LINKING THE DYNAMICAL REFERENCE FRAME TO THE ICRF

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Abstract.

The latest JPL planetary and lunar ephemerides, DE405, are referenced to the International Celestial Reference Frame (ICRF) with an accuracy that approaches 1 *mas* for the four innermost planets, the sun, and the moon. This has been accomplished mainly by 18 VLBI observations of the Magellan Spacecraft in orbit around Venus. The ephemeris of Jupiter, however, is not well-determined since the various observations are not consistent within each other. The outer four planets continue to rely almost entirely upon optical observations; their ephemeris uncertainties lie in the 100–200 *mas* range.

1. Introduction

The JPL Planetary and Lunar Ephemerides are now numbered in the 400's, indicating that they are referenced to the ICRF. This reference system has a number of advantages for the ephemerides: 1) the most accurate angular observations are now VLBI measurements of spacecraft near planets with respect to the ICRF, 2) there is also an accurate ephemeris–ICRF frame-tie determination, 3) the ICRF itself is accurate ($< 0\overset{''}{.}001$), 4) the ICRF is stable (there are to be no future net rotations), and 5) timing and polar motion information, distributed by the IERS, is now referenced to the ICRF frame. The only disadvantage, a relatively minor one, is that most of the angular measurements fit by the ephemerides are with respect to the optical reference system, so that an optical–ICRF frame-tie must be applied.

This paper shows the newer ephemeris observations which have enabled the adjustment onto the ICRF. The inner four planets, sun and moon are discussed first, since that system is now well determined in all aspects: relative positions, relative distances, mean motions, and orientation. Then, Jupiter is discussed; there are some remaining inconsistencies between the varied observations which have yet to be resolved. The outer four planets are mentioned at the end.

2. The 4 Inner Planets, Sun and Moon : relative angles, distances, and inertial mean motions

Ranging measurements determine accurately not only the relative angles and distances between the measured planets, but also the bodies' mean motions with respect to inertial space. This has been discussed elsewhere (see e.g., Standish & Williams, 1990). The result is that for the sun, moon, and inner four planets, the relative angles are known well below 1 *mas* and the distances are known below the 1 km level. The inertial mean motions are known to an accuracy of about 20 *mas/cty*; this relatively large uncertainty come from the uncertainties in the masses of the asteroids which perturb the inner solar system, as discussed by Williams (1984).

Ranging, however, will not determine the orientation of the ephemerides with respect to an outside reference frame.

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3. Orientation onto the ICRF

There are two sets of data which align the ephemerides onto the ICRF:

• The frame-tie determination of (Folkner *et al.*, 1993): The radio sources of the ICRF are connected to the radio antennas via VLBI observations; those antennas are connected to LLR telescopes via geodetic ground surveys; the LLR telescopes are connected to the moon via LLR observations; the sun and planets are connected to the moon through the lunar dynamics. This set of connections is used as an observation of the sun and planets, taken wrt the ICRF. The estimated uncertainty is about 3 *mas*.

• VLBI observations of spacecraft either approaching or orbiting a planet: The VLBI observations w.r.t. the ICRF radio sources are combined with the spacecraft ephemeris to give the planet in the radio frame. These observations are almost purely one-dimensional, measuring along the baseline between the two antennas. They are almost entirely in right ascension when taken between Goldstone and Madrid since those sites are at comparable latitudes. Of these, there were 6 observations of Magellan orbiting Venus, all in 1994, with uncertainties from 1.8 to 4.0 *mas*. There are also 12 observations of Magellan taken between Goldstone and Canberra from 1990 to 1994 with uncertainties from 1.1 to 3.2 *mas*; they split nearly 50-50 between right ascension and declination. Two observations of the Phobos spacecraft, approaching Mars in 1989, have uncertainties of 3.3 and 6.2 *mas*.

The above observations serve to orient the whole inner system of DE405 onto the ICRF with an accuracy of about 1 *mas*. A confirmation of this estimate came in July 1997 with the arrival of the Pathfinder spacecraft at Mars. The ephemeris error, determined by JPL's navigation, was about 1.1 km. With Mars at a distance of 1.3 AU, this down-track error is the equivalent of 1.2 *mas*.

