1.3 EXTRAGALACTIC REFERENCE FRAME

THE DYNAMICAL REFERENCE FRAME

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Abstract. Planetary and lunar ephemerides continue to improve in accuracy as they continue to be adjusted to newer and more accurate observational data. An additional improvement will be that of the orientation of the ephemerides; in the future, the ephemerides produced at JPL will be based upon the reference frame of the radio source catalogues. Recent planetary observations have been made directly with respect to the radio reference frame, and these observations have shown a satisfying degree of absolute accuracy and internal consistency; they enable the automatic orientation of the ephemerides onto the radio reference system during the ephemeris adjustment process.

1. Introduction

Lunar and Planetary Ephemerides continue to improve for a number of reasons.

- Newer and more accurate observations increase the internal accuracy of the motions.
- Most of the relevant astronomical constants are now accurately known from other sources.
- Recent and future positional measurements of the planets provide a direct tie between the planetary and radio source reference frames.

In the past, the ephemerides of the inner planetary system, Mercury through Mars including the Moon, have been very well determined in a relative sense, due to the highly accurate ranging observations. The orientations of the systems, however, have been less certain by orders of magnitude (Standish & Williams 1990).

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The paper discusses the observational data set involved in the creation of the ephemerides, concentrating upon reference frames and how the data have influenced the orientation of previous ephemerides produced at JPL. The recent progress of determining frame-ties is described, and it is shown how it is now possible to automatically orient the ephemerides onto the radio reference frame by fitting to recent VLBI measurements of the planets. Arguments for and against basing the ephemerides onto the radio reference frame are presented.

2. Orientations of Past Ephemerides at JPL

Lunar and planetary ephemerides are adjusted to various types of observational measurements in a least squares sense. The accuracy of the ephemerides relies primarily upon the accuracy of these data. Similarly, the accuracy with which the ephemerides are oriented onto any particular reference frame depends upon both the accuracy of the measurements of the planets with respect to that frame and the accuracy of that frame itself. If there is more than one frame involved, frame-ties must be applied in order to have the data sets be consistent among themselves.

Table 1 lists the various types of observations to which the ephemerides are adjusted and shows both the approximate accuracy of the observations and the frames to which they are referenced. The planetary ranging observations are virtually independent of outside reference frames; they tend to refer the position of the measured planet with respect to the orbit of the earth. The lunar laser ranging (LLR) data are sensitive to the earth's orientation also; but, if the locations of the LLR telescopes are not constrained, that sensitivity is alleviated. Therefore, of the earlier data types, only the optical observations are referenced to an outside reference frame. Consequently, the earlier JPL ephemerides (up to and including DE130) were oriented automatically by the optical observations and thus were aligned onto the origin of the FK4 reference frame. The optical observations, however, as shown in the table, are two orders of magnitude less accurate than the other data types. (The ranging measurements are comparable to millisecond observations, since one kilometer at one AU subtends an angle of $0.''0014$.) It is now known that systematic errors remain in the FK4/FK5 optical systems amounting to tenths of arcseconds; as such, the past orientations onto the optical frame represented one of the least accurate features of the ephemerides.

Starting with DE200, the first J2000-based ephemeris from JPL, attempts were made to orient the ephemerides onto the mean equator and mean dynamical equinox of J2000 (Standish 1982). These attempts were not entirely successful, however. First, there is more than one definition of

TABLE 1. The observations to which the ephemerides are adjusted.

Observation	Accuracy	Reference Frame
Radar-ranging	2 km → 100 m	Earth Orbit
s/c ranging	100 m → 7 m	Earth Orbit
LLR	30 cm → 3 cm	Earth Orientation and Orbit
Transits	0.″5 → 0.″2	Optical
Astrolabe	0.″5	Optical
Astrometry	0.″5	Optical
Occultations	0.″1	Optical
Thermal Emission	0.″03	Radio
VLBI : Magellan	0.″002	Radio
VLBI : Phobos	0.″001	Radio
VLBI : Ulysses	0.″003	Radio
CCD Astrometry with QSO's	0.″03	Radio

the ecliptic (Standish 1981); secondly, the determination of the mean of a non-periodic quantity is poorly-defined; and, thirdly, the precession of the equator, from the mean weighted epoch of the observational data to J2000, was inaccurate due to the now-known error (-0.″3/century) in the value of the J2000 precession constant.

