Autonomous Optical Navigation for the Pluto Fast Flyby Mission

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submitted for AAS/AIAA Astrodynamics Specialist Conference
August 14-17, 1995
Halifax, Nova Scotia, Canada

Abstract

Pluto and its moon Charon form the only major planetary system as yet unvisited by interplanetary spacecraft. Numerous proposals for missions to Pluto have been considered in recent years. One such mission that has been under development at JPL is the Pluto Fast Flyby (PFF). Two small spacecraft would be launched in 2001 on direct trajectories from Earth to Pluto. The spacecraft would follow radial trajectories out to Pluto with encounters occurring six months apart after an interplanetary cruise of 9-10 years. Pluto-relative trajectories for the flybys are essentially linear with approach velocities between 15 and 20 km/sec, giving rise to the name "Fast Flyby". This paper will discuss applications of optical navigation techniques during the encounter phase of this mission. In particular, the introduction of partial autonomy by migration of some traditional ground-based techniques to the spacecraft flight system will be described.

The optical navigation campaign envisioned for this mission is divided into two major phases. The first, or "far encounter", phase covers the period from 6 months to 2-3 days before closest approach. Activity during this phase will be similar to traditional OPNAV support for previous missions such as Voyager and Galileo. Pictures will be taken with the spacecraft's onboard camera and transmitted to Earth for processing by ground-based navigation personnel. The optical "observables" extracted during the image processing will then be combined with the radiometric data using standard ground-based orbit determination procedures. Orbit determination solutions will be produced to support pre-encounter maneuvers and the design of science observations around closest approach. The 1σ B-plane error ellipse size is expected to be on the order of 20 km for a data cutoff at 3 days before closest approach. Unfortunately, the corresponding uncertainty in the time-of-flight or downtrack direction is much larger, on the order of 200 sec or ≈ 3000 km, as illustrated in Figure 1(a). This is due to large Pluto ephemeris errors and insensitivity of the optical data to changes in Pluto's position along the line-of-sight from the spacecraft to Pluto. In the far encounter phase, the line-of-sight is nearly parallel to the spacecraft's Pluto-relative velocity vector (V_∞).

With downtrack uncertainties of a few thousand kilometers, large mosaics composed of many tens of individual frames would be required to guarantee capture of the target body in a science observation taken within a few minutes of closest approach. There is neither the time or storage memory available to accommodate such large mosaics during the PFF encounter. Optical measurements taken within a few days of closest approach can reduce the downtrack uncertainty. As the spacecraft moves closer to Pluto, the line-of-sight direction rotates away from the velocity vector, allowing the optical data to measure the downtrack position, as shown in Figure 1(b). This is the

motivation for the second, or "near encounter", phase of the Pluto optical navigation campaign which will cover the period from 3 days to a few (2-4) hours before closest approach. The long one-way light time at Pluto (-4 hours) and data rate limitations make it impossible to return the pictures taken during this phase for traditional ground-in-the-loop processing. Thus, the data processing and orbit determination solutions will be performed onboard the spacecraft. The introduction of (at least a partial) autonomous navigation capability represents a significant departure from previous mission operations and is the first proposed Use of such technology for a JPL interplanetary mission.

