Navigation Considerations for Low-Thrust Planetary Missions

Peter J. Wolff
Fabrizio Pinto
Bobby G. Williams
Robin M. Vaughan

Send correspondence to:
Peter J. Wolff
Jet Propulsion Laboratory
MS 301-125J
4800 Oak Grove Drive
Pasadena, CA 91109-8099

818-354-7426
Peter. J. Wolff @jpl. rrasa.gov

The upcoming launch of the solar electric propulsion (SEP) mission New Millennium Deep Space 1 and proposed future SEP missions such as Pluto Express necessitates an analysis of the operational issues related to the navigation of low-thrust missions. Low-thrust technologies such as SEP can provide a specific impulse an order of magnitude larger than that achievable with conventional chemical propulsion systems. This provides increased options in the design of missions using small launch vehicles. The presence of a solar electric propulsion system can reduce or eliminate the need for planetary fly-bys which eases launch window constraints due to the alignment of solar system bodies. Also, low thrust mission design can be more robust because a spacecraft does not have to be controlled to a single prescribed trajectory (as with standard ballistic missions). If a spacecraft deviates significantly from its nominal trajectory, mission objectives can still be met by redesigning the trajectory "on-the-fly." Although low-thrust technology provides enhanced flexibility in trajectory design, the inherent   nature of low-thrust systems presents significant challenges to the orbit determination analyst. SEP uses a low but continuous thrust which lasts for clays or weeks. On the other hand, chemical propulsion provides thrusts at a higher level for much shorter periods of time (a few seconds to tens of minutes). When the thrust is deactivated, the spacecraft is essentially in free fall and the dynamics affecting the equations of motion are precisely known which makes high accuracy orbit determination possible. For low-thrust missions, errors in the execution of the commanded thrust profile induce stochastic perturbations which are three orders of

magnitude larger than the typical stochastic disturbances (usually caused by outgassing and solar pressure mismodeling) considered in conventional ballistic navigation. The presence of this high level of dynamic stochastic disturbances limits the achievable orbit determination accuracy and it necessitates the use of more sophisticated estimation strategies in the navigation process.

Low-thrust mission operations may be complicated by the need for relatively frequent uplinks to update the commanded thrust profile because of observed trajectory dispersions (determined by the navigation system) or due to updates in the guidance laws. One way to reduce these operational costs is to embed the guidance and navigation into an autonomous onboard system. In fact, one of the primary objectives of the Deep Space 1 mission wiii be to demonstrate its autonomous onboard guidance and navigation system. However, conventional ground based radiometric navigation tracking data wiii aiso be processed for the purpose of system validation and fault recovery. This paper wiii concentrate on the use of ground based navigation techniques applied to low-thrust missions.

Covariance Analysis

Covariance analyses were performed for the initial phase of the Deep Space 1 mission. This initial phase spans from launch (July 98) to the flyby of the asteroid McAuiiffe (Jan 99). The SEP engine was assumed to be activated from ~30 days after launch until -60 days before the asteroid flyby. To simplify the covariance analysis the regularly scheduled deactivation of the thrusters on a weekly basis was ignored. The thrust errors were modeled as exponential i y correlated stochastic accelerations with a time constant of five days, a steady state sigma of 10-7 m/s^2, and a batch size of six hours. Passes of range and doppler data were scheduled twice a week from NASA's Deep Space Network stations. The doppler was weighted at 1 mm/s for a 60 second compression time and the range was weighted at 20 meters. The information content of the range was assessed by comparing the position uncertainty for cases with doppler-only against cases employing both doppler and range.
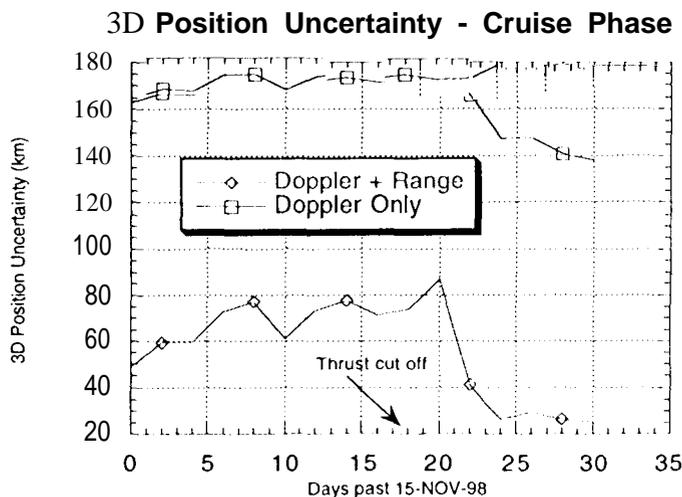
3D Position Uncertainty - Cruise Phase