For the ephemerides, there is now a preferable reference frame. Table 1 shows that VLBI observations of spacecraft near to planets now exist at the milliarcsecond level. When used in conjunction with the spacecraft's orbit about the planet, these measurements refer the planet to the reference frame of the radio source catalogue. Of course, these observations are inconsistent with the optical observations, since the two corresponding reference frames are not coincident. However, since the VLBI measurements are so much more accurate than the optical ones, they tend to dominate the orientation of the ephemerides. To correctly use the two types of observations in the same adjustment, though, a frame-tie between the two frames should be introduced.

3. Ties Between Different Reference Frames

For an optimum adjustment of the ephemerides, all of the available observational data must be referenced onto the same reference frame. Consequently, the relations between the different reference frames must either be known or be determined as part of the adjustment process. Fortunately, enough progress has been made in this respect, so that the necessary relations now seem sufficiently well-determined. In particular, there have been determinations of the ties between the IERS radio catalogue and the dynamical reference frames (as represented by the JPL ephemerides), between the IERS catalogue and the FK5, and between the IERS catalogue and the Hipparcos reference frame. These frame-ties are discussed here.

3.1. PLANETARY EPHEMERIS - IERS FRAME-TIE

Folkner et al. (1994) have determined a tie between the IERS radio catalogue and the JPL planetary ephemerides by doing a joint analysis of VLBI and LLR observations. Basically, processing VLBI observations with the IERS catalogue determines a set of coordinates for the VLBI stations in the radio frame; similarly, processing the LLR data, using a given ephemeris, determines a set of coordinates for the LLR telescopes in the ephemeris frame. Since the two sets of coordinates don't involve the same stations, a geodetic survey between the two sets is used for the comparison. The differences in the comparison define the rotation matrix which produces optimum agreement; that rotation is the frame-tie, expressed by three differential angles about the x-, y-, and z- axes, respectively.

An alternative determination of the same frame-tie may be produced by processing the VLBI measurements listed in Table 1 and solving for the rotation of the ephemeris which gives the best fit to the data; again, the resultant rotation is the frame-tie.

Comparison of the two methods for DE200 shows agreement at the milliarcsecond level:

(-0.″002, -0.″012, -0.″006) [±0.″004] for the former method;
(-0.″002, -0.″003, -0.″002) [±0.″002] for the latter.

Importantly, DE200 is very close to the IERS reference frame, differing by only 0.″01; thus, the transformation from the DE200 reference frame onto that of the IERS will not represent a major change.

3.2. OPTICAL - RADIO SOURCE FRAME-TIES

A comparison by Ma et al. (1990), using 28 sources visible in both optical and radio wavelengths, provides a frame-tie between the FK5 and a radio source catalogue aligned using the adopted value of 3C 273. Their result,

(+0."030, +0."053, +0."023) [±0."020], is still being modified by later studies, now using 50 sources (Johnston 1994). A similar study is reported by Kumkova et al.(1994). The eventual uncertainty of these frame-ties, however, will probably not improve much below the quoted value of 0."020, owing to the inherent uncertainties of the FK5 itself.

Similarly, measurements of 11 radio stars with respect to both the Hipparcos reference frame and the IERS radio frame are enabling a frame-tie to be determined between those two (Lestrade et al., 1994). Kovalevsky (1994) mentions a similar effort by the Hipparcos Science Team. Zacharias et al. (1994) discuss the links of both optical systems to the radio source reference frame.

4. The Orientation of Future JPL Ephemerides

With VLBI measurements now relating the inner planet system to the radio reference frame, the present intention is to base future JPL ephemerides on that frame. This seems especially advantageous since the radio frames, the IERS frame itself or a similar one specified by the IAU, have stable orientations at the sub-milliarcsecond level.

