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A URANUS–NEPTUNE–PLUTO OPPORTUNITY†

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Abstract—Recently, NASA has announced a change of philosophy toward smaller, faster spacecraft. A notable example of the new philosophy are plans for a Pluto fast flyby mission, involving a 150 kg spacecraft which can reach Pluto in about 7 years. In this paper, automated software is used to investigate multiple-encounter missions to the outer planets which can also be flown by the Pluto fast flyby spacecraft. A particularly important result of this analysis is the discovery of a three-planet opportunity with Uranus, Neptune and Pluto.

1. INTRODUCTION

Pluto is the only known planet in the solar system that has not been explored by spacecraft. Lately, missions to Pluto have attracted great interest because its atmosphere is expected to freeze before 2020 and is not expected to reappear until after 2237. This is due to the fact that Pluto recently passed through perihelion. Additional characteristics of scientific value that motivate missions to Pluto include water ice discovered on Pluto's moon (Charon), carbon dioxide and nitrogen ices on Pluto, transfer of gases between Pluto and Charon and comet impacts. Because of Charon's large size relative to Pluto, astronomers have classified them as the only example of a double planet.

Following the philosophy of "faster, better, cheaper," the Jet Propulsion Laboratory has proposed a Pluto fast flyby mission that would launch two identical small spacecraft (≈ 150 kg) to Pluto before 2000. Using small spacecraft enables missions to be designed with high launch V_∞s (≈ 17 km/s), which opens a new realm of gravity-assist trajectories.

Currently the baseline mission to Pluto is a ballistic (direct) trajectory. Figure 1 shows a launch V_∞ contour plot for ballistic Earth–Pluto trajectories. Table 1 is the legend for the time of flight/launch date plots. Since Pluto's position does not change much relative to the Sun over several years, this contour plot remains valid for many years before and after 2001 (i.e. it repeats every 12 months). Using high launch energies eliminates the need to use the inner planets for gravity assist and allows for a rapid trajectory to Pluto (7–12 years).

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Advanced software developed by Patel[1] allows automated searches for multiple-encounter ΔV gravity-assist trajectories. This automated search algorithm (based on an earlier version developed by Williams[2]) solves the restricted n-body problem using the "patched-conic" theory described by Battin [3]. Breakwell and Perko[4] demonstrate that for interplanetary trajectories the patched-conic theory is reasonably accurate. Williams and Longuski[5–8] and Patel and Longuski[9] demonstrate that this algorithm cannot only identify known trajectories, but can be used to discover new trajectories much more efficiently.

2. OUTER PLANET TOURS

Previous authors[10] have explored various trajectories to Pluto, but limited their analysis to low launch energies. This paper explores alternative trajectory options to Pluto using high energy gravity-assist trajectories which could be used as alternative or complementary missions to the Pluto fast flyby mission[11].

In the early 1980s Wallace *et al.*[10] discovered missions to the far outer planets that used Jupiter for a gravity assist. They demonstrated that, due to the slow motion of Jupiter with respect to the outer planets, there are about 4 launch years for every 12 year period of Jupiter in which a Jupiter gravity assist can be employed. A particularly interesting trajectory is the four-planet grand tour, Jupiter–Uranus–Neptune–Pluto (E5789). Longuski and Williams[5] demonstrated that the last four-planet grand tour opportunity occurs in 1996. Both of these studies assumed larger spacecraft would be launched and therefore assumed low launch energies. Williams[12] later discovered that by increasing the launch energy, the launch window could be extended to 1997 and 1998. Following the current philosophy of smaller,

