Venus transfer legs followed by a $2^\pm$ ΔV–VGA and then either a $3^\pm$ or a $4^\pm$ ΔV–VGA. The baseline trajectory described in the introduction uses a 2^+ ΔV–VGA followed by a 4^+ ΔV–VGA. It is similar to a trajectory presented in Ref. 19. The characteristics of a trajectory similar to the baseline with a flight time of 12.0 years are presented in Table 8.

We discovered several other trajectories to Pluto with launch dates in late 2000 and early 2001. As expected, none of these trajectories outperforms the baseline, but several of them do have substantial injection margins. Characteristics of one of these trajectories that is well suited for the Pluto Express mission are presented in Table 9. The Earth–Venus transfer for this trajectory is type III, instead of the more efficient type I or II as used by the baseline.

Table 9 Trajectory XI characteristics: EVVVJP ($2^- \Delta V$–VGA, $4^+ \Delta V$–VGA)

Launch	8/10/2000	$C_3 = 12.2$ km^2/s^2
Perihelion	1/3/2001	0.644 AU (min)
Venus 1	9/3/2001	$V_\infty = 7.16$ km/s
Perihelion	9/14/2001	0.705 AU
Maneuver	4/25/2002	$\Delta V = 392$ m/s, 1.60 AU
Venus 2	11/13/2002	$V_\infty = 9.84$ km/s
Perihelion	11/19/2002	0.716 AU
Maneuver	2/2/2004	$\Delta V = 432$ m/s, 2.99 AU
Perihelion	5/14/2005	0.648 AU
Venus 3	6/2/2005	$V_\infty = 14.5$ km/s, $\Delta V = 2.04$ km/s
Jupiter	6/24/2006	$V_\infty = 18.8$ km/s, flyby radius $= 7.7 R_J$
Pluto	8/8/2012	$V_\infty = 19.9$ km/s
Total deterministic postlaunch $\Delta V = 2.87$ km/s		
Navigation ΔV, $\Delta V_{NAV} = 250$ m/s		
Injection margin, 233 kg		

Asteroid Flybys

Scientific return on missions to the outer solar system can be increased by taking advantage of asteroid flyby opportunities as the spacecraft passes through the asteroid belt. The Galileo spacecraft flew by two asteroids during its VEEGA (Venus–Earth–Earth gravity-assist) trajectory to Jupiter. The first spacecraft encounter with an asteroid occurred on Oct. 29, 1991, when Galileo flew by Gaspra at a relative velocity (V_∞) of 8 km/s near the aphelion of the Earth–Earth leg of the trajectory. After the final Earth flyby, Galileo flew by Ida (with a V_∞ of 12.4 km/s) and provided images with the first direct evidence of a natural satellite of an asteroid. These flybys added much to our knowledge of asteroids, which, in turn, plays an important part in our understanding of the formation and dynamical evolution of our solar system.

To incorporate an asteroid flyby, we first optimize a trajectory to Pluto with planetary flybys and then search for asteroids that pass "close" to this trajectory. Finally, we reoptimize the trajectory including one or more asteroid flybys. The nontargeted asteroid encounters are strictly a matter of chance. We can, however, give some rules of thumb based on our experience and provide some specific examples.

The resonance (or near-resonance for V_∞ leveraging) of a Venus–Venus leg determines the aphelion radius of that portion of the trajectory, since the perihelion radius is generally close to the orbital radius of Venus. An orbit with a resonance of 2 Venus years has an aphelion radius of around 1.6 AU. Fewer than 5% of all known asteroids have perihelion radii below 1.6 AU (Ref. 20), so Venus–Venus legs with two-year resonances have very few opportunities for asteroid encounters. The aphelion radius is near 2.3 AU for an orbit with a resonance of 3 Venus years. About 20% of all asteroids have semimajor axes less than 2.3 AU, and some encounter opportunities usually occur on these 3-Venus-year legs. For an orbit with a resonance of 4 Venus years, the aphelion radius is around 3.0 AU—larger than the semimajor axes of 70% of all asteroids. These orbits generally have several opportunities for asteroid flybys. The encounter V_∞ for asteroid flybys on the Venus–Venus legs have a fairly uniform distribution between 5 and 15 km/s with relatively few occurring outside this range.

The portion of the trajectory following the last Venus flyby passes through the main asteroid belt. The cost in ΔV to add an asteroid encounter on this part of the trajectory, and the V_∞ of the flyby, depend generally on whether there are a total of two or three VGAs. Since the time from launch to final Venus flyby is usually shorter if there are only two Venus flybys, the heliocentric velocity following the final Venus flyby required to reach Pluto with a total flight time of 12 years tends to be less. Hence the cost in ΔV and the flyby V_∞ also tend to be smaller.

