The Journal of the Astronautical Sciences, Vol. 39, No. 3, July-September 1991, pp. 359–365

TECHNICAL NOTE

The Last Grand Tour Opportunity to Pluto

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Abstract

An automated mission design program permits a thorough examination of gravity-assist trajectories such as the Voyager II flight to Jupiter, Saturn, Uranus and Neptune. The program is applied to the automated design of multiple encounter trajectories to the far outer planets. The most significant result is that the last four-planet grand tour opportunity occurs in 1996 and includes encounters with Jupiter, Uranus, Neptune and Pluto. Other mission designs include Jupiter and one or two other planets and have characteristically short flight times.

Introduction

A new *automated* mission design tool [1, 2] has been developed from preexisting *interactive* software [3] used at JPL (the Jet Propulsion Laboratory). The new program removes the tedium of human interaction and permits the search for all trajectories involving gravity-assist bodies to be performed automatically. By specifying a range of launch dates and launch energies and a sequence of target planets, the mission designer can examine all the trajectory families available. The program approximates trajectories as conic sections by solving the Lambert problem for each leg of the trajectory. The energy of arrival with respect to a body must be matched with the energy of departure. The gravity assist is assumed to act impulsively. In addition, for the trajectory to exist, the gravity-assist body must be capable of sufficiently bending the V_∞ vector. The theory, limitations and advantages of the *patched conic* approach are described in [4].

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The new program has been applied to the Voyager II example and successfully identifies the Grand Tour. It has also verified that the next Voyager II type grand tour recurs in the year 2153, 175.8 years later. The main limitation of the program is that precise arrival times must be solved for by more sophisticated techniques such as the *multi-conic* method or by *numerical integration* of the restricted n-body problem [5]. It is well known that the solution for time is a difficult problem in celestial mechanics. With the patched conic approach, the arrival time at Jupiter can be overestimated by several days, due to the gravitation of the planet which accelerates the spacecraft during the flyby. At Neptune or Pluto, the error in time of arrival can accumulate to several weeks, but this error is small in comparison to the total travel time of one or more decades in a typical grand tour. Mission designers at JPL have found by experience that the patched conic technique is sufficient to demonstrate the *existence of gravity-assist trajectories.* Once existence is shown, the more sophisticated (and time consuming) techniques are applied to a particular mission of interest.

In this paper the results of a systematic search for future missions to the outer solar system are reported.

The Last Four-Planet Grand Tour Opportunity

The possibility of a five-planet grand tour involving a launch from Earth and successive encounters with Jupiter, Saturn, Uranus, Neptune and Pluto was examined. Such a trajectory *path* is succinctly described by the nomenclature E56789. It was soon discovered that, for unconstrained time of flight, many such families exist, but the flight times can easily exceed 200 years. In the interest of mission feasibility the time of flight was constrained to 7500 days (20.5 years) and the launch V_∞ was set to an energetic 12 km/s (compared to Voyager's 10.2 km/s). With these constraints a search for trajectories was made for the period between January 1, 1965 and January 1, 2180 with a step size of 20 days. No trajectories were found which reach Pluto. However, classical Voyager II Grand Tour (E5678) trajectories were found for launch years ranging from 1967 through 1982. After 1982 they did not repeat until the year 2153. Figures 1 and 2 show the relative positions of the outer planets for the periods 1977–1986 and 2147–2156. Clearly these families of trajectories are governed by the synodic period of Uranus and Neptune which is 172 years. Note that Fig. 2 indicates that Pluto would still not be in an advantageous position for the latter opportunity.