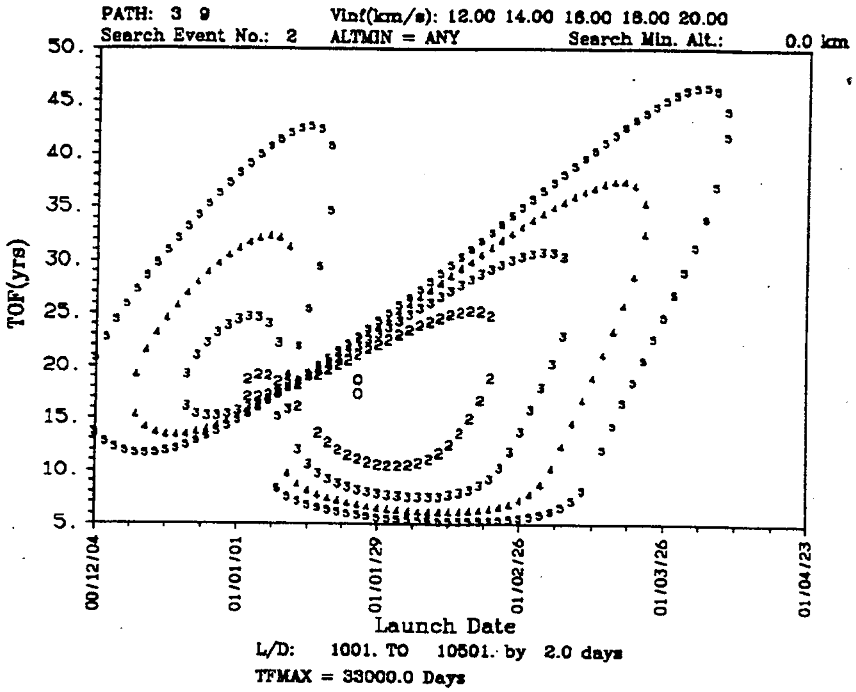

Fig. 1. Earth–Pluto pork-chop plot.

Table 1. Legend for time of flight/launch date plots

PATH	The sequence numbers refer to the planetary path of the trajectory, e.g. PATH: 3 9 implies Earth–Pluto. (See Fig. 1.)
Vinf	The sequence numbers are the V_∞s of launch. The values of V_∞s in the plot itself are designated by 0, 2, 3, ... (0 was used in lieu of 1 because it is more easily distinguished). For example, the numeral 3 on the plot refers to a V_∞ of 16.0 km/s.
ALTMIN	This value refers to the minimum flyby altitude allowed in the original file.
L/D	Launch date range in calendar dates where 1001 refers to 1 October, 2000. Also the increment of the launch date is shown by "BY 2 DAYS."
TFMAX	This value represents the maximum allowable time of flight.
Search Event No.	Event displayed in the path sequence, e.g. if Search Event No. = 2, then the time of flight-L/D plot refers to Pluto arrival (for the path 3 9).
Search Min. Alt.	This value refers to the filtering value of minimum altitude. For example, if the original file was created with ALTMIN = −5000 km, then Search Min. Alt. = 0.0 km would filter out the trajectories with flyby altitudes below 0.0 km. (See Fig. 2.)

faster spacecraft, larger launch energies could be used to extend the grand tour mission.

2.1. Four-planet grand tour opportunity

In order to find additional grand tour missions to Pluto, a search between the launch years 1992 and 2005 is conducted with launch V_∞ ranging from 12 to 22 km/s. Figure 2 shows the 1996 opportunity (where $V_\infty \doteq 14$ km/s) that corresponds to Longuski and Williams' last grand tour. Also additional opportunities exist in 1997, 1998, 1999 and 2000 which confirms Williams' result that increased launch energy extends the launch window. Increasing the launch energy extends the four-planet grand tour to Pluto, but due to the planetary positions, flyby altitudes at Jupiter are low. Jupiter emits intense radiation and high energy particles that can easily damage unshielded spacecraft, so close flybys (as low as several Jovian radii) should be avoided. The trajectories with launch dates during the early part of 1996 have very high flyby altitudes which indicate only minimal gains from a Jovian gravity assist. This can be seen from the plots of the conic trajectories (Figs 3 and 4). The Jupiter–Uranus leg of the 1995 launch is posigrade (Fig. 3), while for the 1997 launch the Jupiter–Uranus leg is slightly retrograde (Fig. 4). During the 1996 opportunity, the Jupiter flyby has little effect on the trajectory, implying that an E789 trajectory might be equivalent. A refined search of the 1996 launch space for both the E5789 and E789 sequences demonstrates that these two families are very similar and Jupiter merely perturbs the E5789 trajectory. After 1996, the Jupiter flyby must provide sufficient bending to make the trajectory retrograde. Since the high energy trajectories necessarily require spacecraft with low mass, it is not desirable to

