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Trajectory options to Pluto via gravity assists from Venus, Mars, and Jupiter

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TRAJECTORY OPTIONS TO PLUTO VIA GRAVITY ASSISTS FROM VENUS, MARS, AND JUPITER

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Abstract

In this paper we use analytic and numeric techniques to assess trajectory options for the Pluto Express sciencecraft to be launched early in the next decade. These techniques have been developed by the authors in previous works and have been shown to be highly efficient and thorough. 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 with no upper stage. In addition, no gravity assists involving the Earth are permitted. Using the aforementioned techniques, we found suitable trajectories with launch windows before, near, and after the date of the baseline launch. We also discovered several asteroid flyby opportunities for the baseline mission and for a backup trajectory.

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 relatively low mass spacecraft (with a dry mass of approximately 100 kg) on a direct trajectory using a Titan IV or Proton launch vehicle and 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, with no upper stage, to place the spacecraft on a trajectory with gravity assists at Venus and Jupiter.[1] The baseline trajectory (for this trajectory type in the study) launches in March 2001 and flies by Venus three times before using a Jupiter gravity assist to reach Pluto in about 12 years. (This trajectory is designated by VVVJGA to indicate 3 Venus gravity assists and 1 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 impact 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:[2]

1. Launch date: October 2001 - December 2002
2. Post-launch deterministic $\Delta V \leq 3500$ m/s
3. C_3 such that propellant and payload can be launched on a Delta 7925 with no upper stage
4. Flight time ≤ 12 years
5. No Earth flybys

The 3500 m/s post-launch ΔV and 12 year flight time are not hard limits but serve as guidelines for examining and comparing trajectories. Although initially

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the flyby radius at Jupiter is not constrained, we use 5 Jupiter radii as a guideline for the minimum flyby radius in order to mitigate the radiation damage to the spacecraft.

We describe the methods we have developed to search for trajectories with the characteristics given above, and we present some trajectories resulting from our search. We apply these same methods to identify early launch opportunities (pre-baseline) in late 2000[3] 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 we use are STOUR[4] (Satellite Tour Design Program) and MIDAS[5] (Mission Design and Analysis Software). Both of these programs were originally developed at JPL.

Numeric Software Tools

STOUR was modified by Williams[6] to provide the capacity of automated design of patched-conic gravity-assist trajectories. (The original version was interactive — not automated.) 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[7] incorporated into STOUR the ability to determine an estimate of local minimum ΔV for powered flybys and broken-plane 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.[8–15] 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 focused on trajectories that use a Jupiter gravity assist. In the time frame we are considering, a Delta 7925 with no upper stage cannot launch the Pluto Express spacecraft directly

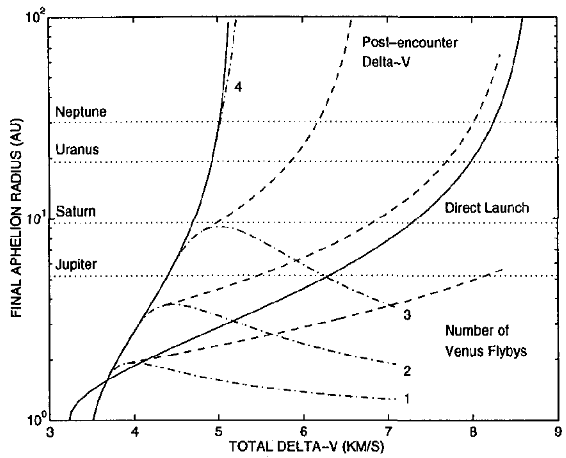

Fig. 1. Venus Gravity Assist Potential. (Multiple Venus Encounters without V_∞ Leveraging.)

to Jupiter (keeping the flyby radius above 5 Jupiter radii) such 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 which 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 Venus gravity assists is shown in Figure 1. For this figure 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. The minimum flyby altitude at Venus is assumed to be 250 km. The time-of-flight problem between Venus gravity assists is not taken into account for the multiple Venus flybys, so these contours represent potential and may not be realizable.

