NEW CELESTIAL REFERENCE SYSTEM

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Abstract

The IAU (1976) System of Astronomical Constants, the FK5 and new lunar and planetary theories are being introduced in 1984. The investigation and planning for the transition has revealed the complex interdependencies between observational techniques and the reference systems, and their strong link to the rotating and orbiting Earth. The inaccuracies in our knowledge of the star positions, astronomical constants and the rotation and motion of the Earth are embedded in subtle ways in the observations and the reference coordinate systems. For example, the FK4 reference system in 1950.0 coordinates rotates with respect to an inertial system. Details are given for the conversion to the new system.

The concepts for a future reference system are developed, based on separating the real motions involved such that observations from various moving platforms can be related to the appropriate coordinate system, without involving motions which are not intrinsically involved in the observations. Therefore, reference systems determined or utilized in space, while affected by aberration and parallax, would logically be defined with no dependence on precession, nutation, polar motion, or Universal Time, which are all concerned with motions of the Earth's surface.

I. INTRODUCTION

The recommendations adopted by the 1976 IAU General Assembly included the following changes to the fundamental reference system: (1) a revised value for the constant of precession; (2) a new standard epoch, designated J2000.0; (3) the use of the Julian century as the unit of time for precession and proper motion; (4) a new stellar reference frame, the FK5, to correspond as closely as possible to the dynamical reference

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frame as determined from relevant modern observations; (5) an amended expression for Greenwich mean sidereal time, based on the equinox correction adopted for the FK5; (6) a new procedure for the computation of stellar aberration, together with the removal of the E-terms from the mean places of stars; (7) a new theory and reference pole for nutation; and (8) new definitions of time scales to be used with dynamical theories and ephemerides.

At the IAU General Assembly of 1979 in Montreal, the IAU (1979) Theory of Nutation was adopted. While the advisability of the details of this resolution are still being discussed, it is certain that a change will be introduced both for the series coefficients and for the reference pole. Also at the 1979 IAU General Assembly, the principle that the FK5 reference frame correspond as closely as possible to the dynamical reference frame was reiterated and the form of the correction was adopted. Subsequently, Fricke (1980) has recommended the following correction to the right ascensions of the FK4 stars:

$$E(T) = 0\overset{s}{.}035 \pm 0\overset{s}{.}003 + (0\overset{s}{.}085 \pm 0\overset{s}{.}010)(T-19.50).$$

These corrections to the present reference coordinate system are important improvements necessary to satisfy the observational data (Fricke (1975)). However, as the implementation of these changes is considered, the problems of the past, which have become embedded in the present reference system, become apparent. Therefore, some of the complexities involved in these changes will be discussed in detail and some suggestions for consideration for future reference systems will be presented.

II. TRANSITION: FK4 TO FK5, 1950.0 TO 2000.0

A. Equinox Correction

A critical element of the new reference frame is the location of the equator and equinox. In order to specify the location of the equinox, it is first necessary to define the equinox. The origin of right ascension of a star catalog reference system is designated as the catalog equinox. The dynamical equinox is usually defined as the intersection of the mean ecliptic plane and celestial equator, but this definition is not adequately precise. Specifically, the dynamical equinox is defined as the average location of the ascending node of the Earth's moving mean orbit on the equator. This is different by about 0".1 from the average location of the assending node of the Earth's instantaneous orbit on the equator, because in this case the Earth's velocity also has a component due to the motion of the mean orbital plane.

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The correction to the FK4 equinox (E(T)) and its time derivative (called the "motion of the equinox") represent an offset of the origin of right ascensions of the FK4 catalog from the dynamical equinox, and the offset is increasing with time (see Figure 3). The recommended value of E(T) is valid for stars of magnitude 4.9, approximately the mean magnitude of the FK4. Since there is a detectable magnitude dependent systematic error in the FK4 right ascensions, the brightest and faintest star in the FK4 will receive corrections which average about $\pm\ 0\overset{s}{.}005$ from the recommended value of E.

Since the correction E will be added to the right ascensions of all the stars in the FK4, the FK5 right ascensions of the local meridian for any observer for any instant (i.e., the local sidereal time (LST)) will also be increased by the value of E. Since the Greenwich Sidereal Time (GST) is equal to the LST plus the longitude λ (west positive), either the GST or λ must change. Since it is undesirable to have a time-dependent correction to the observer's longitude, the choice is to introduce the change in the GST.