The possibility of a four-planet grand tour was investigated next with the sequence E5789 (without Saturn). Here the range of launch dates searched (with a step size of 20 days) was between January 1, 1985 and December 31, 2049. Figure 3 presents the discovery of such a trajectory with a launch date in 1995. Note that this single case is surrounded by numerous occurrences of E578 trajectories. Figure 4 displays a more refined search over a smaller range of launch dates, with a 1 day step size, and indicates that there may be opportunities between 1992 and 1995. These possibilities were first noted in [6]. In Fig. 5 the effect of different launch V_∞s (12, 13, and 14 km/s) is shown for launches in 1995. The lower bound (at a time of flight of 6100 days) is due to the altitude constraint of -1000 km. The concept of allowing subsurface flybys in early mission

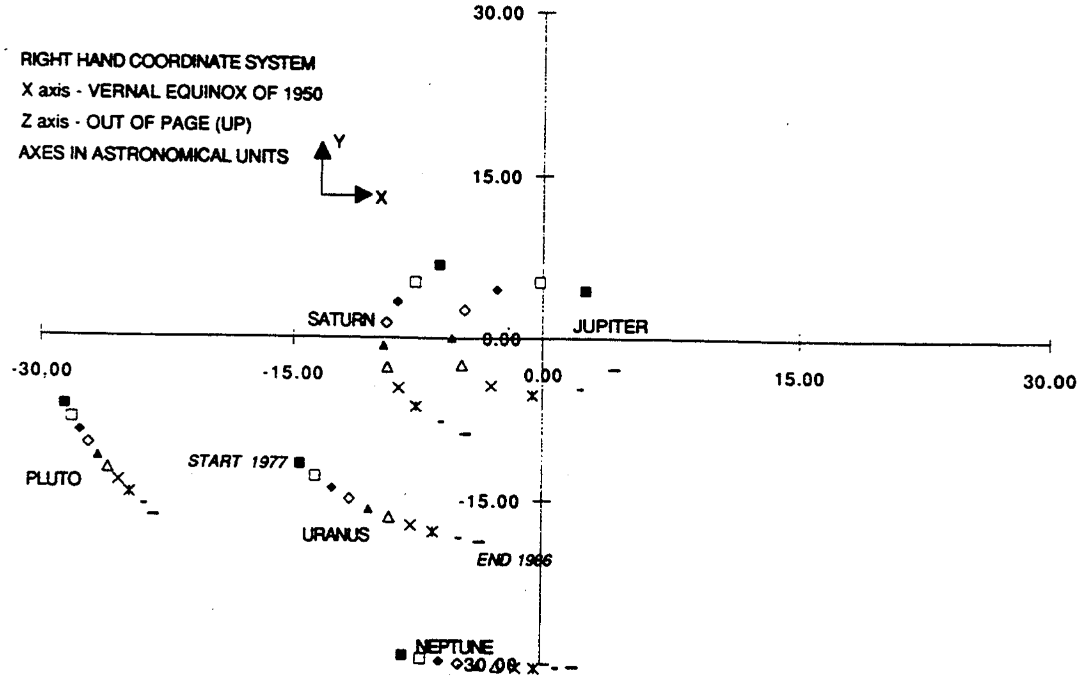

FIG. 1. Positions of the Outer Planets (1977–1986).

design studies is quite common and is useful in studying trends. In refined mission design the flyby altitudes must of course be positive, and this constraint is often maintained by propulsive maneuvers. For the case of $V_\infty = 12$ km/s all