As the Earth launch energy increases, the V_∞ at Venus increases. The solid line in Figure 1 represents the final aphelion radius if the $\mathbf{V}_\infty$ can be turned parallel to the velocity of Venus (with respect to the Sun), $\mathbf{V_V}$. A single gravity assist can turn the $\mathbf{V}_\infty$ a limited amount. This turn angle decreases as the 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 $\mathbf{V}_\infty$ parallel to $\mathbf{V}_\mathbf{V}$, and the single flyby curve in Figure 1 leaves the 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.

The dashed lines in Figure 1 represent the performance that can be achieved with a maneuver immediately after the final Venus gravity assist. The dashed lines originate from the point on each curve beyond which it is more efficient to add ΔV after the final Venus flyby.

The 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 from the figure, a single Venus gravity assist and subsequent ΔV requires more total ΔV than a direct launch to reach the radius of Jupiter, but multiple Venus gravity assists have the potential to outperform a direct launch.

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.[16] The potential of these ΔV-VGA trajectories is shown in Figure 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 is presented in Reference 17.)

The aphelion on the transfer leg of the $2^\pm$ ΔV-VGA is slightly larger than the semi-major 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

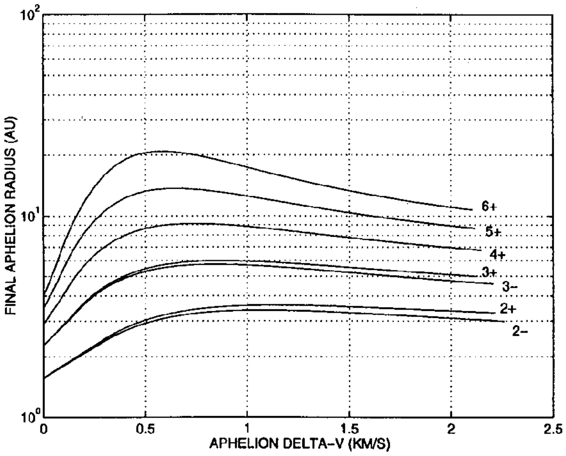

Fig. 2. ΔV-VGA Performance Versus Aphelion ΔV.

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 the Cassini 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 date at Venus for trajectories launched from Earth is shown in Figure 3. (This type of plot is known as a *pork-chop plot.*) The launch date for the STOUR run ranges from October 1, 2001 (designated 11001) to January 1, 2003 (30101) in steps of 5 days. The plotted numbers 0, 2, 3, and 4 correspond to the Earth launch V_∞s 3.0, 3.5, 4.0, and 4.5 km/s, respectively. Type I and II trajectories (transfer angle less than 360°) are clearly distinguished from the Type III and IV trajectories (transfer angle between 360° and 720°) which have longer flight times.

Figure 4 shows the time of flight (TOF) for trajectories from Venus to Pluto which fly by Jupiter. (The type of plot in Figure 4 is a generalized pork-chop plot for trajectories which 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_∞s 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

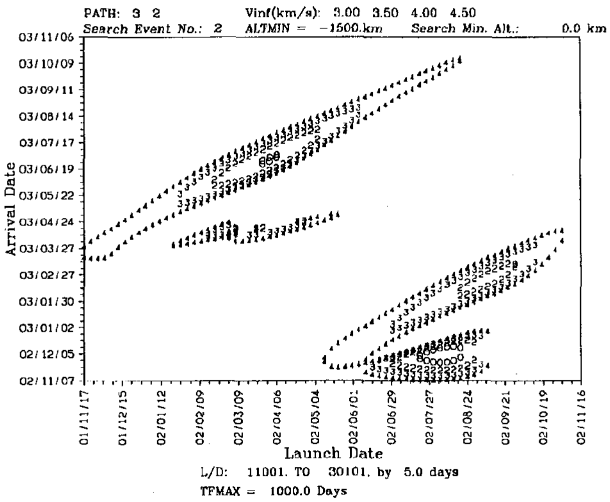

Fig. 3. Earth-Venus Launch Opportunities.