F i g u r e I

Figure 1 shows that the addition of range to the orbit determination process reduces the position uncertainty to approximately one third of the uncertainty of the doppler only case. This quantitatively shows the benefit of providing the spacecraft with a transponder that has ranging capability. The plots also show the sharp decrease in position uncertainty after the thrusters (i.e., the stochastic disturbance) has been turned off. It takes about ten days for the range+doppler case to reach a steady state position uncertainty of -25 km.

During its cruise phase, the Deep Space 1 onboard navigation system employs optical observations of a constellation of beacon asteroids. These optical measurements were used to augment the ground based radiometric doppler data and the results are displayed in figure 2. The addition of optical measurements did not improve the uncertainties of the range+doppler case and those results are not displayed. The effect of the asteroid uncertainty (100 - 1000 km) was accounted for by deweighting the optical observations with a data noise sigma of 3 pixels. When the center finding error is assumed to be small (.1 pixels), we are implicitly assuming that the asteroid ephemeris errors are also very small. Figure 2 shows that if the ephemeris errors are negligible, the doppler+beacon asteroid strategy is competitive with the range+ doppler scenario. However, the assumption of negligible ephemeris errors is not realistic, and therefore, it would be prudent to retain a ranging capability for the spacecraft.
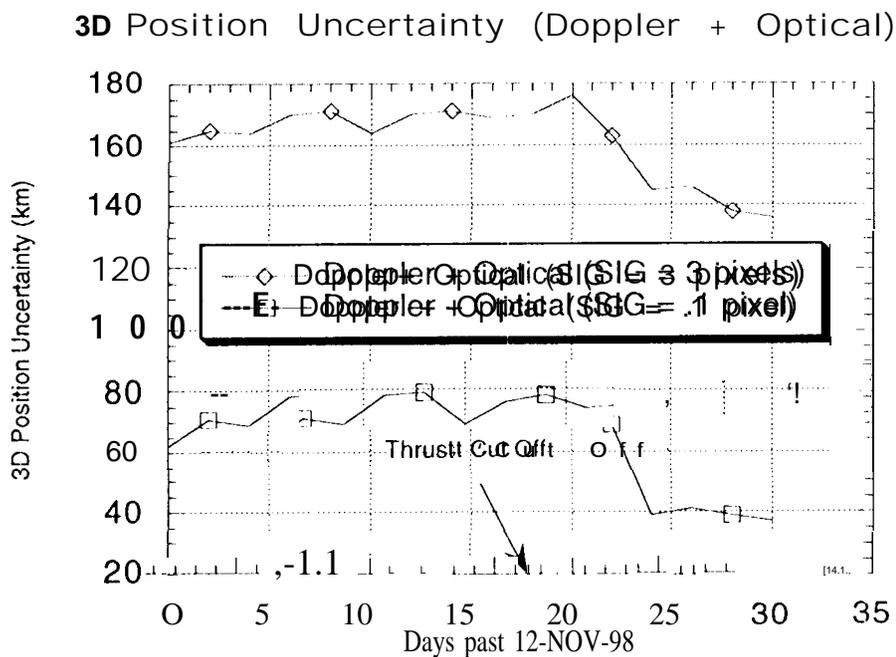
3D Position Uncertainty (Doppler + Optical)

Figure 2

Although the results reported here were applied to a particular SEP mission, we believe the

analysis could be applicable to other types of low-thrust missions utilizing solar sails or nuclear electric propulsion. In addition the covariance analysis techniques will be extended to account for non-optimal choices for the parameters defining the stochastic thrust errors. Also, this paper will report on techniques for calibrating the SEP engine via the reduction of radiometric data. We expect to use data simulations to analyze these engine calibration scenarios.

Acknowledgments

References

Riedel, J. E., et al., "Navigation for the New Millennium: Autonomous Navigation for Deep Space 1", Proceedings of the 12th International Symposium on Space Flight Dynamics, Darmstadt, Germany, 2-6 June 1997.

Kakuda, R., Sercel, J., Lee, W., "Small Body Rendezvous Mission Using Solar Electric Ion Propulsion: Low Cost Mission Approach and Technology Requirements", lAA-L-0710, IAA International Conference on Low-Cost Planetary Missions, Apr 12-151994.