When the nutation in right ascension is removed from GST, we have the Greenwich Mean Sidereal Time which is directly related to the Universal Time scale (UT1) by a formula. Since GMST is to increase by the amount E, either UT1 or the formula must change. Rather than introduce a discontinuity of the size of E in UT1, the equation is changed to:

$$\text{GMST of } 0^h\text{UT1} = 6^h41^m50\overset{s}{.}5484 + 8640184\overset{s}{.}8129T_u + 0\overset{s}{.}0931T_u{}^2$$

where T_u is measured in Julian centuries from J2000.0 (JD 2451545.0).

There will be small discontinuities and periodic variations in the measured value of UT1 due to systematic differences between FK4 and FK5 star positions and due to the new theory of nutation. The small periodic changes in UT1 can be calculated retroactively, so new tables of Δ UT1 = UT1-UTC can be prepared based on the FK5.

Since the revised formula defines the "fictitious mean Sun," another possible consequence of the equinox correction is an increase in the difference between the fictitious mean Sun and the true Sun (projected onto the equator). The ephemeris of the Sun is being corrected based on observational data, so the formula for the mean longitude of the true Sun will change somewhat. In any case, the change due to the equinox correction is small compared to the other differences between the fictitious mean Sun and the true Sun.

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B. Other differences between FK5 and FK4 reference systems

1. Precession Constant

The new value of the general precession in longitude (a correction at B1900.0 of +1$''$10 per century to Newcomb's value of luni-solar precession and -0$''$029 per century to planetary precession (Lieske, et al (1977)) will be used with the FK5, while Newcomb's value was used with the FK4. Considering now only the change in the constant of precession and not the equinox correction, in both right ascension and declination the mean and apparent places of the stars and their centennial variations are not affected by the change in the constant of precession, because the precession correction is compensated for by corrections to the proper motions. For this reason also, the new value of the precession constant should be used with the FK5 catalog, but not with the FK4 and prior star catalogs.

The primary impact of the change in the constant of precession will be for the motions of solar system objects, where the equivalent of a correction to proper motions of the stars is a correction to the sidereal mean motions and to the rates of the mean longitudes of nodes and pericenters.

2. E-Terms of Aberration

The E-terms of aberration, or elliptical terms, have a maximum amplitude of 0$''$34 and were embedded in the mean places of stars to simplify the computation of aberration corrections. With the use of computers and the interest in improving accuracies, the separation of E-terms is a source of confusion, complication, and inaccuracy, so they are being removed from the mean places of epoch J2000.0. The calculation of apparent places of stars should now be based on stellar aberration computed rigorously from the Earth's velocity vector with respect to the solar system barycenter. There should be no impact from this change as long as all mean places or astrometric positions in the FK4 system are converted to FK5 mean places or astrometric positions without E-terms, and algorithms for the computation of stellar aberration do not remove the E-terms. The E-terms at epoch B1950.0 in the sense of FK5-FK4 are of the form:

$$\Delta\alpha = +\ 0''341 \sin(\alpha + 11^h15^m) \sec\delta$$

$$\Delta\delta = +\ 0''341 \cos(\alpha + 11^h15^m) \sin\delta + 0''029 \cos\delta$$

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3. New Standard Epoch and Julian Century

The conversion from tropical to Julian units of time in the FK5 means that precession, proper motion, and centennial variations will be given per Julian century of 36525 days instead of per tropical century of 36524.2198781 days. The new standard epoch is J2000.0 which is 2000 January 1.5 (TDB) = JD 2451545.0. On this system, J1950.0 is 1950 January 1.0 = JD 2433282.5, whereas the old standard epoch designated 1950.0, (now denoted by B1950.0) was 1950 January $0^{d}.923$ = JD 2433282.42345905.

The computational convenience of the new system is obvious, but algorithms for the computation of local apparent places must be adjusted to the new epoch and unit of time. If done correctly, this change will have no significant effect on the apparent hour angles or declinations of stars.

4. FK5-FK4 Systematic Differences

The systematic differences between the FK5 and FK4 represent distortions of the FK4 system in position and proper motion, to the extent that they are known. These are expected to be less than $0''.2$, except in parts of the southern sky, where observational data for both the FK4 and FK5 are sparse. Because the differences are systematic, they will not cancel out in comparisons between theory and observations and they will result in changes of astronomical measurements, for example UT1, that previously used the FK4 system.

5. Nutation

The new theory of nutation will cause periodic variations in the computation of apparent places, the largest of which have amplitudes of $0''.045$ in longitude and $0''.007$ in obliquity with a period of 18.6 years, and $0''.042$ in longitude and $0''.020$ in obliquity with a period of 183 days. These changes will affect the comparison of theory with observations and the determinations of UT1, so new tables of UT1-UTC will be required. In a similar way, determination of the Earth's polar motion will be affected.