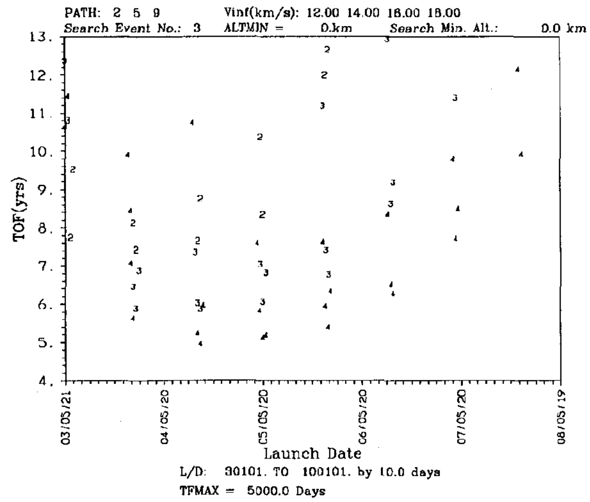

Fig. 4. Venus-Jupiter-Pluto Trajectory Opportunities.

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 which increase the V_∞ at the following Venus flyby. With V_∞ leveraging, the flyby dates at Venus (on the Earth-Venus leg) differ somewhat from 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

We found several trajectories to Pluto by modifying a trajectory with three Venus flybys that we originally developed for the Cassini mission to Saturn. This trajectory was discovered by starting with a complete analytic solution,[17] using STOUR to determine the appropriate launch date, and 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. 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 savings 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 — it is not a V_∞ leveraging maneuver. In our STOUR runs, we place this maneuver after the final Venus flyby. The trajectories from STOUR are then optimized using MIDAS. In the MIDAS runs the total ΔV may be reduced using V_∞ leveraging by adjusting the flyby dates and including a maneuver between Venus flybys.

The following sequences are examined using STOUR:

EVVV(ΔV)JP
EVVV(ΔV)P
EVV(ΔV)JP
EVMVV(ΔV)JP
EVMVV(ΔV)P
EVMV(ΔV)JP
EVVMV(ΔV)JP

A few different trajectories are identified using this approach. Only one of the trajectories identified by Methods 1 and 2 was rediscovered. This appears to be due to the inability of STOUR to do V_∞ leveraging. The one trajectory that was rediscovered has no V_∞ leveraging maneuver.

Results

Trajectories to Pluto

Characteristics of ten of the trajectories, identified by the methods described above, are presented 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 August 23, 2002. (Recall that we are considering the time period from October 2001 to December 2002.)

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, the trajectories in Table 1 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 the table, 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 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 by comparing Trajectory IX to Trajectory VI and Trajectory VIII to Trajectory VII. Trajectory VI uses a maneuver of 254 m/s between the first two Venus encounters to increase the V_∞ from 6.04 km/s to 8.14 km/s and uses a maneuver of 465 m/s before the final Venus flyby to increase the V_∞ to 12.53 km/s. Trajectory IX uses a Mars gravity assist between the first two Venus encounters to increase the V_∞ from 6.73 km/s to 13.42 km/s, resulting in a savings of 350 m/s in total deterministic ΔV. A similar comparison can be made between Trajectories VIII and VII, where the savings in total ΔV is more than 500 m/s.

Injection Margin

An important parameter in mission design is the injection margin — the difference in mass between what 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 trajectories listed in Table 1 are summarized in Table 2 along with their injection margins.[18] In determining the injection margin, we assume a launch vehicle contingency of 10% and an adapter mass which is 5% of the injected mass. We use the rocket equation to determine the propellant mass.

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

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

$$m_i = m_{s/c} + m_p + 0.15 m_p$$

and

$$m_f = m_{s/c} + 0.15 m_p$$

where

m_i is the total injected wet mass (initial mass),
m_f is the total injected dry mass,
$m_{s/c}$ is the mass of the spacecraft (excluding the propellant tanks), and
m_p is the mass of the propellant.

We assume an I_{sp} of 320 s and the total injected dry mass (spacecraft and propellant tanks) to be 235 kg. The total post-launch ΔV, ΔV_{TPL}, is the sum of the deterministic post-launch ΔV, ΔV_{PL}, and the navigation ΔV, ΔV_{NAV}. The navigation ΔV is a rough estimate based on the number of flybys and ranges from 200 m/s to 300 m/s. The injection margin is then the injected mass capability (with a 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 $\Delta V + \Delta V_{PL}$). 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 trade-offs between trajectory design and spacecraft design.

