

PLUTO FAST FLYBY: A NAVIGATION ASSESSMENT

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INTRODUCTION

Pluto and Charon are puzzling because they are so different from the other eight planets in almost every respect. Pluto is the smallest planet, and nominally the most distant, so its enigmatic nature is not surprising. Its **unique** characteristics include an orbit which is highly inclined and is so elliptical that the planet is closer to the Sun than Neptune from 1980 to 1999. Furthermore, the Pluto-Charon system is exceptional because the pair are more equal in mass than any other primary-satellite pairing in the solar system. Pluto may even be an enormous comet-like structure and not a "planet" at all. Yet Pluto remains the only major body in the solar system so far unvisited by spacecraft. For these reasons, there is great interest in surveying the Pluto-Charon system with robotic explorers.

The proposed NASA/JPL mission to Pluto, known as Pluto Fast Flyby (PFF), will send a pair of technologically innovative spacecraft to the Pluto-Charon system early in the next millennium. Reaching their destination within reasonable time limits, however, (less than 10 years) requires the spacecraft to be flung toward Pluto with high injection energies (C3). Thus as the mission name suggests, each encounter with Pluto (spaced 6 months apart) consists of a quick-look flyby, with heliocentric encounter velocities of 14 km/s. Acquiring close-up science images at these high velocities will demand special orbit determination procedures during the near-encounter phase.

STATEMENT OF PROBLEM

The ninth planet has been observed for only 25% of its orbital period and consequently has large uncertainties associated with its ephemeris. This lack of knowledge, combined with the insignificant mass of Pluto and the long round-trip light time, has created a singularly unique challenge for spacecraft navigation and orbit determination. To meet this challenge, PFF will rely on optical navigation to a far greater extent than has any previous mission, and will include a capability to process optical navigation data autonomously. This feature will be necessary in order to update spacecraft trajectory knowledge near Pluto closest approach,

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MISSION DESCRIPTION

originally envisaged as a straightforward flyby, the mission has evolved into a plan to also deliver probes onto the surfaces of Pluto and Charon. As part of this new mission strategy, the PFF project will collaborate with IKI (Russian Space Agency). IKI will contribute two probes (ZONDs), one for each spacecraft.

overall spacecraft dimensions are approximately 1.6 m x 1.5 m x 1.2 m. The high gain antenna is about 1.5 m in diameter. Total spacecraft wet mass, including ZOND, is about 150 kg. The ZOND has a mass of 5.5 kg, with another 10 kg of associated spacecraft accommodation mass. The spacecraft will be loaded with 24 kg of monopropellant hydrazine, capable of performing approximately 350 m/s of Δv .

Telecommunication with PFF will be at X-band frequencies (uplink and downlink) with a nominal downlink rate of about 40 bits/s at encounter range (to a 34 m DSN station). Available radiometric data types will include two-way coherent doppler and two-way range.

in addition to supplying ZONDs, IKI will provide the boosters for launch. Thus the launch vehicle nominally assigned to the PFF mission is the Proton vehicle, with a two stage solid-motor stack on top. This arrangement will provide PFF with a C3 of approximately $250 \text{ km}^2/\text{s}^2$. The booster will place PFF on a 9 year ballistic trajectory toward an encounter with Pluto. Launch is tentatively set for February 2001. See Figure 1.

Figure 1 PFF Trajectory

Correcting likely injection errors caused by the booster is a necessary activity early in the mission. Two clean-up maneuvers will occur within two months of injection. These maneuvers are critical because no other maneuvers are planned for $8\frac{1}{2}$ years. The expected mean magnitude of each maneuver is on the order of 20 m/s.

Upon satisfactory completion of the second maneuver, the navigation sub-system will enter a low-activity monitor-mode. Tracking data will be collected during the long cruise and the spacecraft monitored to ensure nominal performance, but navigation activities as such will go dormant for 8½ years.

PIF represents a departure from traditional tracking schedules for interplanetary spacecraft. PIF philosophy requires the mission to operate with far less navigation data than has been the norm for previous deep space missions. Thus during the long, uninterrupted cruise phase, only a paucity of doppler and range will be collected. The baseline schedule calls for 8 hours of tracking per month. (During maneuvers and the encounter, coverage will increase substantially.)