The new theory of nutation incorporates a new reference pole called the Celestial Ephemeris Pole (CEP). This reference pole has no diurnal motion with respect to a space-fixed coordinate system or an Earth-fixed coordinate system and it is the center of the quasi-circular diurnal paths of the stars in the sky. This means that the new nutation theory implicitly includes the dynamical variation of latitude. Therefore, separate corrections for this effect should not be used with the new theory. This change will not affect complete reductions of observations, but will remove a diurnal variation that was left when observations were reduced using nutation only.

6. Relativistic Light-Bending

The relativistic bending of light rays in the Sun's gravitational field can reach 1".8 at the solar limb and decreases almost linearly with angular distance from the Sun. Anywhere within 120° of the Sun the deflection is greater than 0".002. The magnitude of the deflection (θ) which is radially away from the Sun's center is:

$$\theta = k\left(\frac{1+\cos D}{\sin D} + \frac{1}{4} \sin 2D\right)$$

where D is the angular distance from the Sun and k = 1.9742 x 10^{-8} radians = 0".0040720 is the deflection at D = 90° (Brandt (1974), Wade (1976)). This correction is valid for the stars and outer planets. For the inner planets a more complex expression is required to rigorously represent the various possibilities.

C. Effective Coordinate Systems

The various corrections mean that there are different effective coordinate systems currently in use and different relations between these systems and the FK5 reference system. There are four distinct effective coordinate systems, two are identified with the FK4. The changes from the FK4 to the FK5 are designed to eliminate, as far as current knowledge permits, the difference between these systems. However, time and improved observational accuracy will eventually again reveal the four separate systems.

1. The effective apparent FK4 coordinate system (figure 1) is developed from observations of apparent places of stars and planets. Observed positions, other than photographic, are usually apparent places. To convert these to the FK5, add the systematic differences FK5-FK4, the correction to the zero point of right ascension (E), and the light-bending effect. No correction for E-terms of aberration, precession, nutation, or the epoch change should be made. In Figure 1, the moving true origin of right ascension fails to maintain a constant distance from the moving dynamical equinox by the amount of the "motion of the Equinox," which is actually the motion of the origin of right ascension. In principle, the motions of all three defining planes are independent.

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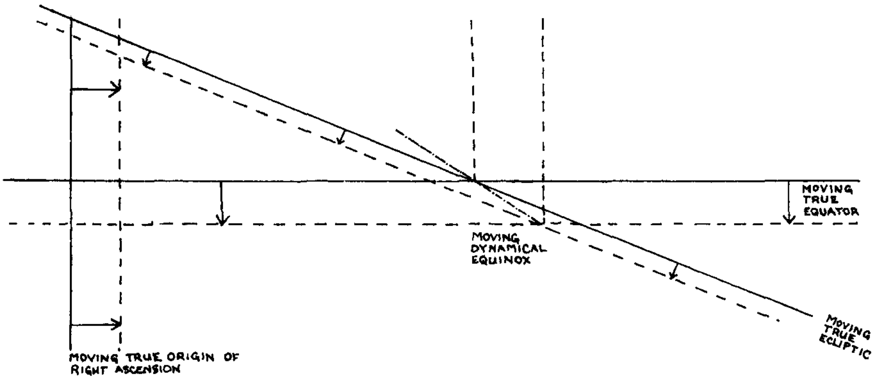

Fig. 1- Effective Apparent System

2. The effective astrometric FK4 coordinate system (Figure 2) is ordinarily referred to the mean equator and equinox of B1950, and is the system defined by star catalogs, such as the FK4 itself. Astrometric positions of solar system objects are computed to be immediately comparable with star positions. To convert these to the FK5, add the systematic differences and zero point corrections, remove the E-terms, change the precession constant (which changes the proper motions of the stars), and change to epoch J2000. No correction for the change in nutation or light-bending is ordinarily required. In Figure 2, the correction of -0$''$.03 per century to planetary precession implies that the B1950 mean ecliptic has a slight residual motion; the correction of +1$''$.10/cy to luni-solar precession implies a residual motion of the B1950 mean equator; and the resultant residual motion of the B1950 mean dynamical equinox is almost compensated for in right ascension by the residual motion of the "equinox" (B1950 mean origin of right ascension).

