CELESTIAL REFERENCE FRAMES : DEFINITIONS AND ACCURACIES

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ABSTRACT. The determination of a specific catalogue or ephemeris reference frame is a highly over-determined problem, depending on the particular selection of which coordinates, which objects and at what time(s) the determination is made. The consistency which various determinations exhibit is dependent upon the accuracy of the catalogue or ephemeris itself. This paper discusses the accuracies of the three most prominent celestial reference frames: stellar catalogues, the lunar and planetary ephemerides and the radio source catalogues.

The FK4 stellar catalogue contains known systematic errors amounting to a few tenths of an arcsecond; the FK5 will yield nearly an order of magnitude improvement; HIPPARCOS and Space Telescope expect 0".002 by the mid 1990's; optical interferometry should approach 0".01 within a couple of years, tens of micro(!)arcseconds after a couple of decades. Present-day lunar and planetary ephemerides have accuracies at the level of 0".01 for the moon and inner four planets; 0".1 for the outer planets. Further observational data will permit continued improvement. Radio source catalogues now show internal consistency of 0".001.

I. INTRODUCTION

A given celestial catalogue does not explicitly define its own reference frame. Neither does a given set of lunar and planetary ephemerides. The reference frame of a given catalogue is only implied by the actual coordinates of the catalogue. In general, only three independent coordinates at one specific instant of time are necessary and sufficient for defining a frame uniquely. However, when speaking of a reference frame for a catalogue, one envisions some global set of general coordinates, applied over an extended interval of time.

Any actual attempt to determine the orientation of a reference frame for a full catalogue automatically invokes a specific set of weighted coordinates over a specific set of time points. On the other

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hand, during a subsequent application of such a determined orientation, a different weighted selection of coordinates is used. The two sets may not be consistent. That depends upon the accuracy of the catalogue or ephemeris.

Section II presents the known systematic corrections for the FK4 stellar catalogue, estimates the uncertainties expected for the FK5 and mentions the accuracies expected from future improvements to the stellar reference catalogues. Section III gives realistic estimates of errors in modern lunar and planetary ephemerides along with a comparison of two relatively recent, but independently created, ephemerides. Section IV gives accuracies of radio source catalogues, derived from inter-catalogue comparisons.

II. THE FUNDAMENTAL STELLAR CATALOGUES, FK4 AND FK5

The fundamental stellar catalogue, the FK4 (Fricke and Kopff, 1963) has known systematic errors which have been estimated by Fricke and his colleagues at Heidelberg. These may be categorized as global errors, zonal errors and individual errors, both in the listed 1950 positions and in the listed proper motions. Application of these corrections, along with the incorporation of additional observational data, have been used to produce the FK5.

The global systematic corrections to the FK4 are Δp, a correction to Newcomb's value of the general precession in longitude; D, an offset to the declination system; E, the equinox offset at 1950 and $\dot{E}$, the equinox drift. Table I gives numerical values for these

Table I. Known corrections to and estimated uncertainties of the fundamental stellar catalogue, FK4.

Equinox Offset at 1950	E	= $0''.525 \pm 0''.045$
Equator Orientation	D	= $0''.00 \pm 0''.02$
Equinox Drift	$\dot{E}$	= $(1''.275 \pm 0''.150)$/cty
1976 Precession Correction	Δp	= $(1''.10 \pm 0''.15)$/cty
[VLBI Precession Correction]	Δp	= $(0''.94 \pm 0''.08)$/cty
Zonal uncertainties		$\pm 0''.3$, $\pm 0''.3$/cty
Individual uncertainties		= 2-3 X Zonal uncertainties

Application of Known Corrections to FK4/5-Based Optical Observations

astrometric : $\Delta\alpha = E + [\dot{E} - \Delta p_\alpha]\,T$; $\Delta\delta = D + [-\Delta p_\delta]\,T$

apparent : $\Delta\alpha = E + [\dot{E}]\,T$; $\Delta\delta = D$

$[\Delta p_\alpha = \Delta p\,(\cos\epsilon + \sin\epsilon \sin\alpha \tan\delta),\ \Delta p_\delta = \Delta p\,(\sin\epsilon \cos\alpha)]$

corrections along with their uncertainties. Included are also uncertainty estimates for the zonal and individual errors. It is seen that, in general, one may expect a few tenths of an arcsecond uncertainty in the FK4.