The changing of the frame of the ephemerides onto that of the radio catalogue will involve modifications to the ephemeris adjustment process. However, these are relatively minor.

- Observations which are based upon reference frames other than that of the radio sources will have to be transformed before processing. The obvious examples are the optically-based observations, which form the major part of the observations of the Jovian planets.
- The equations of motion for the lunar librations are derived under the assumption that the reference frame is that of the dynamical ecliptic and equinox. The resultant formulation will require pre- and post-applications of the frame-tie rotation.
- The orientation of the earth, to which the LLR data is sensitive, should now be done in the IERS reference frame using the IERS formulation and earth orientation parameters. However, since the IERS determinations do not extend back to the time of the beginning of the LLR data (1969), the earth orientation will not be strictly homogeneous for the LLR data.

There are distinct advantages to changing the frame of the ephemerides onto that of the radio source catalogue.

- The VLBI measurements will orient the ephemeris frame with unprecedented accuracy.
- With the advent of CCD astrometry, the capability now exists of measuring the outer planets and/or their satellites along with the positions

of a number of QSO's (Stone and Dahn, 1994). Since positions of the QSO's are well-known in the radio catalogues, the whole CCD reduction process can be done in that frame.

- The reference frame will remain stable between different ephemerides at the milliarcsecond level; in the past, it was not unusual to see a difference of 0."04 between two ephemerides.
- The orientation of the earth will be done directly in the frame of the ephemerides themselves.
- If the VLBI observations eventually span a decade, they will begin to contribute to the determination of the inertial mean motions of the inner planet system.

5. Ephemeris Mean Motions

The possibility of determining mean motions with VLBI observations is significant. The accurate ranging measurements, especially those of the Mariner 9 orbiter (30 m, 1971-2) and of the Viking Lander (10 m, 1976-82), enabled the mean motions of Mars and the earth to be determined with unprecedented accuracy; however, the mean motions of the ephemerides do not remain accurately-known over extended periods of time. The uncertainties remain small only for times which are relatively near to the measurements themselves; away from those times, the accumulated effects of the perturbations of the asteroids begin to accumulate.

To account for the forces of asteroids affecting the ephemerides, the gravitational effects of Ceres, Pallas and Vesta are modeled directly: the orbits of these asteroids are approximated using mean keplerian orbits, and their forces upon the sun, moon, and planets are included directly in the equations of motion. Corrections to these three masses may be determined during the adjustment process.

For nearly 300 other asteroids, the following procedure is used: the density of each is assigned according to the taxonomic class (C, S, or M); the volume is computed from the estimated diameter; using the derived masses, the summed forces of the three taxonomic classes upon the Moon, Earth and Mars are computed for each day and stored upon a file; and the file is interpolated during the integrations. Corrections to the density of each taxonomic class may be determined during the adjustment process.

Even with such attempts to account for the asteroid perturbations, large uncertainties still exist. The mass of Ceres is uncertain at the 5-10% level; those for Pallas and Vesta, 10- 20%; for the rest, the masses may be as much as 100% uncertain, due to large uncertainties in the estimations of both the densities and the diameters. The net effect is that uncertainties in the mean motions of the earth and Mars (the best-known of all the planets) can grow to 0."01/century or more (Williams 1984).

6. Conclusions

The orientation of all of the planets in the solar system, done accurately with respect to the same, stable reference frame, will represent a major milestone in planetary ephemeris improvement. Many factors now make it advisable to pursue this goal: to base the future JPL ephemerides upon the radio source reference frame.

- The radio frame is accurate, stable, accessible and well-defined.
- Frame-ties between the radio frame and the previously-used reference frames now exist.
- Earth orientation is now done with respect to the IERS frame.
- VLBI observations of the inner planets with respect to the IERS frame have now being taken, so that the ephemeris may be automatically aligned onto that frame.
- CCD measurements of the outer planets and their satellites, in conjunction with measurements of QSO's, are now able to refer those positions onto the radio frame.

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