Navigation activities will begin in earnest once again approximately 6 months from encounter. At this time the spacecraft range to Pluto will be 1.4 au (220 million km). Optical navigation, arguably the most powerful data type within the navigation sub-system for this mission, will commence imaging. Opnav images are required in order to accurately define the Pluto-relative location of the spacecraft in the plane-of-sky, because even in year 2010 the position of Pluto will be uncertain by several thousand kilometers. Pluto will be discernable to the camera as an optical magnitude 6.5 source, and the field of view of the camera will easily encompass any uncertainty in Pluto's ephemeris. Current plans call for a opnav budget of 75 to 100 pictures during the six month approach to Pluto. The 9 year arc of radiometries is useful only for determining the radial position of PIF, providing an estimate of time-to-go. The radio data will not, however, contribute in a major way to any maneuver design during approach because of the complete absence of any sensitivity in the doppler data to Pluto's mass.

A total of five maneuvers are planned during Pluto approach. Two statistical maneuvers, placed at -5 months and -7 weeks, will correct trajectory errors and maintain the targeting of PIF (and ZOND) to collide with Pluto. Preliminary analysis has shown that data arcs including two to five opnav images for the -5 month maneuver and seventeen to twenty opnavs for the -7 week maneuver are sufficient for maneuver design. The magnitudes of these early maneuvers are expected to be small. The ZOND will be released at -1 month to fall onward into Pluto. Two days after probe separation the mother craft will perform a trajectory deflection maneuver (TDM) -- slowing it by 15 minutes and retargetting the PIF spacecraft for a flyby of Pluto at an altitude of 14,000 km. The magnitude of the trajectory deflection maneuver equals approximately 10 m/s. Between twenty and thirty opnav pictures will be included in the data arc for the TDM maneuver design. Two clean-up maneuvers at -17 days and -3 days will follow TDM. The magnitudes of these statistical maneuvers are expected to be small.

Orbit determination updates will occur regularly after the last maneuver until -4 hours from closest approach to reduce pointing uncertainties in the science instruments -- necessary in order to guarantee a high probability of capturing the near-encounter observations. This last phase of OD will be performed onboard the spacecraft. The autonomous OD system will acquire and process opnav pictures in the intervals between far-encounter science observations. This system represents a new capability for interplanetary spacecraft and heralds a significant departure from traditional navigation procedures.

A prototype design of the autonomous opnav/OD system for PFF is undergoing testing. The design attempts to maintain simplicity by exploiting the special conditions of the PFF mission. Image processing is facilitated by the assumption of regular shapes for Pluto and Charon. The nearly linear flyby geometry of the mission simplifies the dynamic model. Thus a shift in Pluto's image center from its predicted location determines a proportional shift in the time of spacecraft closest approach, thereby correcting observation times. This "late pointing update" restores the Pluto-relative geometry assumed in original observation designs. Preliminary analyses have shown that this system can reduce the uncertainty associated with the time of closest approach from about 3 minutes (no autonomous opnavs) to about 10 seconds.

NAVIGATION PERFORMANCE

The 10 requirements levied upon navigation by the project are the following. Knowledge of the spacecraft at time of closest approach should not be uncertain in the B-plane by more than 70 km (B.R=50 km, B.T= 50km), nor uncertain in the time of closest approach by more than 10 seconds. For the ZOND at time of release (equivalent to time of impact), an uncertainty in the B-plane of 350 km (B. R=250 km, B.T= 250km), and an uncertainty in the time of flight of 210 seconds will suffice.

The accompanying Figures 2 and 3 illustrate OD dispersions of ZOND and PFF for the baseline tracking schedule. The dispersions are well within project specifications for delivery of ZOND and PFF to their targets. Analysis also indicates a total mean mission Δv approximately equal to 55 m/s, well within the 350 m/s capability of the spacecraft.

