Pioneer and Voyager Jupiter Encounter Orbit Reconstruction in the ICRF System

by

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Exploration of the Jovian system with spacecraft began when Pioneer 10 encountered Jupiter in December of 1973; Pioneer 11 followed a year later. In 1979 the twin Voyager spacecraft began their investigation of the outer Solar System with passes through the Jovian system, and in 1992 the Ulysses spacecraft made a close approach to Jupiter in order to obtain a gravity assist for its mission to explore high solar lattitudes. Since December of 1995 the Galileo spacecraft has been in orbit about Jupiter and, five years after Galileo's arrival, the Cassini spacecraft visited the planet on its way to Saturn.

We have been using data acquired by these spacecraft together with Earth based observations in an effort to determine the gravity field of Jupiter and its Galilean satellites and to improve the ephemerides of those bodies. The work is essentially an update of that of Campbell and Synnott (1985) incorporating the high quality Ulysses, Galileo, and Cassini data. Many of our results have already been reported in the scientific literature (Anderson *et al.* 1998; Anderson *et al.* 2001a; Anderson *et al.* 2001b) and at scientific meetings (Jacobson 2001).

A necessary byproduct of the work is the reconstruction of the spacecraft trajectories. All trajectories previously produced by the Pioneer, Voyager, and Galileo flight projects have been referred to the FK4/B1950.0 coordinate system, the standard system in use at the time the respective projects began. We, however, are performing our Jovian data analysis in the International Celestial Reference Frame (ICRF) (Ma *et al.* 1998), the reference frame of the current JPL planetary and satellite ephemerides as well as the standard frame of the international astronomical and planetary science community. This frame was also used by the Ulysses and Cassini projects. A discussion of our reconstruction of the Galileo prime mission trajectory appears in Jacobson *et al.* (2000). Analysis of the Ulysses and Cassini trajectories may be found in McElrath *et al.* (1992) and Roth *et al.* (2002), respectively. This paper reports on our reconstruction of the Pioneer and Voyager trajectories.

In our global data analysis we determined the orbits of all the spacecraft, the planet, and satellites by adjusting parameters in the dynamical model of their motions to obtain a fit to our observational data. The motion model includes gravitational dynamics (attractions of the satellites, Jupiter, the Sun, and other solar system planets) which affect the spacecraft and satellites and non-gravitational dynamics (solar radiation pressure and thrusting maneuvers) which affect only the spacecraft. The fundamental adjustable parameters included:

- epoch position and velocity of each spacecraft and each Galilean satellite
- elements of the Jupiter orbit
- GM's of the planetary system and the Galilean satellites
- gravitational harmonics of the planet and Galilean satellites
- Jupiter pole orientation angles
- reflectivities in the spacecraft solar radiation pressure models for Ulysses, Galileo, and Cassini; the Pioneer and Voyager reflectivities were retained from previous analyses
- spacecraft maneuvers
- non-gravitational accelerations for Pioneer, Voyager, and Cassini

The observational data set included:

- spacecraft Doppler tracking
- spacecraft range (except Pioneer 10 and Galileo)
- spacecraft very-long baseline interferometry (VLBI) from Ulysses and Galileo
- spacecraft optical navigation imaging from Voyager and Galileo
- satellite Earth based astrometry
- satellite mutual events (mutual eclipses and occultations)
- satellite eclipse timings (eclipses by Jupiter)

The optical navigation data, originally referenced to B1950.0 system, were modified; the reference star locations were replaced with ICRF positions from the Hipparcos and Tycho catalogs. The new positions are the best available ICRF positions of the stars. In order to obtain an adequate fit to the observations we also had to adjust the following parameters in the observation model:

- one-way Doppler bias and drift
- range biases
- spacecraft camera pointing

Besides the change in reference system, our Pioneer and Voyager reconstructions have benefited from improvements in dynamical and observational modeling which have become available since the original work on these missions (Null 1976; Campbell *et al.* 1980, and Campbell *et al.* 1985). Because the locations of the Earth tracking stations are well known in the ICRF system, we no longer need to account for errors in those locations. For the same reason errors in the ephemeris of the Earth may be considered negligible. Recent Earth based observations together with the data from Ulysses, Galileo, and Cassini have reduced the Jupiter ephemeris error to a level which now has only a small effect on the determination of the spacecraft trajectories. The current satellite ephemerides which are based on high precession numerical integration are significantly more accurate than the analyical theory (Lieske 1977) used previously. This increased accuracy enhances the contribution of the optical navigation data to the determination of the Voyager trajectories.

Because of problems with their attitude control systems, the Voyager spacecraft were subject to rather large non-gravitational accelerations. To properly account for these accelerations in the processing of the Voyager tracking data, a sequential stochastic estimation procedure was used. Such a procedure was also used to account for camera pointing errors when processing the optical navigation data. Software limitations prevented the proper simultaneous processing of both types of data in all previous work on the Voyager trajectories. Our current analysis, however, is not subject to those limitations, and we obtain an excellent fit to both data sets. Morever, the current software also permits us to model the station dependent biases in the Voyager range data.

The paper provides a detailed discussion of determination of the Pioneer and Voyager Jupiter encounter trajectories and how that determination relates to our overall Jovian system analysis. We also compare our results to those previously reported.

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