THE REFERENCE FRAME OF THE EPHEMERIDES

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ABSTRACT. Complete ephemerides of the moon and the four inner planets could be created solely from ranging data alone. Such ephemerides would then be independent from any outside astronomical reference system, and, therefore, would define their own unique reference frame. In fact, this is nearly the case with present-day ephemerides; the accuracy of the ranging data tends to dominate most of the least squares adjustment.

This paper outlines the process of creating the lunar and planetary ephemerides along with the orientation of the ephemerides onto the dynamical equinox. The resulting accuracies of these processes are given and a number of uses for the ephemerides are highlighted.

1. INTRODUCTION

Historically, the only observations of the moon and planets were optical positions. Essentially, these were differential measurements, be they from transit circles, zenith tubes, photographic plates, astrolabes, etc. The object's position is measured in relation to the positions of the stars in the background, and hence in relation to the relevant stellar catalogue. Any systematic errors in the positions and/or proper motions of the stellar catalogues were transmitted directly into the ephemerides.

It is now known how big some of these errors have been in the past. The most recent set of revisions to the IAU adopted set of astronomical constants contains corrections to positions and rates of about 1$''$.0 and 1$''$.0/cty, respectively. Optically-based ephemerides using the former system undoubtedly share errors of comparable size. Use of the more recent (1976) system of astronomical constants would provide only an order of magnitude improvement - still not satisfactory by present-day standards and requirements.

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In complete contrast, modern ephemerides of the four inner planets and the moon are determined almost entirely by the highly accurate ranging observations: radar echos from planetary surfaces, radio ranging to spacecraft transponders, laser ranging to the lunar reflectors. As a result, the relative positions, inertial motions, and even the orientation of the reference frame are all essentially independent of any other astronomical reference frame.

This paper discusses the creation of modern lunar and planetary ephemerides, describing how they are derived independently from any other astronomical reference frame and how their orientation in space is determined. The major uncertainties associated with the ephemerides are estimated, and some of the uses of the ephemerides are mentioned.

2. THE EPHEMERIS CREATION PROCESS

Modern day ephemerides for the moon and the inner four planets are determined almost entirely from just the ranging data to which they are fit. While optical observations of the planets are also included in the data set, their effect is significant only for the outer five planets. Even for these planets, other new data types are now being used with greater accuracy than that which can be provided by the optical data.

It is not difficult to visualize how the inter-body ranging can be used to determine relative positions and motions. Especially after a few years, during which the bodies have completed a number of orbits, the whole system can be determined with accuracies comparable to the observational ranging data.

What is not generally realized, on the other hand, is that the planetary motions with respect to inertial space are also determined from just the ranging data alone (see, e.g., Newhall et al., 1983, p.162; Standish, 1982, p.185). A given range measurement is invariant under rotation; the dynamical system, however, is not. Motion which is possible in inertial space is not possible in a rotating frame.

Since they are taken from the spinning earth, the lunar laser ranges are sensitive to the direction of the pole of the earth's rotation and, therefore, to the of-date celestial equator. Data over an extended period of time, then, will provide determinations of the earth's orientation (see, e.g., Dickey et al., 1985; Newhall et al., 1987). Furthermore, from the solar perturbations upon the lunar orbit, the ranges are sensitive to the of-date ecliptic. As a result, for successful data reduction, it is necessary that both the true equator and the true ecliptic be represented accurately in the ephemerides, at least over the time span of the lunar laser ranging data.

From ranging data alone, then, one can infer planetary and lunar positions and velocities, the locations of the celestial equator and ecliptic, and, consequently, the position of the dynamical equinox and the value of the true obliquity.

3. ORIENTATION OF THE EPHEMERIS FRAME

Most of the earlier JPL ephemerides have been oriented onto the equator and equinox of the (B1950.0) FK4 optical reference system. The ephemeris fits have included optical data which have served mainly to orient the ephemerides, i.e., determine the zero-point of right ascension. However, some of the ephemerides have been oriented onto the dynamical equator and equinox, since the locations of the equator and the ecliptic are known from the observational data to which the ephemerides are fit.

JPL Ephemerides DE102, DE119 and DE121 have been oriented onto the dynamical equinox of B1950.0; DE200 is oriented onto the equinox of J2000. The process of this orientation is described by Standish (1982) and is confirmed, using a different method, by Chapront-Touze and Chapront (1983). Future ephemerides with DE#'s greater then 200 (implying J2000.0) will be oriented similarly.