4. Problems with Jupiter

The situation with the ephemeris of Jupiter is less satisfying. There is a wide variety of observations of Jupiter, but they are not all consistent with each other. Figures 1-3 show the residuals vs. DE405. Transit observations of Ganymede and Callisto taken at La Palma, are represented by stars, each star showing the mean of the residuals taken over an opposition of Jupiter; the open boxes show the opposition means of transit observations of the limbs of Jupiter, taken from Washington.

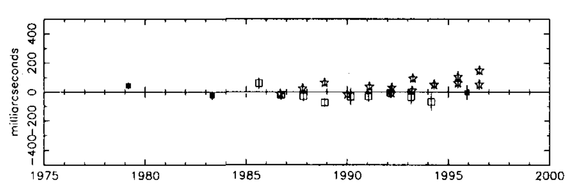

Figure 1. Right Ascension residuals of Jupiter

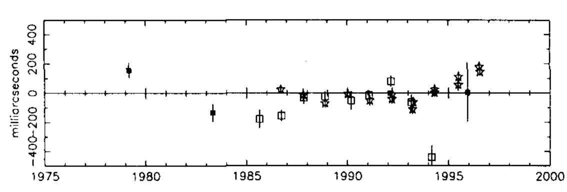

Figure 2. Declination residuals of Jupiter

The Voyager 1 point, shown as a filled square in 1979, is from JPL Navigation's Orbit Determination Program's fitting to the standard tracking data, range and doppler; the VLA observation,

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filled square in 1983, measured the thermoelectric emission of Jupiter w.r.t. the radio source background; the Ulysses point, filled square in 1992, is from an ODP fit to range, doppler, and VLBI; and the Galileo ODP, filled square in the end of 1995, is a fit to range and doppler during approach.

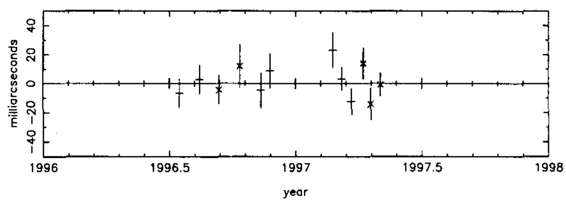

Figure 3. VLBI residuals of Jupiter

Figure 3 shows the Galileo VLBI, taken while in orbit around Jupiter; the ×'s mark the Goldstone–Canberra observations and the –'s are from Goldstone-Madrid. (Note the difference in scales between the figures.) These VLBI observations anchor the ephemeris firmly in 1996-97.

One can see from the figures that while the right ascension residuals seem to be fairly well-behaved, except for a slight positive trend from La Palma, the declination residuals show a more serious problem. Both the Voyager 1 and VLA points are nearly $3\,\sigma$ away from zero and there is a definite positive trend in the La Palma opposition means. Since the 1996-1997 VLBI points are so dominant, there is no chance of flattening the La Palma points. Further, there is no explanation for the poorly fitting Voyager 1 and VLA residuals. If one were to increase the weight of these two observations during the fitting process, the La Palma points would be even further away from the axis. The uncertainty in the Jupiter ephemeris is therefore estimated as a tentative 50 *mas* during the latter half of the 1990's; it could be worse at other times.

5. The outer four planets

The ephemerides of the outer four planets continue to be markedly less well-determined than those of the inner planets. The orbital periods are long; they cover decades, during which observational techniques have changed and during which the planets move through different zones of the optical catalogues. Not surprisingly, the ephemerides of Saturn through Pluto have uncertainties in the 100–200 *mas* range.

6. Summary

The inner four planets, sun, and moon have ephemerides which are well-determined with respect to the ICRF at the 1 *mas* level. Jupiter's ephemeris is fit to a variety of observations, but problems still exist; the uncertainty is estimated at 50 *mas* during the present few years, but probably worse at other times. The ephemerides of Saturn through Pluto have uncertainties in the 100–200 *mas* range.

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