ON THE REFERENCE FRAME OF THE PLANETARY EPHEMERIDES

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ABSTRACT. The planetary and lunar ephemerides have their own inherent reference frame which is one of the key frames to be considered in the unification of the many present day frames, both celestial and terrestrial. The use of this frame requires an understanding of its own accuracies, both internal(i.e., relative) and external(e.g., w.r.t. the FK4 system or w.r.t. the dynamical equinox). Such accuracies are discussed in this paper. Also noted are the expected improvements in the future which will be obtained from newer data types.

I. INTRODUCTION

Present-day astrometry is now experiencing a great increase in the number of observational techniques, objects being discovered and measured, and observational data types. Furthermore, the accuracy of the measurements has increased by orders of magnitudes. Along with all of this, there has arisen a number of different reference frames, both celestial and terrestial, against which these observations are being made. As often as not, these observations invoke a combination of reference frames in the reduction of the data. As such, there is a present need for the unification of the existing reference frames involving the process of relating each frame to the others. This problem is discussed in a recent paper by Williams et al.(1983). As evident from the titles of the papers in this present colloquium, there is a number of researchers who are now attempting to provide these necessary frame-ties.

One of the key elements in the question of reference frames is that of the planetary and lunar ephemerides, which have their own inherent reference frame. When using the ephemerides to establish a frame-tie, it is necessary to understand the features of the reference frame - its derivation and its expected accuracies. That is the purpose of the present paper.

This paper briefly describes the creation of the ephemerides,

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concentrating on the accuracy of the inner planetary system (Mercury through Mars, including the Moon), giving both the internal accuracies and also the accuracy of the orientation of the system to an external reference frame.

II. THE CREATION OF THE EPHEMERIDES

Almost twenty years ago, the Jet Propulsion Laboratory(JPL) initiated a program to develop planetary ephemerides of the highest possible accuracy by using all relevant observational data. The program still exists today at JPL, and the resultant ephemerides continue to be improved as newer and more accurate observational data become available.

The creation of planetary ephemerides involves a least-squares fitting process of a numerically-represented dynamical model to observations of the actual solar system. Different features of the model are determined with different accuracies according to the nature and accuracy of the different sets of observations. In the following, these different features are discussed separately with the data which is most important in their determination.

Accuracies are presented in this paper which are intended to be the most realistic accuracies that can be estimated. These are not to be confused with the formal accuracies which arise from the least-squares fitting process, which are almost always overly optimistic due to systematic errors in either the observational data or in the representation of the physical model.

A. The Relative Inner Planetary System

Distance measurements to the terrestrial planets provide the key elements of the inner planetary system. A more detailed discussion of this by J. G. Williams may be found in a paper by Newhall et al.(1983, Section VII-D). These data include the radar measurements and the Mariner 10 fly-by ranging to Mercury and Venus and the Mariner 9 Orbiter and Viking Lander ranging to Mars. These distance measurements along with the dynamical properties (equations of motion) are sufficient, by themselves, to determine both the relative inner planetary positions and also the motions with respect to inertial space. This is done without any reference or measurement of an object outside of the solar system. The inner planetary system may then be considered as being well-determined in two respects: 1) relative positions and motions and 2) overall rotation with respect to inertial space - strictly from ranging measurements alone.

It is often difficult to envision the second point. An analogy may be that an unaccelerated particle travels in a straight line with constant speed, only in an inertial frame. Similarly, an elliptical Keplerian orbit does not rotate in inertial space. In the real case, the planetary orbits are nearly Keplerian; the perturbations are small; only the errors in computing these perturbations are what lead to the uncertainties of the motions with respect to inertial space.

Table I presents realistic accuracies for the inner planets at the time of the mean epoch of the observational data (about 1975).

	Relative Longitude w.r.t. Earth	Orbital Plane w.r.t. Ecliptic	Inertial Mean Motion
Mercury	0".010	0".030	0".14/cty
Venus	003	010	06
Earth	-	-	03
Mars	003	003	03

TABLE I. Realistic accuracies of the relative inner planetary system.