4. EPHEMERIS UNCERTAINTIES

The uncertainties in the masses of the asteroids, the possibility of determining them from planetary ranging, and their contributions to the uncertainties of the planetary motions are discussed by Williams (1984). From the present set of planetary data, it is possible to improve the mass determinations of only the asteroids, Ceres, Pallas and Vesta. The remaining uncertainties of these and of all of the other asteroid masses lead to an uncertainty in the mean motions of the inner planets of about 0".03/century.

The determination of the dynamical equator and equinox at the mean epoch of the lunar laser ranging data (now about 1977) has an accuracy below 0".01. However, the process of transforming the equinox to J2000 (via precession) introduces a further error due to the uncertainty in the value of precession, now about 0".1/cty. Certainly, within a very few years, this value will decrease with better determinations of precession coming from Lunar Laser Ranging (LLR) and Very Long Baseline Interferometry (VLBI).

Similarly, the longitude of the moon at epochs removed from the present is affected by the uncertainty in the value of the lunar tidal deceleration. Future LLR data will serve to improve this value.

The uncertainties associated with the preceding discussions are listed in Table I. In contrast to formal errors, the values given are intended to be realistic assessments.

Table I. The uncertainties associated with the main features of the ephemerides.

Quantity	Uncertainty	Major Cause
inertial motions (planetary)	0\".03/cty	asteroid masses
origin at E & E	0\".02	precession to J2000
lunar longitude	0\".5/cty**2	tidal deceleration

5. EPHEMERIS USES

5.1. Navigation

The primary function of the JPL Planetary Ephemeris Development Program is the support of spacecraft navigation. It was realized in the 1960's that the then-existing planetary and lunar ephemerides were not adequate for this purpose. The program at JPL is still continuing as the accuracy demanded by navigation continues to increase.

5.2. Lunar Laser Ranging

As implied by the earlier discussions, the lunar and planetary motions are tightly coupled. Accurate ephemerides of each are necessary for the computation of the other. Also, the orientation of the planetary system, as described above, is vitally dependent on the lunar observations. In fact, for the past decade, it has been necessary to handle the moon and planets simultaneously with respect both to the least-squares adjustments and to the numerical integrations.

5.3. Astronomical Reductions

There are a number of astronomical observations which are strongly affected by the motion of the earth. In order to extract data pertinent to the observed object, it is necessary to remove the signature of the earth's motion from the observation, often to a high degree of accuracy. For example, the observed timings of a millisecond pulsar yield information about the period, change of period, pulsar position and proper motion - only after the accurate removal of the earth's motion. Also, circumstances surrounding ancient eclipse observations rely heavily upon the earth's orientation (UT) and upon the moon's longitude (and hence, its tidal deceleration).

5.4. Relations Between Reference Frames

The ephemeris also enters into a number of the efforts to relate the different astronomical reference frames (for a discussion, see Dickey et al., 1987).

6. REFERENCES

Chapront-Touze,M. and Chapront,J.: 1983, Astron. Astrophys. 124, 50-62.

Dickey,J.O., Newhall,X X and Williams,J.G.: 1985, 'Earth Orientation from Lunar Laser Ranging and an Error Analysis of Polar Motion Services', J. Geophys. Res., 90, 9353-9362.

Dickey,J.O., Newhall,X X, Standish,E.M. and Williams,J.G.: 1987, 'Reference Frames: Determinations and Connections", this volume.

Newhall,X X, Standish,E.M. and Williams,J.G.: 1983, 'DE102: a numerically integrated ephemeris of the Moon and planets spanning forty-four centuries', Astron. Astrophys. 125, 150-167.

Newhall,X X, Williams,J.G. and Dickey,J.O.: 1987, 'Earth Rotation from Lunar Laser Ranging', this volume.

Standish,E.M.: 1982, 'The JPL Planetary Ephemerides', Cel. Mech. 26, 181-186.

Standish,E.M.: 1982, 'Orientation of the JPL Ephemerides, DE200/LE200, to the Dynamical Equinox of J2000', Astron. Astrophys. 114, 297-302.

Williams,J.G.: 1984, 'Determining Asteroid Masses from Perturbations on Mars', Icarus 57, 1-13.