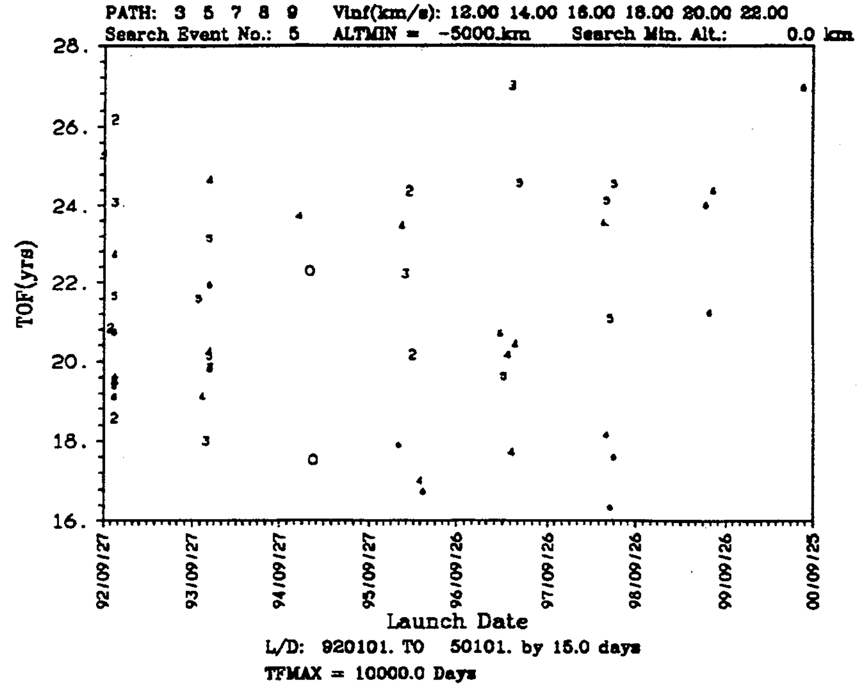

Fig. 2. Jupiter–Uranus–Neptune–Pluto (1992–2005).

increase the mass by adding shielding. Therefore, a conservative constraint of 10 Jovian radii (flyby altitude or $h_p \geqslant 10R_J$) for the Jupiter flyby altitude eliminates trajectories after 1996. If a less conservative constraint on the flyby distance at Jupiter ($5 < h_p < 8R_J$) is allowed, then launches during 1997 are possible (Fig. 5).

Even though these trajectories do not reach Pluto before 2010 (the proposed latest date for scientific investigation of Pluto's atmosphere), serious consideration should be made to fly these grand tour trajectories. The planetary alignment that allows this grand tour trajectory will not repeat again for several centuries since the synodic periods of Uranus–Neptune and Neptune–Pluto are 172 and 491 years, respectively. The weak link in this trajectory path is the Jupiter–Uranus leg that becomes retrograde after the 1996 opportunity causing the flight time to become too long. A search for trajectories[1] with the path E57 (Earth launch–Jupiter–Uranus) demonstrates that the fast family (3 years < TOF < 10 years) of E57 trajectories starts to break down after 1996, but

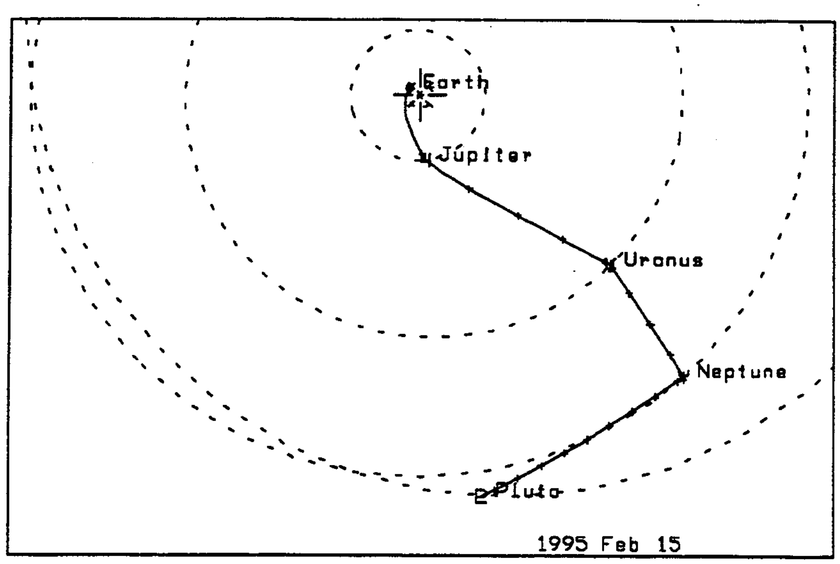

Fig. 3. 1995 Jupiter–Uranus–Neptune–Pluto trajectory.