Table 1 Trajectory Characteristics

Trajectory I EVVJP [2^+ΔV-VGA]		
Launch	**4/3/2002**	**$C_3 = 14.77$ km^2/s^2**
Perihelion	8/10/2002	0.696 AU
Perihelion	5/23/2003	0.696 AU
Venus 1	6/15/2003	$V_\infty = 6.21$ km/s
Manuever	1/14/2004	ΔV = 547 m/s, 1.62 AU
Perihelion	9/11/2004	**0.664 AU (min)**
Venus 2	10/2/2004	$V_\infty = 10.21$ km/s, ΔV = 2.953 km/s
Jupiter	2/7/2006	$V_\infty = 13.60$ km/s, **flyby radius = 9.2 R_J**
Pluto	4/3/2014	$V_\infty = 14.83$ km/s
Total deterministic post-launch **ΔV = 3.500 km/s**		

Trajectory II EVVJP [3^+ΔV-VGA]		
Launch	**4/3/2002**	**$C_3 = 13.24$ km^2/s^2**
Maneuver	8/18/2002	ΔV = 708 m/s, 0.63 AU
Perihelion	8/21/2002	**0.627 AU (min)**
Perihelion	6/9/2003	**0.627 AU (min)**
Venus 1	7/12/2003	$V_\infty = 8.90$ km/s, ΔV = 402 m/s
Manuever	5/16/2004	ΔV = 384 m/s, 2.33 AU
Perihelion	5/11/2005	0.657 AU
Venus 2	5/29/2005	$V_\infty = 12.73$ km/s, ΔV = 2.102 km/s
Jupiter	8/4/2006	$V_\infty = 16.31$ km/s, **flyby radius = 12.2 R_J**
Pluto	4/3/2014	$V_\infty = 15.48$ km/s
Total deterministic post-launch **ΔV = 3.595 km/s**		

Trajectory III EVVJP [2^-ΔV-VGA]		
Launch	**5/11/2002**	**$C_3 = 12.92$ km^2/s^2**
Perihelion	9/29/2002	**0.640 AU (min)**
Perihelion	6/30/2003	**0.640 AU (min)**
Venus 1	8/3/2003	$V_\infty = 7.18$ km/s
Manuever	2/16/2004	ΔV = 285 m/s, 1.58 AU
Venus 2	9/17/2004	$V_\infty = 9.19$ km/s, ΔV = 3.328 km/s
Perihelion	9/21/2004	0.717 AU
Jupiter	2/6/2006	$V_\infty = 13.46$ km/s, **flyby radius = 9.4 R_J**
Pluto	5/11/2014	$V_\infty = 14.61$ km/s
Total deterministic post-launch **ΔV = 3.613 km/s**		

Table 1 Trajectory Characteristics (continued)

Trajectory IV EVVJP [3^-ΔV-VGA]		
Launch	**5/13/2002**	**$C_3 = 14.53$ km^2/s^2**
Maneuver	9/29/2002	ΔV = 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, ΔV = 721 m/s
Manuever	7/1/2004	ΔV = 365 m/s, 2.30 AU
Venus 2	5/7/2005	$V_\infty = 12.34$ km/s, ΔV = 2.223 km/s
Perhelion	5/15/2005	0.706 AU
Jupiter	8/1/2006	$V_\infty = 16.11$ km/s, **flyby radius = 12.5 R_J**
Pluto	5/13/2014	$V_\infty = 15.22$ km/s
Total deterministic post-launch **ΔV = 3.452 km/s**		

Trajectory V EVVJP [2:1 Venus-Venus]		
Launch	**7/17/2002**	**$C_3 = 26.63$ km^2/s^2**
Venus 1	11/1/2002	$V_\infty = 10.11$ km/s
Perihelion	11/20/2002	**0.682 AU (min)**
Venus 2	1/25/2004	$V_\infty = 10.11$ km/s, ΔV = 2.534 km/s
Perhelion	1/29/2004	0.719 AU
Jupiter	8/16/2005	$V_\infty = 11.26$ km/s, **flyby radius = 6.9 R_J**
Pluto	7/17/2014	$V_\infty = 13.79$ km/s
Total deterministic post-launch **ΔV = 2.534 km/s**		