Figure 2 ZOND Dispersions at ZOND Release

Figure 3 PFF Dispersions at -40 Days and Closest Approach

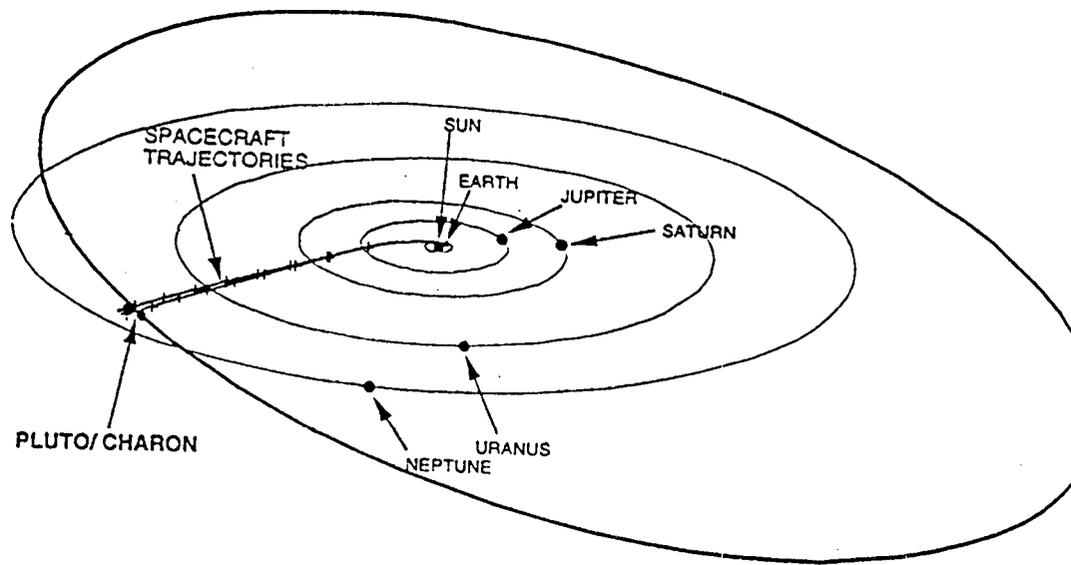
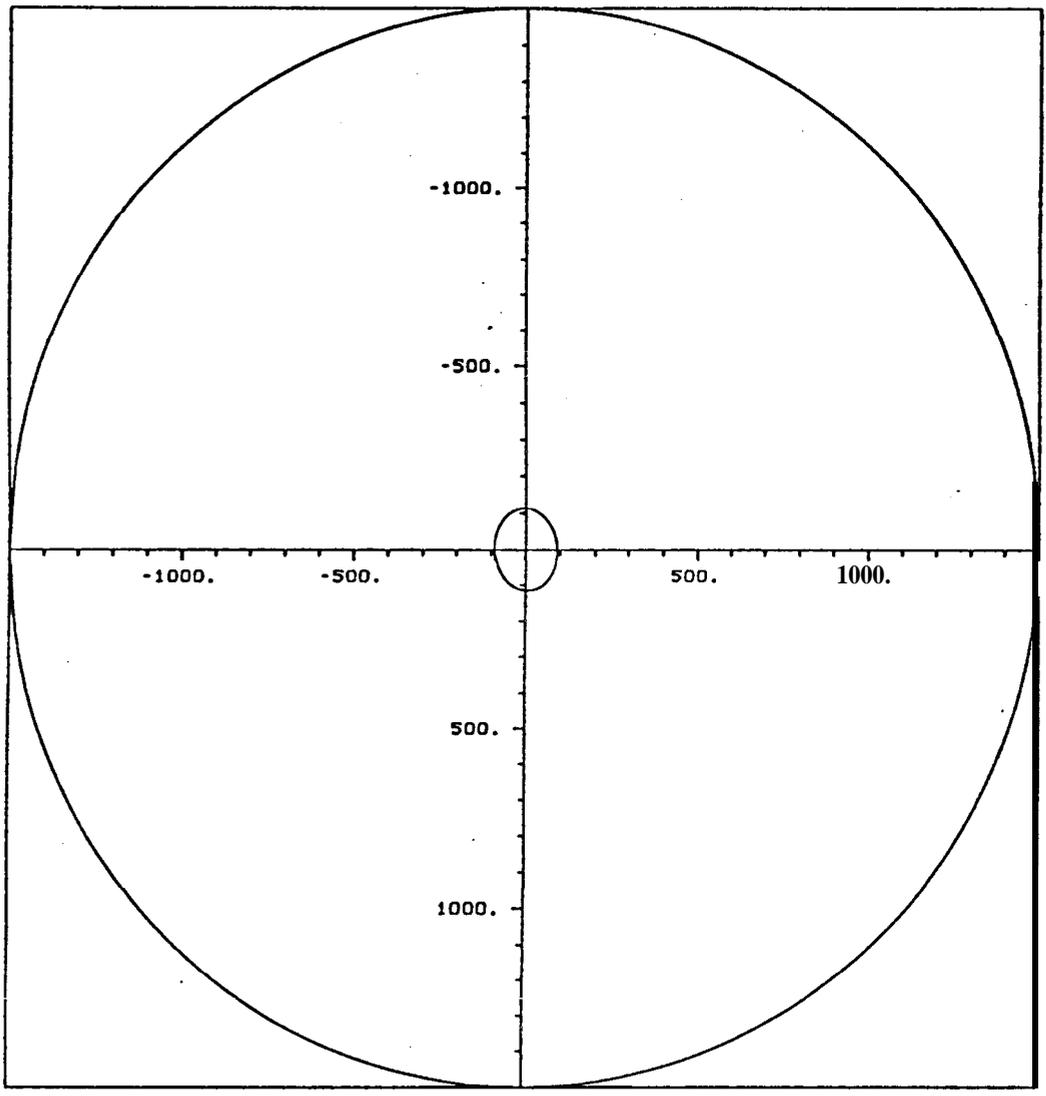