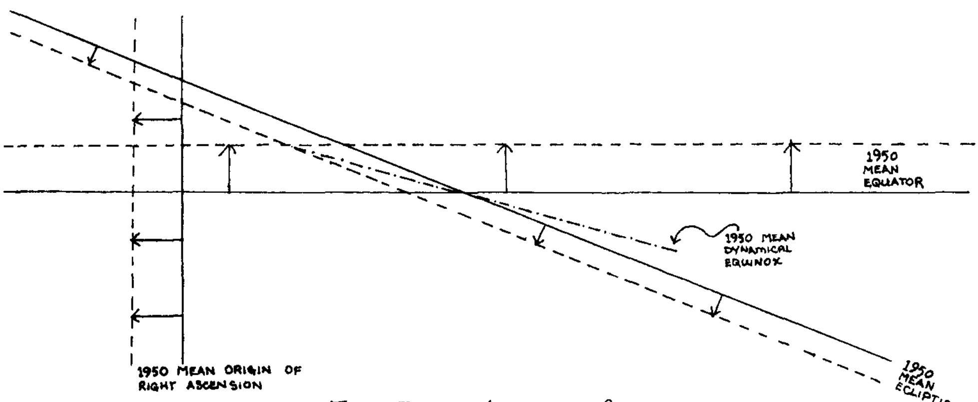

Fig. 2- Effective Astrometric System

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3. A non-rotating coordinate system is defined by the numerical integration of equations of motion of solar system bodies. An equivalent non-rotating coordinate system is defined by distant objects which are considered to have negligible proper motions (Figure 3). This system is usually referred to the epoch B1950 and an equatorial coordinate system. It differs from the effective astrometric FK4 system by the E-terms of aberration and the systematic errors of the FK4; but in addition, it differs because its mean equator, ecliptic, and origin of right ascension are fixed, whereas those in the astrometric system are moving. Because of these motions, each of these three reference planes will coincide with the corresponding plane in the inertial frame at a certain epoch. In principle, therefore, one must specify the three epochs of coincidence of the reference planes to completely define the relationships between the inertial and astrometric systems.

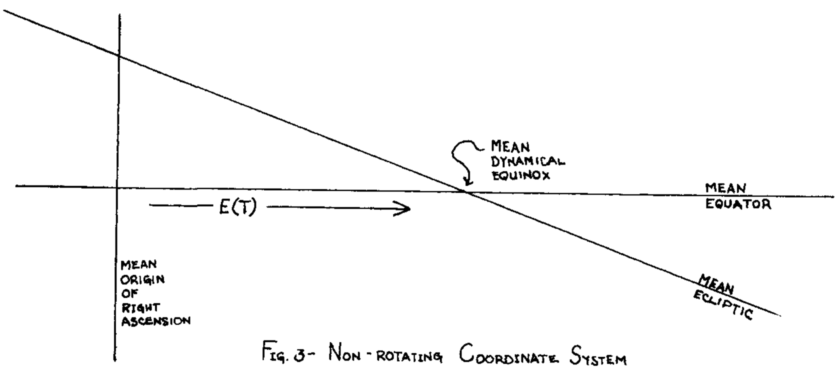

FIG. 3- NON-ROTATING COORDINATE SYSTEM

4. The effective geometric system (Figure 4) results from the conversion of computed lunar or planetary ecliptic longitude and latitude coordinates to B1950 equatorial coordinates, using Newcomb's precession constant. The geometric frame is intended to be an inertial frame, but fails to achieve this because of the error in the precession constant. The origin of right ascension is automatically set to the intersection point of the ecliptic and the mean equator. Because of the inadvertent motion of the 1950 mean equator, the mean origin of right ascension also moves, but at a rate rigorously related to the error in precession, having no connection with the motion of the origin of right ascension in the effective astrometric system. The rectangular coordinates of the Sun tabulated in the American Ephemeris are in this system.

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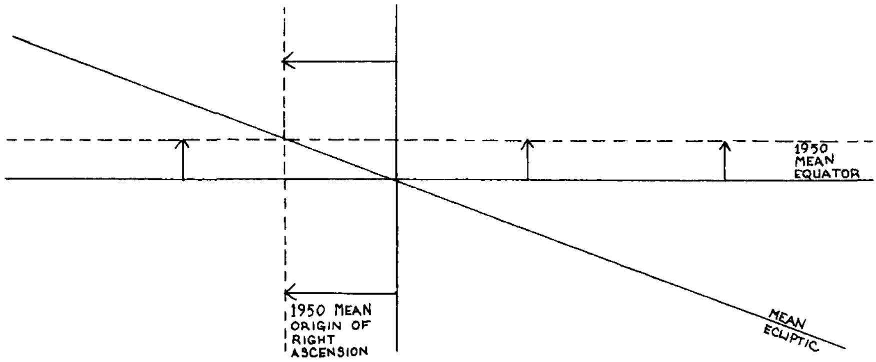

Fig. 4- Effective Geometric System

III. FUTURE REFERENCE SYSTEM

The FK5 reference system and the IAU (1976) System of Astronomical Constants have been designed to provide a workable system free from known errors. Where changes have been introduced, it is felt that the remaining uncertainties are an order of magnitude smaller than they were before. It is hoped that this system will have a long and useful lifetime and will serve the astronomical requirements well.