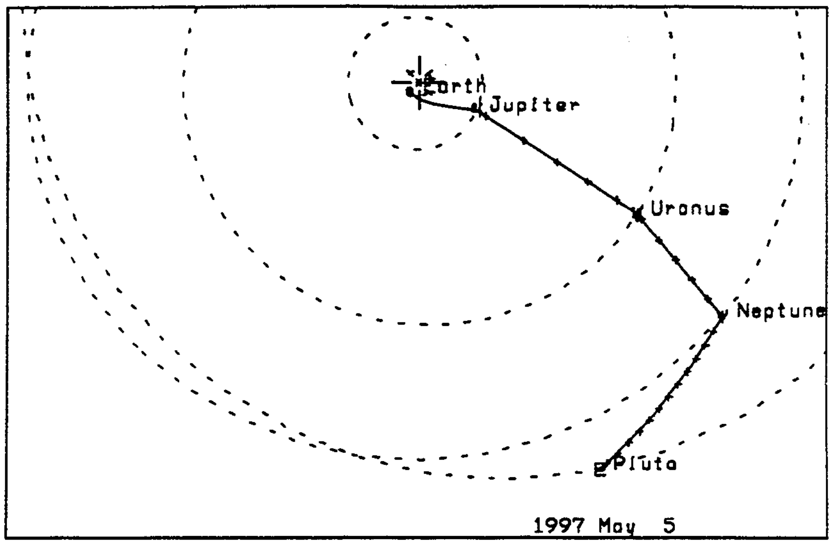

Fig. 4. 1997 Jupiter–Uranus–Neptune–Pluto trajectory.

reappears in 2005. By this time the outer planet legs of the E5789 path have broken down due to the planetary positions.

2.2. Three-planet tour opportunity

Since the four-planet grand tour of E5789 fails after 1996 due to the misalignment of Jupiter and Uranus, Jupiter is eliminated from the path in order to study a three-planet tour, E789. Figure 6 shows the initial search between the launch dates 1985 and 2015. A large range of launch dates is chosen to determine which launch dates correspond to the switch between the posigrade and retrograde Uranus–Neptune leg. Flyby altitudes at Uranus [1] are very high for launch dates in 1990 which indicates that Uranus does not provide much gravity assist during this launch window. (This is similar to the trend discussed for the E5789 trajectories.) Figure 7 shows the patched-conic trajectory for the 2000 launch date while Table 2 shows the launch, flyby and arrival conditions for this trajectory. Figure 8 is a refined search for E789 trajectories with a 2000 launch date and shows that

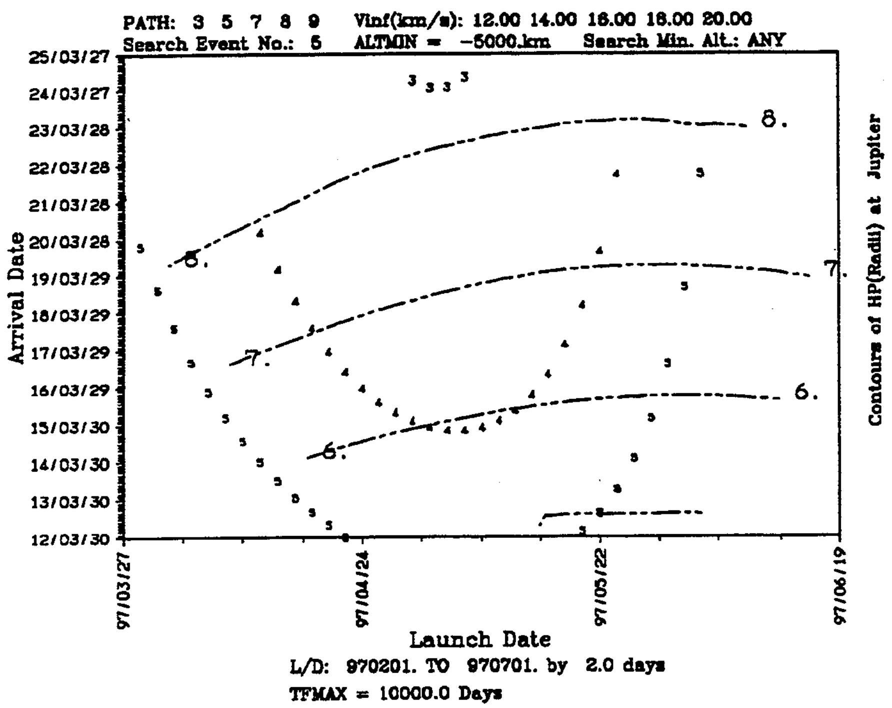

Fig. 5. 1997 Jupiter–Uranus–Neptune–Pluto.