The numbers for Mercury and Venus are dominated in the most part by uncertainties in the planet's topography which affects the radar measurements from the surface. Those for the Earth and Mars could, in principle, be greatly smaller since the observational data has higher accuracy (50 meters ~ 0".00007 for Mariner 9; 10 meters ~ 0".00001 for Viking). However, Mars is affected by the uncertainties in the masses of the outer planets and the asteroids. The size of these uncertainties is discussed and estimated by Williams(1983).

B. The Lunar Ephemeris

The lunar ephemeris is fit to the lunar laser ranging data, covering the time span starting in 1969 and continuing at present. The creation of the lunar ephemeris is discussed by Newhall et al.(1983) and by Dickey et al.(1983). Realistic accuracies for the lunar orbit in 1975 are about 0".005 for the relative longitude and the relative plane. However, the longitude has a quadratic (in time) uncertainty of about 0".65/cty , arising from the tidal acceleration. As is seen, the lunar ranging data ties the lunar ephemeris to that of the inner planets.

C. Orientation to the Celestial Equator

The lunar observations are made from stations which are located on the rotating earth. As such, these observations are sensitive to the instantaneous pole of the earth and therefore to the equator of date. Also, the motion of the moon is directly affected by the solar perturbations and therefore is sensitive to the instantaneous ecliptic. Thus, both the equatorial and the ecliptic planes are determined from the lunar data which provides the orientation of the

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inner planetary system to the equator of date. From this, one may also determine the obliquity of the ecliptic, the accuracy being about 0".01.

D. The Location of the Equinox

In order to adjust the inner system to an outside reference frame, one must determine the zero-point in right ascension; i.e., the location of the equinox.

1) The Equinox of the FK4. The Sun and the planets have been observed optically with respect to reference stars whose positions are based on the fundamental stellar reference system, the FK4. The data include the meridian circle observations of the U.S.Naval Observatory from 1911 to 1976. These positions have been modified to account for the systematic errors due to precession and equinox drift (Fricke, 1982), applied with respect to the epoch of 1950. The fitting of the planetary system to these observations serves to orient the system to the 1950 equinox of the FK4. It is felt that the uncertainty of the location of the 1950 FK4 equinox for the inner planetary system is on the order of about 0".05.

2) The Dynamical Equinox of 1975. Since the x-y plane of the planetary ephemerides represents the equatorial plane and since the motion of the earth-moon system is inherent in the ephemeris, the dynamical equinox is implicit in the ephemerides themselves. It is then possible to compute the location of this point at any time by removing the periodic terms from the ecliptic's motion and by solving for the location of the remaining motion. This was done independently by Standish(1982) and by Chapront-Touze and Chapront(1983) using different methods. The results agreed to an accuracy less than 0".0002. Thus one could, if so desired, orient the planetary system to its own dynamical equinox to an accuracy of at least 0".001. This has not been done for the JPL ephemerides, however, which, as stated, are based on the 1950 FK4 equinox.

Since the ephemerides are based on the 1950 FK4 equinox and since one may directly compute the dynamical equinox, it is possible to determine the 1950 equinox offset of the FK4. The result of this process has led to a value of 0".531 which compares with the value determined by Fricke(1982) of 0".525. This surprisingly close agreement must be considered to be coincidental, however, since neither method can be expected to have an accuracy better than about 0".05.

E. Transformation to the Equator and Equinox of J2000.

There remains the process of transforming the ephemerides, oriented well in 1975, to the reference frame of J2000. This is done in two steps: 1) rotate on the z-axis onto the dynamical equinox of date and 2) apply precession up to J2000. The result should then provide the ephemerides in the J2000 system, orientated to the dynamical equinox of that epoch. The major uncertainty of this process is that due to the uncertainty in the value of precession, about 0".15/cty at present, which amounts to about 0".04 from 1975 to 2000. This affects the right ascensions almost directly (0".04 cos ϵ) and the declinations by about 0".016 (0".04 sin ϵ).

The accuracy of this process will improve in the near future as the value of precession improves and as the mean epoch of the observational data approaches the year 2000. In fact, lunar laser ranging is expected to reduce the error in precession from 0".15/cty at present to 0".10/cty by 1987 and to 0".06/cty by 1990 (see Dickey et al., 1983). Similar improvement will be forthcoming from the work done with the VLBI observations.