Trajectory VI EVVVJP [2^+ΔV-VGA, 3^-ΔV-VGA]		
Launch	**7/20/2002**	**$C_3 = 12.74$ km^2/s^2**
Venus 1	12/9/2002	$V_\infty = 6.04$ km/s
Perihelion	12/9/2002	0.719 AU
Maneuver	7/27/2003	ΔV = 254 m/s, 1.60 AU
Perihelion	3/6/2004	**0.691 AU (min)**
Venus 2	3/21/2004	$V_\infty = 8.14$ km/s
Perhelion	3/22/2004	0.718 AU
Manuever	2/3/2005	ΔV = 465 m/s, 2.30 AU
Venus 3	12/31/2005	$V_\infty = 12.53$ km/s, ΔV = 3.062 km/s
Jupiter	2/1/2007	$V_\infty = 19.14$ km/s, **flyby radius = 19.1 R_J**
Pluto	7/20/2014	$V_\infty = 15.64$ km/s
Total deterministic post-launch **ΔV = 3.781 km/s**		

Table 1 Trajectory Characteristics (continued)

Trajectory VII EVVVJP [2^-ΔV-VGA, 2:1 Venus-Venus]

Launch	**7/29/2002**	**$C_3 = 14.34$ km²/s²**
Venus 1	12/14/2002	$V_\infty = 6.25$ km/s
Perihelion	12/19/2002	0.716 AU
Maneuver	8/10/2003	$\Delta V = 529$ m/s, 1.59 AU
Venus 2	2/15/2004	$V_\infty = 10.04$ km/s
Perihelion	3/7/2004	**0.664 AU (min)**
Venus 3	5/10/2005	$V_\infty = 10.04$ km/s, $\Delta V = 3.511$ km/s
Perhelion	5/16/2005	0.711 AU
Jupiter	8/6/2006	$V_\infty = 15.91$ km/s, **flyby radius = 13.1 R_J**
Pluto	7/29/2014	$V_\infty = 14.79$ km/s

Total deterministic post-launch **ΔV = 4.040 km/s**

Trajectory VIII EVMVVJP [2^-M-VGA, 2:1 Venus-Venus]

Launch	**8/9/2002**	**$C_3 = 18.21$ km²/s²**
Venus 1	12/20/2002	$V_\infty = 6.62$ km/s
Perihelion	12/25/2002	0.716 AU
Mars	5/11/2003	$V_\infty = 10.78$ km/s
Venus 2	2/11/2004	$V_\infty = 11.47$ km/s
Perihelion	3/5/2004	**0.641 AU (min)**
Venus 3	5/5/2005	$V_\infty = 11.47$ km/s, $\Delta V = 3.336$ km/s
Perhelion	5/14/2005	0.699 AU
Jupiter	8/5/2006	$V_\infty = 15.85$ km/s, **flyby radius = 13.1 R_J**
Pluto	8/9/2014	$V_\infty = 14.72$ km/s

Total deterministic post-launch **ΔV = 3.336 km/s**

Table 1 Trajectory Characteristics (continued)

Trajectory IX EVMVVJP [2^+M-VGA, 2.75 Venus-Venus]

Launch	**8/14/2002**	**$C_3 = 20.24$ km²/s²**
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	$V_\infty = 12.22$ km/s
Perihelion	3/24/2004	**0.604 AU (min)**
Venus 2	4/19/2004	$V_\infty = 13.42$ km/s
Venus 3	12/28/2005	$V_\infty = 13.42$ km/s, $\Delta V = 2.945$ km/s
Jupiter	2/1/2007	$V_\infty = 19.06$ km/s, **flyby radius = 19.2 R_J**
Pluto	8/11/2014	$V_\infty = 15.50$ km/s

Total deterministic post-launch **ΔV = 3.108 km/s**

Trajectory X EVVVJP [1:1 Venus-Venus, 2:1 Venus-Venus]

Launch	**8/23/2002**	**$C_3 = 16.87$ km²/s²**
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, $\Delta V = 3.159$ km/s
Perihelion	9/22/2004	0.718 AU
Jupiter	2/13/2006	$V_\infty = 13.22$ km/s, **flyby radius = 10.0 R_J**
Pluto	8/24/2014	$V_\infty = 14.07$ km/s

Total deterministic post-launch **ΔV = 3.159 km/s**

Flight Time Analysis

During our initial search, we looked for trajectories that could have 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. (See Table 3.) 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 kg to 51.2 kg as the flight time to Pluto decreases from 12.0 years to 11.0 years. In general, as the flight time decreases, the ΔV immediately following the final Venus flyby increases while the Jupiter flyby radius decreases. The initial legs of the trajectories remain approximately the same.