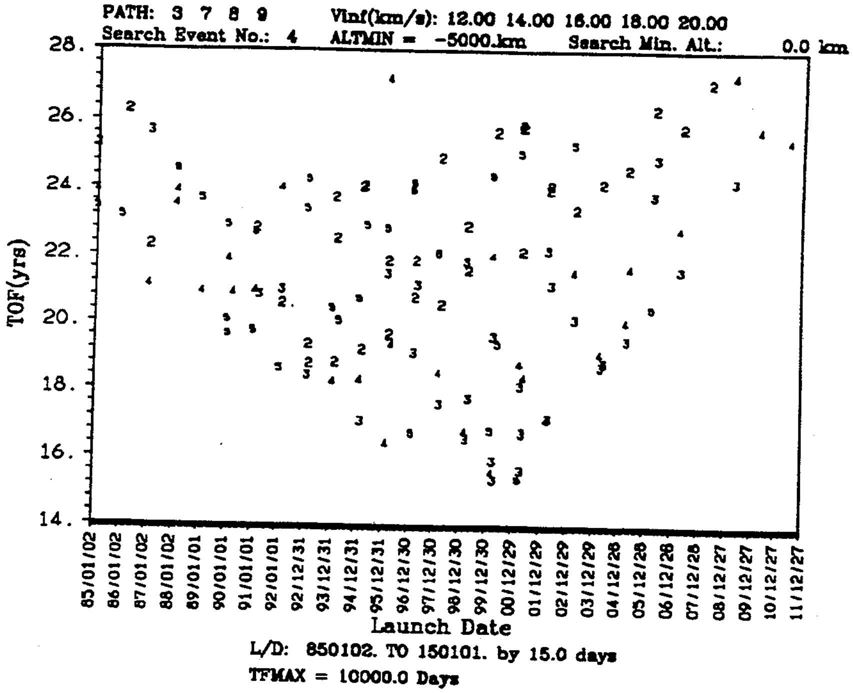

Fig. 6. Uranus–Neptune–Pluto (1985–2015).

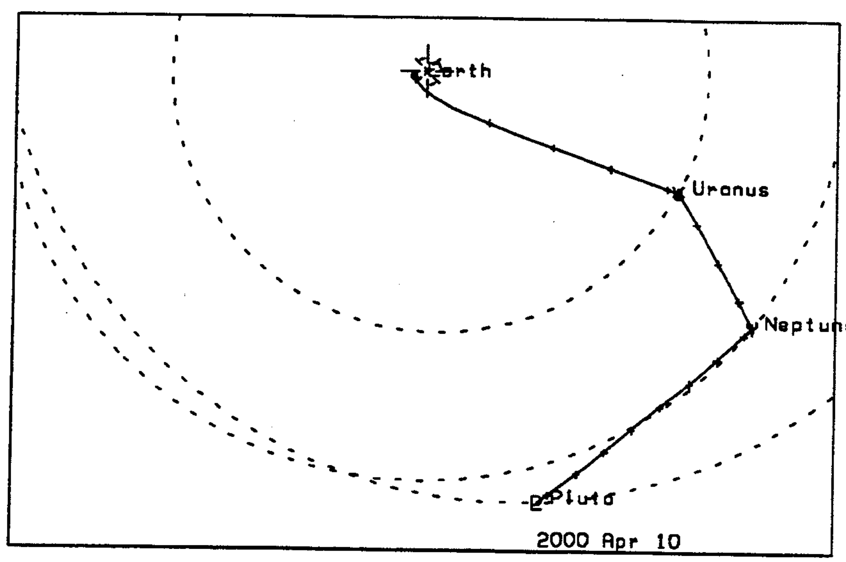

Fig. 7. 2000 Uranus–Neptune–Pluto trajectory.