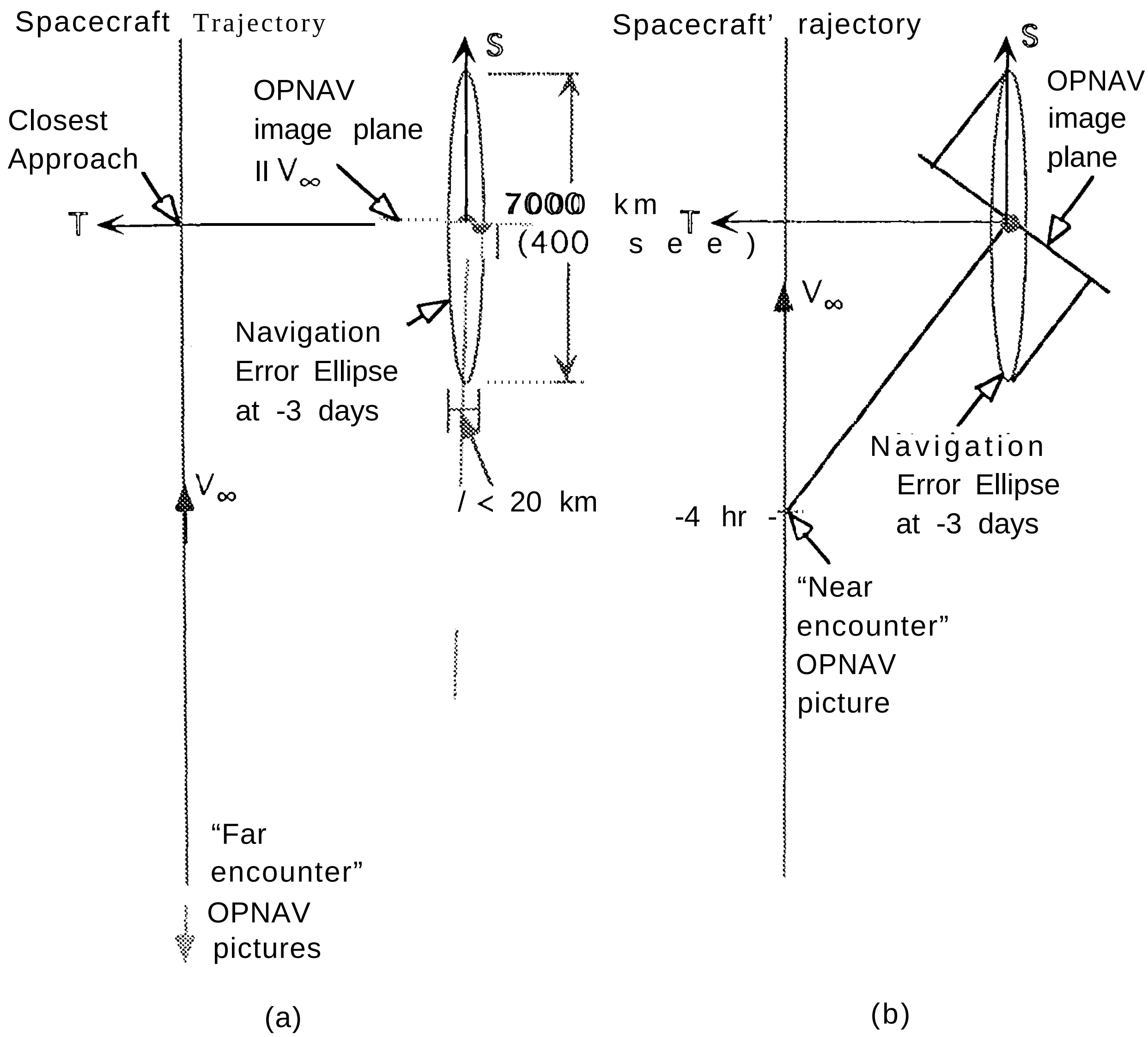

Figure 1 Increasing sensitivity of Optical Navigation data to downtrack position changes. Changes in downtrack position have larger projections onto OPNAV image plane as spacecraft moves nearer to Pluto.

A total of 15-20 pictures will be shuttered in the near encounter phase and processed by the Autonomous Optical Navigation System. The system will estimate the actual time of closest approach from the locations of Pluto and background star images in an OPNAV picture. The accuracy of this estimate will improve dramatically as later pictures are taken and processed. The critical science observations that take place within 1-2 hours of closest approach will have been designed assuming this smaller uncertainty in the time of closest approach. Since this is the dominant error, the geometry assumed in the science designs can be restored by simply shifting the start time of the observations so that they happen at the correct time relative to the actual time of Closest approach. The autonomous system will apply the appropriate time shift to designated block(s) of near encounter science observations. This scenario is illustrated in Figure 2.

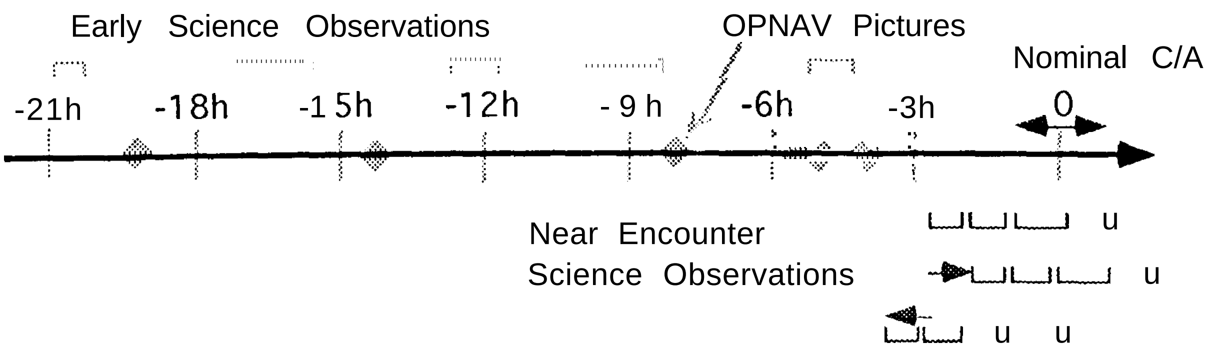

Figure 2 Operational scenario for PFF Autonomous Optical Navigation System. **Start** times of near encounter science observations are adjusted based on solution **for** true time of closest approach from OPNAV pictures.