There have been several thought-provoking papers concerning future reference systems with various concepts and reasons for the recommendations being proposed (Guinot (1979), Eichhorn (1979), Murray (1979), Kovalevsky (1979), Grafarend et al. (1979)). Perhaps now, while the problems of the new system and the interrelationships involved in conversions are fresh in our minds, it is appropriate to consider the general concepts, not the particular details, of an ideal reference system for the future. The existence of an ideal or goal might also provide guidance as observing techniques are revised and decisions are made concerning what observational data should be published.

In considering the ideal reference system, a fresh start should be initiated, unburdened by the past. The character of future astronomical observations should be considered. It appears that the following characteristics of future astronomical observations might have a significant effect on the specifications of a future reference system.

1. There will be an increase in the quantity, quality and variety of observations which are made from instruments that are not located on the surface of the Earth.

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2. There will be an increase in the quantity and quality of observations made at frequencies other than in the visible spectrum.

3. There will be increased interest in accurate positional observations of very faint objects.

4. There will be an increased need for more accuracy in observational data.

In summary, increased accuracy will be sought in observations at all magnitudes and frequencies from all observational platforms.

If the above characteristics are accepted, the increased observations from instruments independent of the Earth's surface will have the most effect on the reference system. Therefore, it appears desirable to establish the reference system independent of a particular observing platform. Then a stellar reference system would be independent of the Earth's orbital or rotational motions.

The independence from the Earth, in addition to the observations of faint objects and observations at nonvisual frequencies, indicates a space-fixed nonrotating reference system. The motions of solar system bodies could be referred to the same system, except that for each planet, including the Earth, there would have to be a planetocentric coordinate system.

The principal difference between this concept and the present system is the separation of the origin from the dynamical equinox. This idea has been suggested before (Guinot (1979)), but apparently the reasons given have not been convincing. The distinction has already been introduced by the terminology <u>catalog equinox</u> which refers to the origin of right ascensions in a star catalog.

In practice, the <u>dynamical equinox</u> is not a desirable origin either theoretically or observationally. A theoretical difficulty of definition has been discussed earlier in this paper, but at some level of accuracy the location of the dynamical equinox is dependent on the orbital theory of the Earth which is being used. The observational difficulty is, simply, that the dynamical equinox cannot be observed. Rather, many observations must be used to determine retroactively the location of the equinox. The most direct object to be observed, the Sun, is subject to the greatest systematic observational errors. In practice today, the catalog equinox is observationally located from the observations of the stars in a given catalog, so that the dynamical equinox is not used. For the reference system, the only use of the dynamical equinox is for determining the catalog equinox when a new reference system is being established, as for the FK5. This is done so the catalog equinox and the dynamical equinox agree to some accuracy, but in practice they will never be the same and will always have some relative motion.

The implication of this fact for the present is that observational data should be recorded and retained in its original observing reference system to the greatest extent possible. This will permit future improvements in knowledge concerning the relations between the coordinate systems to be used to re-reduce the observational data. There should be no non-reversable processing of data and the specific methods and constants used in the processing should be specified. While there may not be any purely impersonal fundamental observations, nevertheless, that should be the goal of positional observations.

IV. CONCLUSION

The astronomical reference system has developed from the observational and computational capabilities of the times. The IAU (1976) System of Astronomical Constants, which are the most accurate, self-consistent set of values which can be determined from current observational data, has been introduced for the FK5 reference system. The details of conversion from the old to the new reference system reveal some of the conceptual problems with reference systems in general.

As we consider future observations of increased accuracies at a wide range of frequencies and magnitudes from many instrumental platforms, it may be desirable to consider new concepts for reference systems. An ideal reference system would be a space-fixed, nonrotating coordinate system. A principal change is the separation of the origin of right ascension from the dynamical equinox. Observational data should be recorded such that the full inherent accuracy of the observations can be realized with improved knowledge concerning the relationships between different coordinate systems.

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