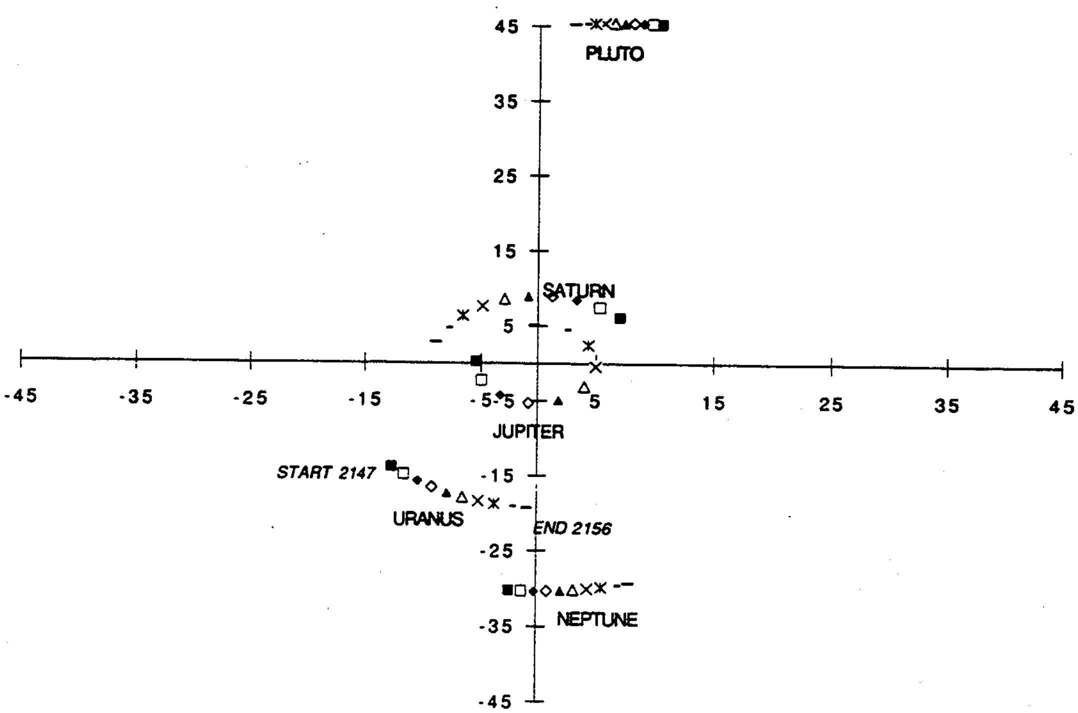

FIG. 2. Positions of the Outer Planets (2147–2156).

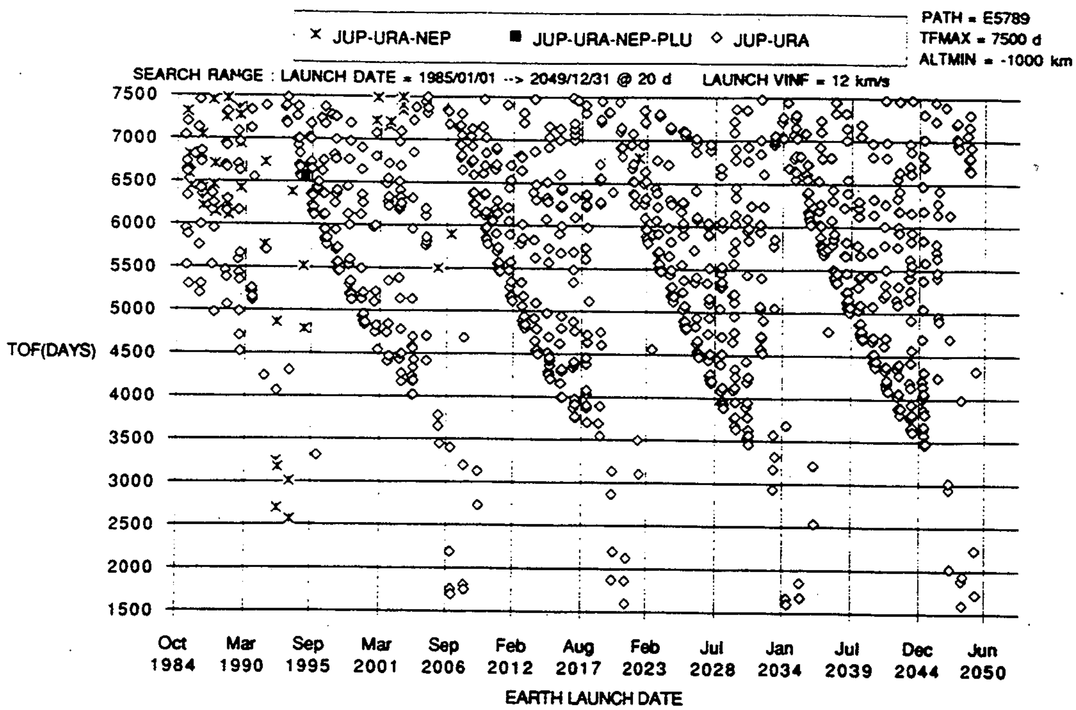

FIG. 3. Jupiter-Uranus-(Neptune)-(Pluto) Trajectories (1985–2050).