A prototype design for the PFF Autonomous Optical Navigation System has recently been completed. The system has three primary components, or blocks, whose functions are summarized below:

- **Image Processing** identifies the Pluto and star images in the current OPNAV picture and estimates the location of their centers. The image centers are the navigation observables to be used to solve for a correction to the time of closest approach.
- orbit **Determination Solution computes** an update to the time of closest approach based on the location of the Pluto image center relative to the star centers.
- **Science Sequence Update** applies the appropriate time shift to the start times of encounter science observations based on the update to the time of Closest approach.

A **Geometry Update** block is also included which is executed before the primary blocks. This component uses the information from the solution generated for the previous OPNAV picture (if any) to update the predicted spacecraft-Pluto geometry for the current picture. This information is then used to generate predicted Pluto and star image information for the Image Processing block. Figure 3 is a high -level block diagram showing the information flow between these. system components.

The philosophy followed for the prototype system design has emphasized maintaining simplicity in the on board algorithms and procedures. Particular conditions of the Pluto Fast Flyby mission have been exploited to reduce complexity. The paper will give a more detailed description of the algorithms implemented within each of the major blocks. Background material will be presented deriving the relevant equations and indicating where simplifying assumptions have been introduced.

The remainder of the paper will analyze the expected performance of the Autonomous Optical Navigation system. Image processing accuracies will be considered along with errors arising from the simplified equation formulation. Initial tests of the system's performance on navigation development computers and in the Flight System Testbed at JPL will be discussed. Results for one sample Pluto trajectory will be presented showing that the uncertainty in the time of closest approach can be reduced to ~10 sec when the last picture is taken and processed 4 hours before closest approach.

The paper will conclude with a short discussion of future system development, describing possible modifications and enhancements that should be considered for the actual flight-qualified system.

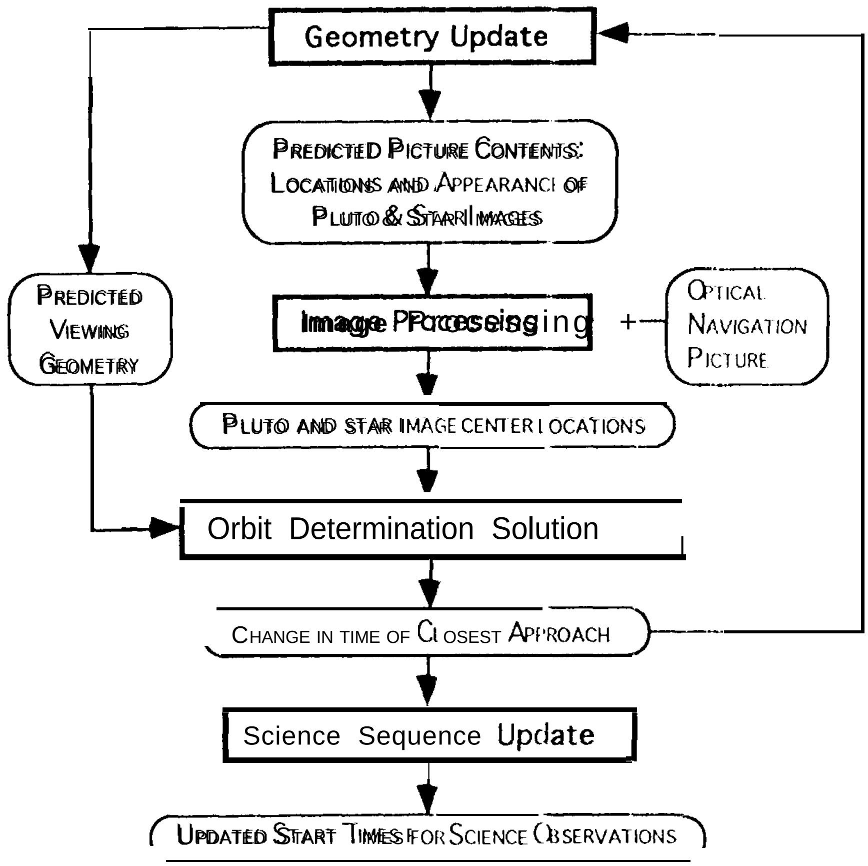

Figure 3 Functional flow chart for PFF Autonomous Optical Navigation System.