Subsequent determinations of the precession value from VLBI and from lunar laser-ranging have indicated that Fricke's correction is about 10-15% too high, implying that there is already a known systematic error in that catalogue.

Table I also shows how the known errors enter differently into both astrometric and apparent positions: different types of observations require different corrections when they are compared or reduced to the new J2000 system.

By the mid-1990's, observations from the HIPPARCOS astrometric satellite are expected to give another order of magnitude increase in accuracy, producing uncertainties as low as a few milli-arcseconds in relative positions and a few milli-arcseconds per year in relative proper motions. Space telescope is expected to reach fainter objects, allowing frame orientations using a number of sources available in the radio source catalogue. However, the establishment of inertial proper motions must unfortunately await a future second set of such astrometric missions. Within the next year or so, modest optical interferometers may produce positions of the brighter stars at the level of 0.″01 (see Johnston et al., 1987), an accuracy which may eventually reach a few micro-arcseconds by the turn of the century (see, e.g., Boyce and Reasenberg, 1984).

III. LUNAR AND PLANETARY EPHEMERIDES

Modern ephemerides of the moon and inner planets are determined primarily by the accurate ranging measurements to which they are adjusted. It has been shown elsewhere (Newhall et al., 1983; Standish, 1982a) not only how the relative positions and motions of these bodies are determined by ranging, but also how the ranging determines their mean motion with respect to inertial space. Furthermore, if desired, the orientation of the system can be adjusted to the dynamical equator and equinox of date, from only ranging measurements alone (see Standish, 1982b).

For purposes of comparing an ephemeris with a celestial catalogue, it is desirable to estimate the uncertainties in geocentric coordinates, namely, right ascension and declination, even though these are not the most accurately determined parameters of the ephemerides. The main strength lies in relative positions and motions. Table II, however, shows that even when expressed in right ascension and declination, modern lunar and planetary positions have achieved a remarkable degree of accuracy.

Table II. Estimated realistic uncertainties for present-day ephemerides: geocentric coordinates given with respect to the dynamical equinox. The table is valid over a two-decade time-span surrounding the mean epoch of the lunar-laser ranging data (~1978).

	Dist	R.A.	Dec.	Mean Motion
Moon	2 m	0″.005	0″.002	[0″.5/cty**2]
Sun	200 m	0″.005	0″.002	0″.01/cty
Mars	50	0″.005	0″.002	0″.01/cty
Venus	100	0″.005	0″.01	0″.06/cty
Mercury	100	0″.02	0″.03	0″.14/cty
Jupiter	100 km	0″.1	0″.1	0″.2/cty
Saturn	500	0″.1	0″.1	0″.5/cty
Uranus	1000	0″.2	0″.2	1"/cty
Neptune	10000	0″.2	0″.2	1"/cty
Pluto	30000	0″.5	0″.5	2"/cty

The lunar laser-ranging data is sensitive to both the of-date equator (station locations) and to the ecliptic (solar perturbations). With these data now covering nearly the full 18.6-year period of the precession of the node, the alignment of the equator to the ecliptic approaches an accuracy of 0″.001. However, a constant offset in longitude introduces uncertainties of 0″.005 and 0″.002 in right ascension and declination, respectively. Mars is determined relative to the earth-sun system by means of the accurate spacecraft ranging; Venus and Mercury less accurately by radar ranges. As described by Williams (1982), the planetary mean motions are affected most by uncertainties in the masses of many asteroids. The error of 0″.01/cty applies only to the mean epoch of the accurate ranging data (~1978); it will grow to about 0″.03/cty for epochs about a decade before or after this date. For epochs remote from present, the uncertainty of the lunar tidal deceleration in longitude produces an error for the moon which is quadratic in time. New data types for the outer planets are rapidly improving these bodies' ephemerides, now approaching the level of 0″.1 or so throughout the present two decades.