III. THE ACCURACY OF THE EPHEMERIDES

The preceeding section discussed how the inner planetary system is oriented with respect to the dynamical equinox. One may then present a table which gives accuracies of the coordinates of the inner planets. Table II gives two such lists: the first is the accuracy of the inner planets covering the years 1960-2000 with respect to the actual dynamical equinox of 1975(the mean epoch of the modern observations); the second list gives the same quantities, but with respect to the dynamical equinox of the year 2000.

	1975 EQUINOX		2000 EQUINOX	
	σ_α	σ_δ	σ_α	σ_δ
Mercury	0".04	0".03	0".06	0".04
Venus	03	02	04	02
Earth	03	01	04	02
Mars	03	01	04	02

TABLE II. Accuracies of the inner planets with respect to the dynamical equinoxes, covering the years 1960-2000.

IV. OUTER PLANETS

The outer planets are tied only weakly to the inner planetary system. With the exception of the Pioneer and Voyager range points to Jupiter, the only data that exists for the outer planets are optical observations. The classical data are the transit observations; more recent are astrometric observations of the planets' satellites against a stellar field. In either case, however, all of the errors associated with the stellar catalogues affect these observations directly. As such, the positional errors for the outer planets are much larger than those for the inner ones - 0".2 for Jupiter increasing to at least 1".0 for Pluto. In addition, there is still the question of the unexplained residuals which remain, for Uranus and Neptune, especially. The source of these could be unknown systematic errors in the optical observations, of which there certainly are some; the source also could be unmodeled mass in the outer regions of the solar system. In any case, the outer planetary ephemerides are certainly not of the quality of the inner ones.

V. FUTURE DATA

In the future there will be certainly more data of the type which has been discussed here and which has been used in fitting the ephemerides. Also, there are a number of newer data types which promise to be of great benefit in the continued improvement of the ephemerides. Some of these will be mentioned here.

A. Spacecraft Tracking Files. With present-day techniques and computer capacities, it is possible to include a virtually unlimited number of parameters in a least squares solution. Therefore, it is planned in the near future to include the spacecraft tracking files from the Pioneer and Voyager mission fly-bys of Jupiter and Saturn into the general ephemeris fit. This will enable a simultaneous solution for all common parameters between the separate missions as well as those in common with the other planetary observations. This will be an improvement over the previous method of simply providing "normal points" separately for each mission. Preliminary analysis of this project indicates that the associated planets will be tied to the inner system with at least twice the accuracy of before.

B. Millisecond Pulsar Timings. With the discovery of millisecond pulsars, a new observational data type is now envisioned which will improve even further, the inertial mean motion of the earth and, therefore, of the whole inner system. The seemingly constant and stable characteristics of these pulsars will allow one to use these as types of celestial clocks, against which one can measure doppler-like signals. With the proable discovery of more of these objects in the future and with loctions in various parts of the sky, the ephemerides of the inner system could attain the accuracy of 0"01 within the next decade.

C. VLBI Measurements. There have already been some measurements of the Galilean satellites of Jupiter with respect to members of the radio source catalogs. As the accuracy of these measurements increases, an ephemeris-catalog tie will be provided directly.

D. Space Telescope and Hipparcos. Data from these missions will provide highly accurate stellar catalogues, a tie between the stellar catalogues and the radio source catalogues, and observations of planetary satellites with respect to the background objects. All of this will serve to improve the optical planetary observations as well as to tie the planetary system to these other catalogues.

VI. CONCLUSIONS

The accuracy of the inner planetary system is now well below the level of 0".1; not only in the relative sense, but also with respect to external reference frames as well. In the near future, the level will approach 0".01. It is further expected that the outer planet ephemerides will also show continued improvement with the addition of newer data types. Jupiter and Saturn will show accuracies of less than 0".1; the others will approach this number within the next ten years or so.

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Discussion:

MORRISON: You said that you were surprised that your solution for the equinox position came close to Fricke's, but are you not using essentially the same data?

STANDISH: Fricke used many other data, including, for example, lunar occultations. I don't see that I can orient the FK4 better than 0".05.

MORRISON: So, your fit is essentially to a subset of Fricke's data?

STANDISH: Yes, a small subset.

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