Table 2. 2000 Uranus–Neptune–Pluto

Earth launch	
Date	April 10, 2000
V_∞	16.0 km/s
Uranus flyby	
Date	June 14, 2004
Altitude	4182 km (0.16 R_U)
Neptune flyby	
Date	December 16, 2007
Altitude	614 km (0.03 R_N)
Pluto arrival	
Date	August 8, 2015
V_∞	17.1 km/s
Total TOF	15.33 yrs

the shortest flight time to Pluto is approx. 15 years. The flyby altitudes at Neptune are shown as contour lines plotted over the launch date/arrival date plot. Notice that the flyby distance at Neptune has a direct relationship with the arrival date at Pluto. For example, if a fixed flyby altitude at Neptune of $1 R_N$ is chosen, then all trajectories (regardless of the launch energy) will arrive at Pluto in June 2019. Even though these trajectories do not meet the requirements for a Pluto flyby before 2010, they include other scientific targets of opportunity (Uranus and Neptune) and could, in addition, provide a follow-on

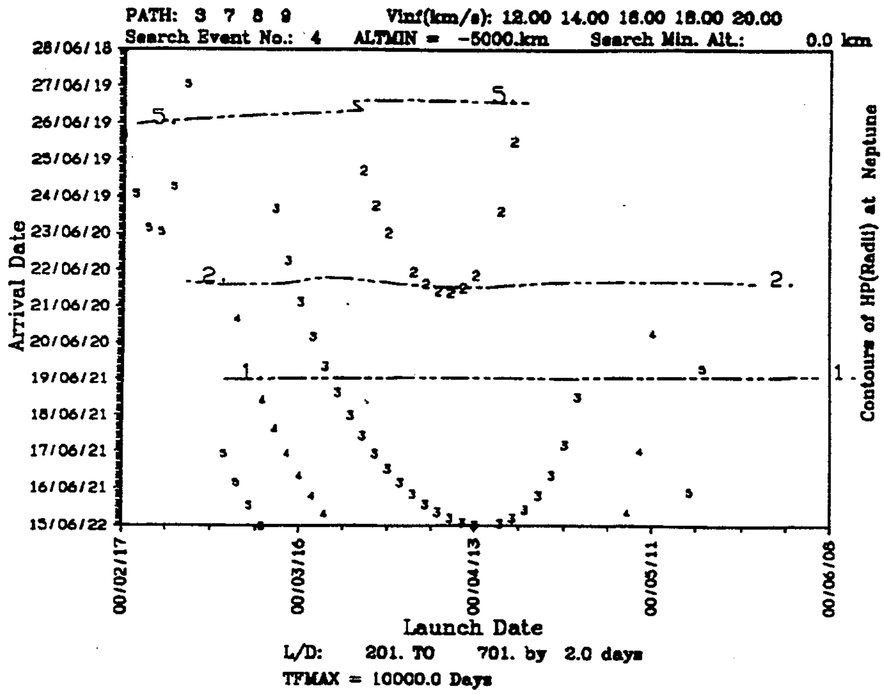

Fig. 8. 2000 Uranus–Neptune–Pluto.

mission to the Pluto fast flyby mission. If launches before 1997 are desired, then the E5789 should be considered because it allows for lower launch energies with faster flight times.

If Pluto is no longer the final destination, then trajectories with the path E78 allow for flight times of less than 8 years. Figure 9 shows the initial search for all E78 trajectories with launch dates between 1985 and 2015. The shortest flight times for these trajectories (approx. 5 years) occur between 1987 and 1996. The shortest flight times after 1996 gradually increase to about 12 years in 2011, after which the