flyby altitudes are positive. In the other cases there are only three launch dates (January 21, 1995, January 30, 1995 and March 3, 1995) in which the flyby altitudes are actually negative (−130 km, −160 km and −400 km respectively) and

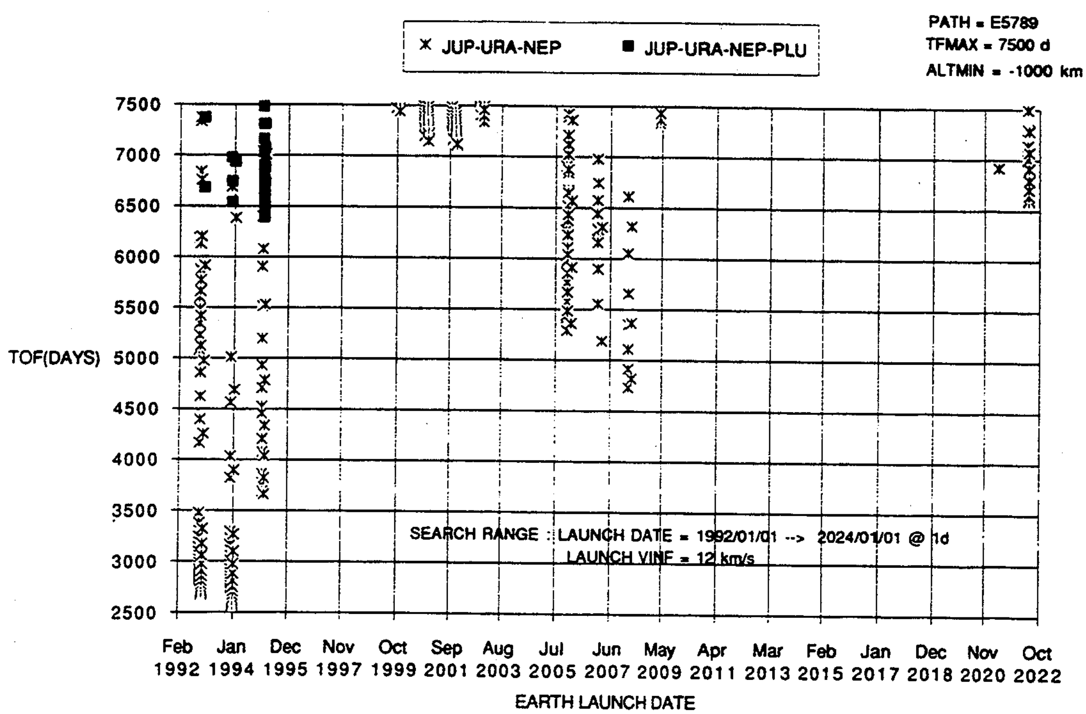

FIG. 4. Jupiter-Uranus-(Neptune)-(Pluto) Trajectories (1992–2024).