Launch Window Analysis

We also briefly examined the launch window for Trajectory V, which has been selected as a backup.[1] Some characteristics of the trajectory for a 23-day range of launch dates and a fixed arrival date are given in Table 4. The impact on the injection margin in this case appears to be relatively small, allowing for ample launch opportunities during the given window.

Table 2 Trajectories to Pluto Using the Delta 7925 (Flight Time: 12 years)

Trajectory Number	Trajectory Type	Launch Date	C_3 (km^2/s^2)	ΔV_{PL} (km/s)	ΔV_{NAV} (m/s)	Injection Margin (kg)
I	VVJ	4/3/2002	14.8	3.500	200	52.0
II	VVJ	4/3/2002	13.2	3.595	200	54.4
III	VVJ	5/11/2002	12.9	3.613	200	55.5
IV	VVJ	5/13/2002	14.5	3.452	200	68.4
V	VVJ	7/17/2002	26.6	2.534	200	80.7
VI	VVVJ	7/20/2002	12.7	3.781	250	-1.1
VII	VVVJ	7/29/2002	14.3	4.040	250	-106.0
VIII	VMVVJ	8/9/2002	18.2	3.336	300	10.2
IX	VMVVJ	8/14/2002	20.2	3.108	300	33.0
X	VVVJ	8/23/2002	16.9	3.159	250	87.0

Earlier Launch Dates

Having found trajectories satisfying our initial constraints, we extended 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 Figure 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 5 or 6 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^+ ΔV-VGA and then either a 3^+ or 4^+ 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 Reference 19. The characteristics of a trajectory similar to the baseline with a flight time of 12.0 years are presented in Table 5.

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 6. The Earth-Venus transfer for this trajectory is Type III, instead of the more efficient Type I or II as used by the baseline.

Asteroid Flybys

NASA has a policy that missions to the outer solar system will include flybys of main-belt asteroids.[20] Galileo flew by two asteroids during its VEEGA (Venus-Earth-Earth Gravity-Assist) trajectory to Jupiter. The first spacecraft encounter with an asteroid occurred on October 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. These 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. Less than 5% of all known asteroids have a perihelion radius below 1.6 AU,[21] so Venus-Venus legs with 2 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

Table 3 Examination of Flight Time to Pluto

Traj. No.	Launch Date	TOF (yrs)	C_3 (km^2/s^2)	ΔV_{PL} (km/s)	Rad.[a] (R_J)
I	4/3/02	12.0	14.77	3.50	9.2
	4/3/02	11.0	14.59	3.82	7.1
	4/5/02	10.0	14.32	4.32	5.1
II	4/3/02	12.0	13.24	3.60	12.2
	4/5/02	11.0	13.26	4.02	9.5
	4/6/02	10.0	13.30	4.68	6.9
III	5/11/02	12.0	12.92	3.61	9.4
	5/12/02	11.0	13.06	3.88	7.3
	5/13/02	10.0	13.26	4.31	5.3
IV	5/13/02	12.0	14.53	3.45	12.5
	5/14/02	11.0	14.59	3.85	9.7
	5/15/02	10.0	14.69	4.48	7.1
V	7/17/02	12.0	26.63	2.53	6.9
	7/19/02	11.0	26.16	2.73	5.3
	7/20/02	10.0	25.99	3.04	3.8
	7/19/02	10.0	25.81	4.03	5.0
IX	8/14/02	12.0	20.24	3.11	19.2
	8/14/02	11.0	20.38	3.61	15.0
	8/14/02	10.0	20.49	4.43	11.0

[a] Flyby radius at Jupiter.