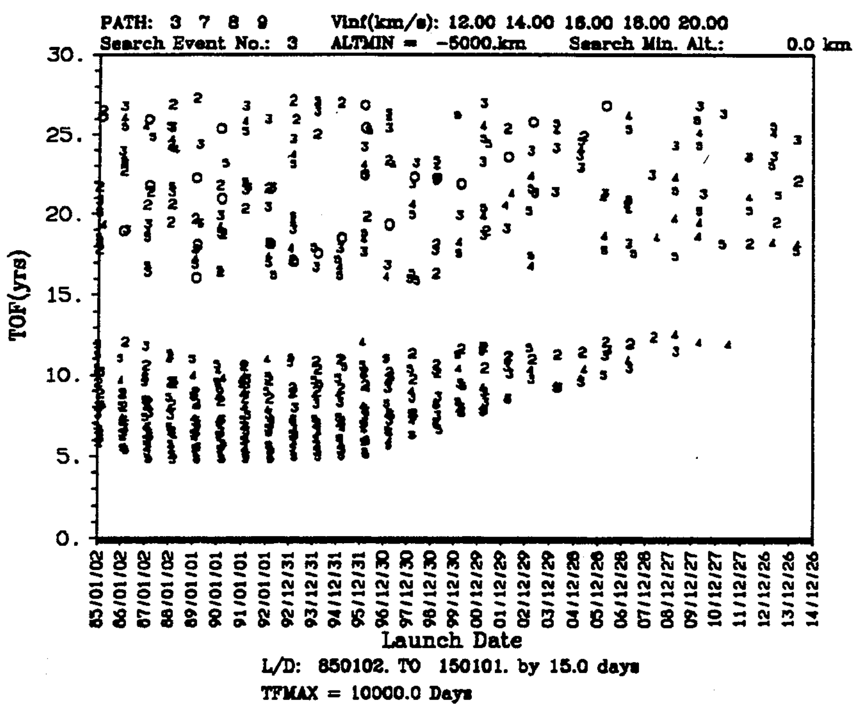

Fig. 9. Uranus–Neptune (1985–2015).

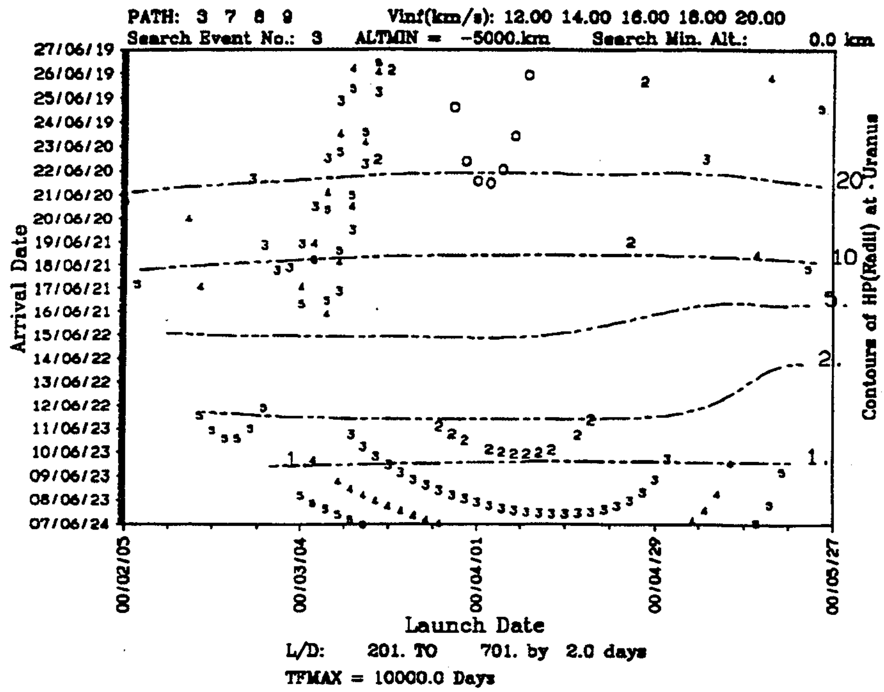

Fig. 10. 2000 Uranus–Neptune.

E78 trajectories with short flight times (5 < TOF < 12 years) cease to exist for nearly 170 years (the synodic period of Uranus and Neptune).

For practical reasons a more reasonable launch date would be 2000 (near the Pluto fast flyby launch date). Figure 10 shows a refined search for E78 trajectories during the 2000 launch window. The contours of the Uranus flyby distances again demonstrate the relationship between flyby altitudes and arrival dates. For example, a fixed flyby altitude of $1 R_U$ sets the arrival date at Neptune (January 2010). If the E78 trajectories are to be considered for possible missions, then a Pluto flyby could also be added at minimal cost. Such trajectories could provide ideal complementary missions to the Pluto fast flyby mission. Also of interest is that the planetary alignment which enables a path of E789 does not repeat again until approx. 2500 (a time delay which is a little greater than the synodic period of Neptune and Pluto).