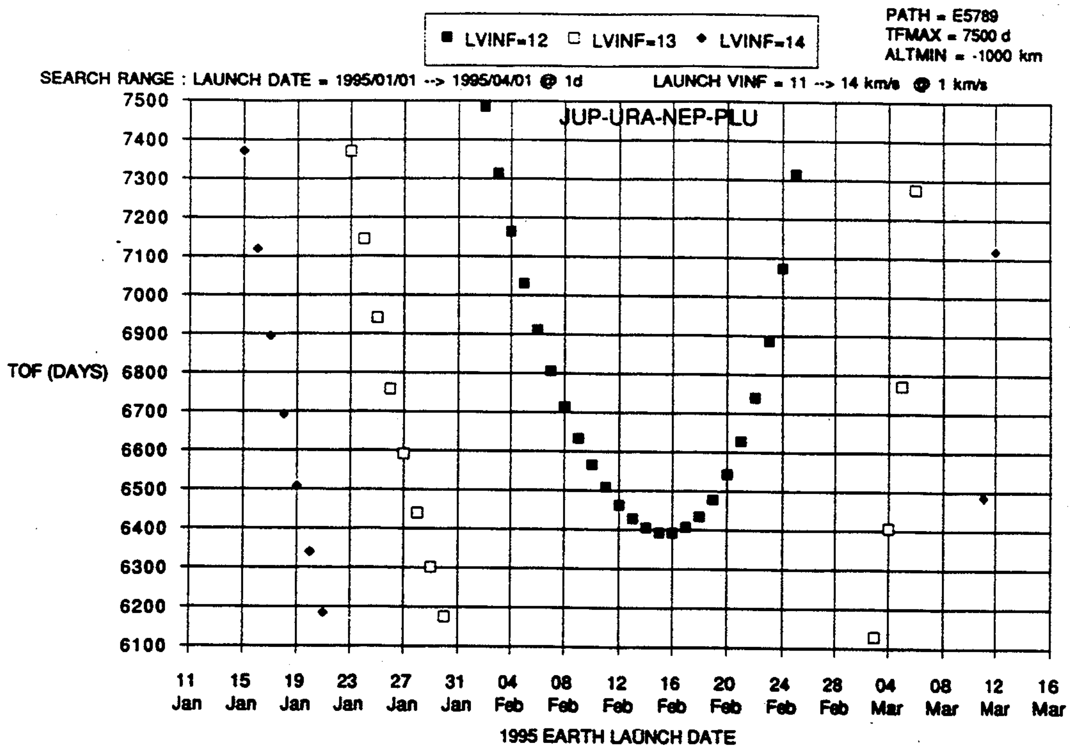

FIG. 5. Jupiter-Uranus-Neptune-Pluto Trajectories (1995).

these all occur on the Neptune flyby for total flight times less than 6200 days. The Neptune encounter changes the spacecraft orbit from posigrade to retrograde in order to reach Pluto.

In order to find the last possible trajectory to Pluto, a search was conducted in the years 1996 and 1997 at one day step sizes and at launch V_∞s of 11, 12, 13 and 14 km/s. In this search no trajectories were found to Pluto in 1997 and presumably none exist afterwards, at least not in the time span searched in Fig. 3. The result for the launch year 1996 is shown in Fig. 6 and contains all positive altitude flybys.

Other Multiple Encounter Opportunities

Other multiple encounter opportunities involving the far outer planets and starting with Jupiter were studied in [1]. Major results are summarized in Table 1. In the table the four-planet opportunity discussed above is included along with three-planet and two-planet opportunities. In all cases except the first one, the launch V_∞ is assumed to be 12 km/s. Only missions with flight times less than 7500 days (20.5 years) are reported. These results are culled from a careful search of the period 1985 through 2049. Note that in the case of E578 that as the separation between Uranus and Neptune increases, the time of flight increases until it reaches 6500 days in the years 2021–2022. After 2022 this family no longer has flight times less than 7500 days. Two-planet opportunities with Jupiter provide fast trajectories to Uranus, Neptune and Pluto and recur regularly according to their respective synodic periods.