The estimates of ephemeris errors in Table II can in some way be substantiated by comparing two different ephemerides, especially if these have been created independently. This is possible using the Center for Astrophysics' PEP740, created in 1983 and the Jet Propulsion Laboratory's DE118, created in 1981. With respect to the values quoted in Table II, both of these ephemerides may be considered somewhat obsolete because of the data to which they are adjusted: we now have the full span of the Viking Lander ranging data, additional radar-ranging, newer data types for the outer planets, nearly 18.6 years of lunar laser-ranging, improved modeling of the asteroid perturbations and improved values for the outer planet masses.

Table III. Geocentric comparison of the CfA ephemeris, PEP740, vs. the JPL ephemeris, DE118, over the time-span, 1969-1983. Comparison is made after the rotation, R_x(-0".0017) R_y(-0".0058) R_z(+0".4648), was applied to the CfA ephemeris. The planetary coordinates were fit with a linear function, the lunar ones with a quadratic. Only significant terms are shown. The rate terms are centennial.

Body	Distance [km]			Right Ascension			Declination		
	const	rate	s.d.	const	rate	s.d.	const	rate	s.d.
Moon	-.0005	-	.0003	-0".0014	0".016	0".0005	-	-	0".0016
				-0".4364/cty**2					
Sun	-	-	.05	-	-0".005	0".0002	-	-	0".0001
Mar	-	-	.27	-0".0006	-0".008	0".0009	-	-0".010	0".002
Mer	-.27	-	.57	-	-	0".0021	-	-	0".006
Ven	-	-	.66	-	-	0".0025	-	-	0".005

Table III shows the result of comparing the two ephemerides in distance, right ascension and declination, after the application of a three-axis rotation to the PEP740 position vectors. This was determined by a least squares fit over the time interval of the comparison, 1969-1983, using the geocentric solar coordinates only. The rotation, given in the table, shows less than a 0".01 adjustment to the equator/ecliptic orientation (x- and y- rotations), but a substantial alignment necessary for the zero-point of right ascension: DE118 was aligned to the FK4 equinox through the incorporation of optical data; no specific alignment was attempted for PEP740.

The resulting ephemeris coordinate differences from the comparison were fit with linear functions in time (quadratic for the moon) and are given in the table. The slight mean motion differences for Mars and the sun are consistent with the uncertainties estimated in Table II. The quadratic term for the lunar motion demonstrates the uncertainty of the tidal deceleration. Comparisons for the outer planets show an order of magnitude greater error than what is now expected.

IV. RADIO SOURCE CATALOGUES

The relative positions of nearly 100 radio sources have now been determined with an accuracy of a milliarcsecond or less (Ma and

Shaffer, 1987). Even a comparison of relatively older catalogues has shown agreement to the level of 0".002, after an orientation adjustment had been performed (Ma, 1986; Sovers and Treuhaft, 1987). These catalogues are essentially absolute in declination at the epoch of observation; they inherit any precession error when transformed to a different epoch. Also, since no absolute right ascension information is present in the measurements, it has been the practice to adopt a somewhat artificial definition for the right ascension orientation. For this, the optically determined position of the source 3C273B (Hazard et al., 1971) has been transformed into the J2000 reference system and then adopted as a defining value.

For absolute positions aligned onto the equator and equinox of J2000, then, one expects an error of $\Delta p \sin\epsilon \cos\alpha\, T$ = 0".003 cos or so in declination, where the present uncertainty in precession is taken as 0".05/cty and the time, T is 0.15 centuries. The right ascension uncertainty is dominated by the expected error of about 0".2 in the position of 3C273B. It is argued by Ma and Shaffer (1987) that future catalogues could well abandon such an artificial orientation: 1) the main strength of the VLBI observations lies in relative angular separations, now well below the milliarcsecond level; 2) radio sources are assumed to have no proper motion and therefore could be expressed by time-invariant positions; and 3) a global alignment could be used which does not depend upon observations of a single source (3C273B shows time-dependent source structure).

V. CONCLUSIONS

The stellar reference system presently shows uncertainties up to nearly a tenth of an arcsecond. However, the future shows promise of dramatic increases in accuracy. Similarly, the lunar and planetary ephemerides continue to be improved, now below the level of 0".01. Radio source catalogues have internal consistencies of 0".001 or less; their orientations, however, are less certain.

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