FIG 1

ZOND IMPACT DISPERSIONS AT PLUTO, 1 sigma

8 hr/mon F2, range, 220 pnavs
Zond release at Enc - 30d



Pluto

	Origin		
B.R Center =		0.	0
B.T Center =		0.	0

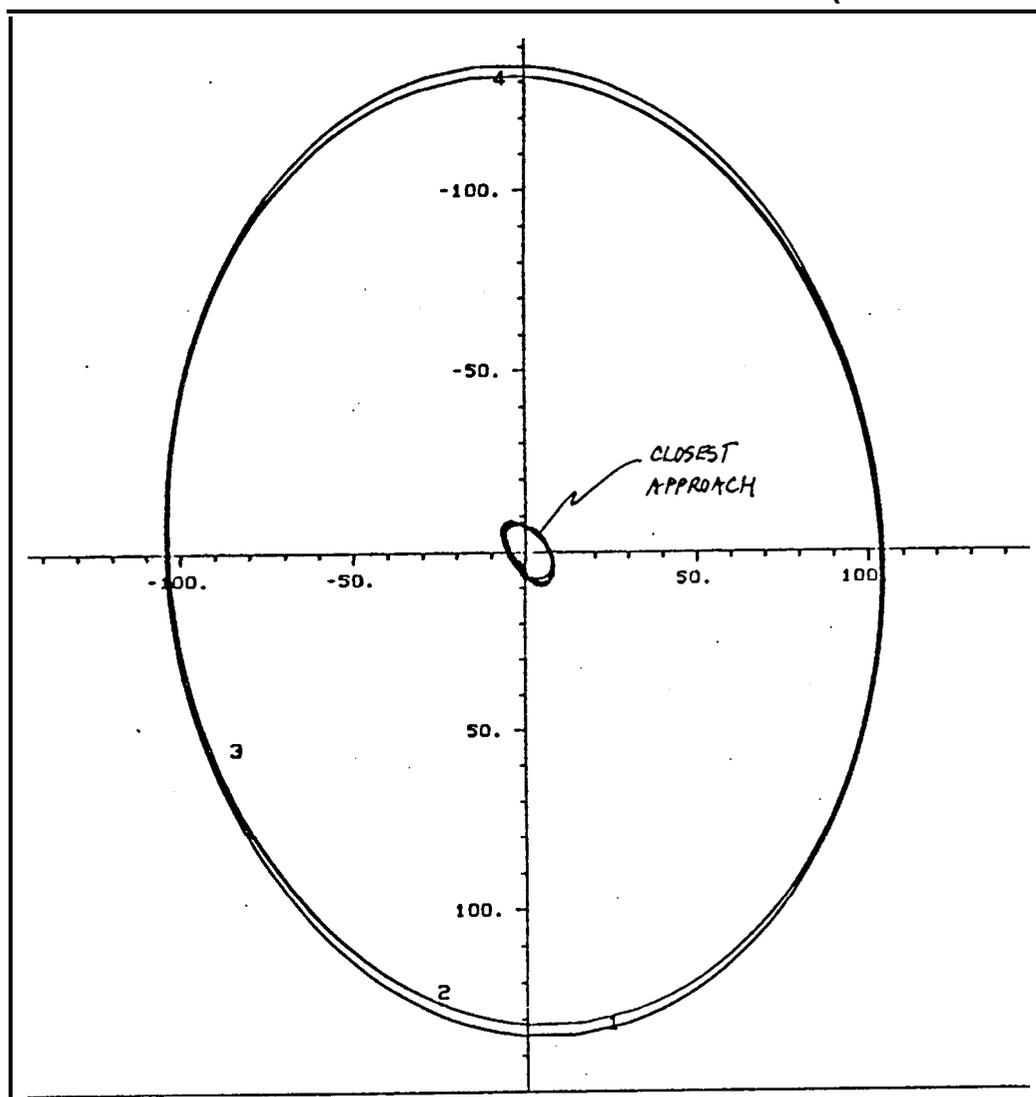
FIG 2

PFF

10

PLUTO B-PLANE AT TDM DATA CUTOFF (Eric - 40 d)

- Legend
- 1) 1 hr/wk F2, 22 opnavs
 - 2) 1 hr/wk F2, range, 22 opnavs
 - 3) 1 hr/wk F2, range, DDor, 22 opnav
 - 4) 3 hr/wk F2, range, 22 opnavs



B.R

B.T

Origin
 B.R Center = -2500. 0
 B.T Center = 14790. 0

FIG 3