3. OPTIMIZED THREE-PLANET TRAJECTORIES

Because of the great potential of the E789 trajectories, a multiconic analysis was performed in order to verify these trajectories and to optimize them with respect to launch energy and flight time. A JPL program called PLATO (planetary trajectory optimization) was used for this purpose[13]. The program minimizes total impulsive ΔV for multiple-flyby trajectories with constraints on flyby parameters and maneuver times and uses multiconic techniques for trajectory propagation[14]. Table 3 shows the

Table 3. Optimized Earth–Uranus–Neptune–Pluto trajectories

	Traj. #1	Traj. #2	Traj. #3	Traj. #4	Traj. #5	Traj. #6
Earth launch						
Date	3/31/96	3/25/96	4/13/00	4/13/00	4/18/01	4/27/04
V_∞ (km/s)	16.72	14.67	15.76	15.86	15.76	15.02
C_3 (km^2/s^2)	280	215	248	252	248	226
Uranus flyby						
Date	2/2000	11/2000	7/2004	6/2004	7/2005	12/2008
Flyby Radius	1.73	2.78	1.22	1.18	1.10	1.10
Total TOF (yrs)	3.85	4.67	4.24	4.20	4.25	4.60
Neptune flyby						
Date	10/2002	6/2004	2/2008	1/2008†	4/2009	9/2013
Flyby Radius	—	1.13	1.10	1.10	1.21	2.24
Total TOF (yrs)	6.54	8.25	7.83	7.74	7.99	9.38
Pluto arrival						
Date	—	2/2013	12/2015	6/2015	4/2017	5/2023
Total TOF (yrs)	—	16.91	15.67	15.21	15.98	19.08

†This trajectory has a post-Neptune maneuver of 822 m/s on 2/2008.

results from this analysis where trajectories 1–6 are given in chronological order of launch date. The minimum flight time for a trajectory corresponding to a particular launch period is constrained by the flyby altitude at either Uranus or Neptune. The flyby radii were constrained to be $\geqslant 1.10$ planetary radii according to guidelines suggested by Weinstein[15]. In general, the launch energies are lower and the flyby altitudes are higher for longer flight times. Trajectories 3–6 in Table 3 minimize the flight time subject to the flyby altitude constraints. Lower launch energies could be achieved for these trajectories at a cost of longer flight times.

As explained previously, the shortest flight times for E78 trajectories are relatively constant until 1996, after which the shortest flight times gradually increase. Trajectory 1 has the shortest flight time to Neptune (6.54 years) for E78 trajectories with launch dates in 1996 constrained by launch energy, $C_3 < 280\ \mathrm{km^2/s^2}$ (or $V_\infty < 16.73$ km/s)[15]. (A higher launch energy could be used to decrease the flight time.) This trajectory does not make it to Pluto. Trajectory 2 has a launch date in 1996 also, but it includes Pluto. The flight time to Neptune is higher than in trajectory 1, but the launch energy is lower. The flight times can be decreased until the flyby radius at Neptune becomes 1.10 R_N (a lower bound according to the guidelines) with a corresponding increase in launch energy.

Trajectories 3–5 have launch dates corresponding to the shortest flight times to Pluto from Fig. 6. Trajectories 3 and 5 are similar but reveal an interesting fact that ties together and helps to explain the characteristics of several previous figures. For launch dates up to and including 2000, the flyby radius at Neptune is the limiting factor in reducing the flight times. Beginning in 2001, the flyby radius at Uranus is the limiting factor. So for launch dates in 2000 and 2001, Uranus and Neptune are being used to their fullest potential as gravity-assist bodies.

To see what effect post-launch maneuvers would have on the flight time, the flight time of trajectory 3 was decreased while keeping the flyby altitude constraints fixed. Trajectory 4 shows that the flight time to Pluto can be decreased by about 6 months with a slightly higher launch energy and a substantial ΔV (822 m/s) after the Neptune flyby.

Trajectory 6 shows what happens to the trajectories for later launch dates (2004 in this case). The minimum flight time to Pluto has increased to 19 years, which is consistent with the trend shown in Fig. 6.

4. CONCLUSION

A re-examination of outer planet mission opportunities with automated software has revealed a new three-planet tour involving Uranus, Neptune and Pluto. This opportunity is consistent with the goals of the Pluto fast flyby mission and has the great advantages of providing second looks at Uranus and Neptune (in less than 8 years) and possibly a second look at Pluto (assuming the Pluto fast flyby mission had previously been flown).

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