The baseline trajectory has many opportunities for asteroid flybys at a relatively low cost in additional deterministic ΔV. For example, a flyby of the asteroid Seraphina (#838, radius 32 km, type P) can be added near the aphelion of the final Venus–Venus leg, increasing the total deterministic ΔV by 0.12 km/s. The relative velocity of the flyby is 7.9 km/s. For an additional cost in total deterministic

Table 10 Potential asteroid flybys on the final Venus–Venus leg of the baseline trajectory

Number	Name	Radius, km	Flyby V_∞, km/s	Increase in total ΔV,[a] km/s	Decrease in injection margin,[a] kg
323	Brucia	20	9.0	0.28	54.5
701	Oriola	23	7.1	0.22	40.3
838	Seraphina	32	7.9	0.12	21.6
1407	Lindelof	12	6.4	0.27	54.0
1907	Rudneva	8	10.8	0.06	10.8
2897	Ole Romer	4	11.4	0.01	2.2
2916	Voronveliya	4	14.5	0.02	2.3
3182	Shimanto	14	6.5	0.07	9.3
5217	1966 CL	3	15.0	0.02	4.3
5432	1988 VN	6	6.7	0.17	31.4
6324	1991 DN1	4	10.7	0.02	2.0

[a]Not including additional ΔV_{NAV}.

Table 11 Potential asteroid flybys following the final Venus flyby of trajectory V

Number	Name	Radius, km	Flyby V_∞, km/s	Increase in total ΔV,[a] km/s	Decrease in injection margin,[a] kg
812	Adele	14	17.0	0.31	67.8
1762	Russell	12	16.1	0.14	24.7
1774	Kulikov	9	16.3	0.10	26.3
2718	Handley	15	18.2	0.27	52.5
2869	Nepryadva	10	20.4	0.42	86.1
3351	Smith	6	14.8	0.35	75.2
5151	Weerstra	8	13.0	0.12	18.9

[a]Not including additional ΔV_{NAV}.

ΔV of 0.02 km/s, we can include a flyby of the asteroid Rudneva (#1907, radius 8 km) at a V_∞ of 11.0 km/s about 200 days before the flyby of Seraphina. Plots of the baseline trajectory with flybys of Rudneva and Seraphina are presented in Ref. 16. Table 10 lists a few asteroids that could be added to the original trajectory. The increase in total ΔV and the flyby V_∞ are for the case in which there is only one asteroid flyby. We constrain the flight time to Pluto to the value without an asteroid and compare the total ΔV for the optimum launch dates only. (The effect on total ΔV may vary over an extended launch period.)

When flybys are added after the final Venus flyby, the increase in total ΔV and asteroid encounter V_∞ both tend to be higher (compared to encounters before the final Venus flyby). For example, for the baseline trajectory, a flyby of the asteroid Thusnelda (#219, radius 22 km, type S) can be added 148 days after the final Venus flyby, increasing the total deterministic ΔV by 0.23 km/s. The relative velocity of the flyby is 25.4 km/s. Or for an additional cost in total deterministic ΔV of 0.24 km/s, we can add a flyby of the asteroid 1983 VM7 (#4692, radius 3 km) at a V_∞ of 22.3 km/s. A flyby of a larger asteroid, Erida (#718, radius 38 km), can be added to the original trajectory with an increase in total deterministic ΔV of 0.32 km/s. For this flyby, the V_∞ is 23.9 km/s.

Trajectory V has a total of two Venus flybys. The Venus–Venus leg is a 2-Venus-year resonant orbit with an aphelion radius of 1.6 AU, providing essentially no opportunities for asteroid encounters. Following the final Venus flyby, however, the trajectory passes through the main asteroid belt, and an asteroid flyby can be included for an increase in total deterministic ΔV of about 0.1 km/s or more. A few potential asteroid flybys are listed in Table 11.

Conclusions

The three methods described in this paper work quite well in discovering trajectories with widely distributed launch windows for the Pluto Express mission. We found many trajectories with positive injection margins using the Delta 7925. The backup trajectory has a launch date in July 2002 (16 months after the baseline), and an excellent launch opportunity exists in August 2000 (seven months before the baseline). We also found opportunities around the time of the baseline; however, according to our study, the baseline trajectory appears to be the most energy-efficient opportunity for launch dates in 2000–2002.

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