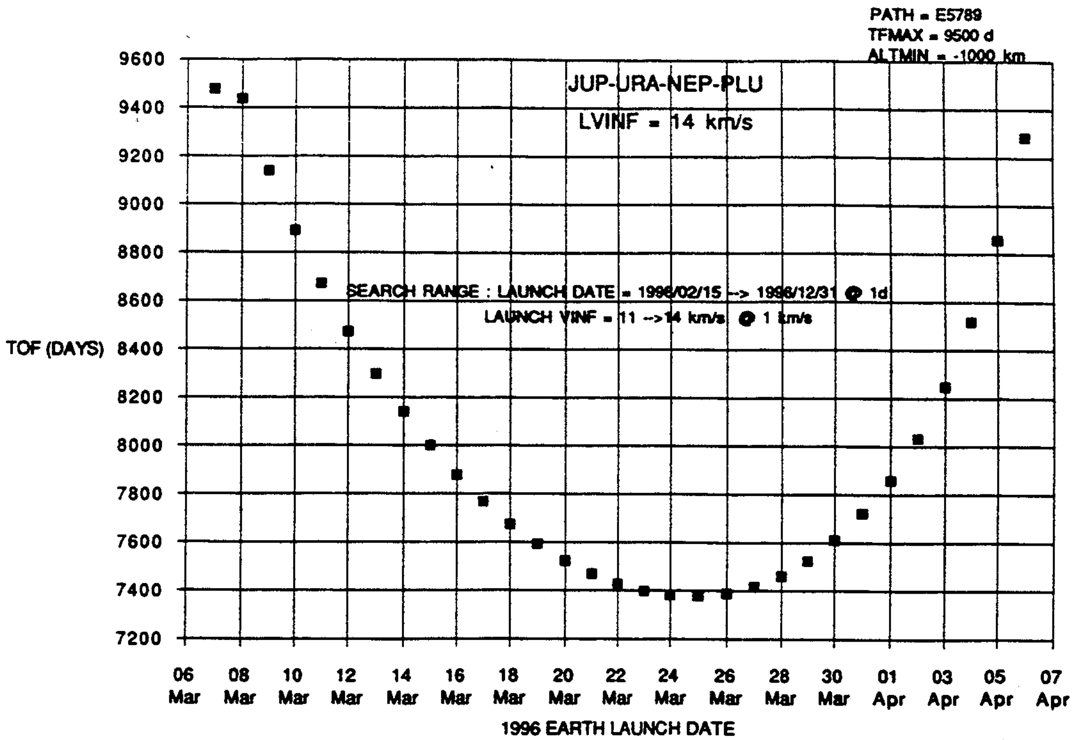

FIG. 6. Jupiter-Uranus-Neptune-Pluto Trajectories (1996).

Conclusions

While there are several examples of two-planet and three-planet gravity-assist trajectories to the outer planets that have short times of flight, there appears to be only one remaining family involving four planets for the foreseeable future. The last grand tour opportunity in this century or the next occurs in 1996 and

TABLE 1. Multiple Encounter Opportunities with Far Outer Planets

Launch	Planets	Flight Time (days)	Comments
1996	Jupiter-Uranus-Neptune-Pluto[a]	7400	Last opportunity for four planets
1993–1995	Jupiter-Uranus-Neptune	2500	Three-planet opportunity
1998	Jupiter-Saturn-Uranus	5000	Three-planet opportunity
2005–2007	Jupiter-Uranus-Neptune	4700	Three-planet opportunity
2016–2019	Jupiter-Saturn-Neptune	2500	Three-planet opportunity
2021–2022	Jupiter-Uranus-Neptune	6500	Last opportunity for E578
2036	Jupiter-Saturn-Uranus	3800	Three-planet opportunity
2037	Jupiter-Saturn-Uranus	4200	Three-planet opportunity
Every 14 years	Jupiter-Uranus	1500	Two-planet opportunity
Every 13 years	Jupiter-Neptune	2500	Two-planet opportunity
Every 13 years	Jupiter-Pluto	2500	Two-planet opportunity

[a]V_∞ = 14 km/s in this case and 12 km/s in all other cases.

includes encounters with Jupiter, Uranus, Neptune and Pluto. The next four-planet opportunity appears to be the Voyager II type grand tour which occurs in the year 2153.

Acknowledgment

The authors thank the following individuals for their assistance and continuing support: D.V. Byrnes, R. E. Diehl, E. A. Rinderle, R. S. Schlaifer, A. B. Sergeyevsky, D. L. Skinner, and D. S. Stetson. This work has been supported by National Aeronautics and Space Administration Grant NGT-50499 (NASA Grants Officer John E. Moore, NASA University Programs Manager John Lynch, JPL Program Administrators Harry I. Ashkenas and Carol L. Snyder, and JPL Technical Monitors Roger E. Diehl and Douglas S. Stetson).

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