Table 4 Launch Window for Trajectory V

Launch Date[a]	C_3 (km^2/s^2)	ΔV_{PL} (km/s)	Total ΔV (km/s)
7/7/2002	25.18	2.82	7.13
7/9/2002	25.49	2.74	7.06
7/11/2002	25.41	2.68	7.00
7/13/2002	26.06	2.61	6.95
7/15/2002	25.75	2.58	6.91
7/17/2002	26.78	2.53	6.91
7/19/2002	26.70	2.52	6.89
7/21/2002	27.14	2.56	6.94
7/23/2002	27.16	2.57	6.96
7/25/2002	25.52	2.69	7.01
7/27/2002	24.65	2.77	7.06
7/29/2002	23.89	2.86	7.11

[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 5 Baseline Trajectory Characteristics

Baseline $[2^+\Delta V\text{-VGA}, 4^+\Delta V\text{-VGA}]$	**EVVVJP**	
Launch	**3/9/2001**	$\mathbf{C_3 = 15.89}$ $\mathbf{km^2/s^2}$
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	$V_\infty = 14.43$ km/s, $\Delta V = 1.674$ km/s
Jupiter	7/11/2006	$V_\infty = 17.75$ km/s, **flyby radius = 9.3** $\mathbf{R_J}$
Pluto	3/10/2013	$V_\infty = 18.13$ km/s
Total deterministic post-launch $\mathbf{\Delta V = 2.253}$ **km/s**		
Navigation ΔV		$\Delta V_{NAV} = 250$ m/s
Injection Margin		**284 kg**

Table 6 Trajectory XI Characteristics

Trajectory XI $[2^-\Delta V\text{-VGA}, 4^+\Delta V\text{-VGA}]$	**EVVVJP**	
Launch	**8/10/2000**	$\mathbf{C_3 = 12.24}$ $\mathbf{km^2/s^2}$
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	$V_\infty = 14.52$ km/s, $\Delta V = 2.044$ km/s
Jupiter	6/24/2006	$V_\infty = 18.82$ km/s, **flyby radius = 7.7** $\mathbf{R_J}$
Pluto	8/8/2012	$V_\infty = 19.93$ km/s
Total deterministic post-launch $\mathbf{\Delta V = 2.868}$ **km/s**		
Navigation ΔV		$\Delta V_{NAV} = 250$ m/s
Injection Margin		**233 kg**

Table 7 Potential Asteroid Flybys on the Final Venus-Venus Leg of the Baseline Trajectory

No.	Name	Radius (km)	Increase in Total ΔV^a (km/s)	Flyby V_∞ (km/s)
323	Brucia	20	0.28	9.0
701	Oriola	23	0.22	7.1
838	Seraphina	32	0.12	7.9
1407	Lindelof	12	0.27	6.4
1907	Rudneva	8	0.06	10.8
2897	Ole Romer	4	0.01	11.4
2916	Voronveliya	4	0.02	14.5
3182	Shimanto	14	0.07	6.5
5217	1966 CL	3	0.02	15.0
5432	1988 VN	6	0.17	6.7
6324	1991 DN1	4	0.02	10.7

[a] Not including additional ΔV_{NAV}.

Table 8 Potential Asteroid Flybys Following the Final Venus Flyby of Trajectory V

No.	Name	Radius (km)	Increase in Total ΔV^a (km/s)	Flyby V_∞ (km/s)
812	Adele	14	0.31	17.0
1762	Russell	12	0.14	16.1
1774	Kulikov	9	0.10	16.3
2718	Handley	15	0.27	18.2
2869	Nepryadva	10	0.42	20.4
3351	Smith	6	0.35	14.8
5151	Weerstra	8	0.12	13.0

[a] Not including additional ΔV_{NAV}.

20% of all asteroids have a semi-major axis 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 semi-major axis of 70% of all asteroids. These orbits generally have several opportunities for asteroid flybys. The encounter V_∞s for asteroid flybys on the Venus-Venus legs have a fairly uniform distribution between 5 km/s 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, depends generally on whether there are a total of two or three Venus gravity assists. 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 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. Table 7 lists a few asteroids that could be added to the original trajectory. The increase in total ΔV and the flyby V_∞ listed in the table are for the case in which there is only one asteroid flyby.

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, 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 8.

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 (sixteen 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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