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Application of the new concepts and definitions (ICRS, CIP and CEO) in fundamental astronomy

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Abstract. The IAU has introduced the International Celestial Reference System (ICRS), the Celestial Intermediate Pole (CIP), and the Celestial Ephemeris Origin (CEO) in order to be consistent with the improved accuracies currently achieved and expected in the future. While the bases of the International Celestial Reference System (ICRS) are different from previous reference systems, the astrometric definitions and methods remain similar and have a number of simplifications. The changes are from a dynamical to a kinematic defining motion, from bright stars to extragalactic reference sources, from a precessing equinox to a more stable fiducial point, and from a reference frame moving with time to a fixed reference frame independent of date. The new definitions necessary for the application of the ICRS to astronomy and astrometry are given and the methods for reducing observations are discussed. Recommendations are given concerning the forms of data to be provided and the reference frames to be used in various cases.

Key words. reference systems – astrometry – time

1. Introduction

From 1991 to 2000, the International Astronomical Union (IAU) resolutions (IAU 1992, 1998, 2001) have modified the astronomical reference systems in order to cope with the rapidly increasing accuracy of the observations. The previous reference system, based on the celestial equator and an origin defined by the ecliptic led to major difficulties. For example, there were several realizations of the equinox, dynamical and catalog, that were significantly distinct (Fricke 1985). Even the dynamical equinox had two competing definitions (Kinoshita & Aoki 1983). In addition, the construction of the fundamental catalogs did not guarantee that the resulting reference frames did not rotate. For all these reasons, two decisions were taken, and adopted by IAU resolutions in 1991 and successive General Assemblies.

In 1991, the IAU decided that the next celestial reference system would be based on positions, observed to be fixed to a sufficient accuracy, of a number of extragalactic radio-sources (IAU 1992) and that it would be barycentric, that is, centered at the barycenter of the Solar System. The International Celestial Reference System (ICRS) does not depend on either the pole of rotation of the Earth or the pole of the ecliptic, which are now subjects of measurement and included as offsets in the precession-nutation models. The origin, or departure point, of the ICRS was to be as close as possible to the mean equinox at J2000.0. This was later achieved with an offset of 78 mas between the origin of the ICRS and the dynamical mean equinox of the JPL ephemerides DE 200 (Arias et al. 1995). Subsequently the equinox of the new ephemerides DE 405 have been oriented to the ICRS with an uncertainty of 1 mas.

In 1994, the structure of the International Celestial Reference Frame (ICRF) was defined and a Working Group was set up to construct it. This work was completed in 1997 (Ma & Feissel 1997) and adopted by the IAU (IAU 1998). The consequence is that the coordinate axes of the ICRF are fixed, to the best available accuracy of the VLBI observations. The ICRF is defined by about 200 primary sources to an accuracy of about 30 microarcsec, and the ICRF is thus the realization of the ICRS by radio sources. It was also decided that the realization, in optical wavelengths, of the ICRS would be provided by the stars of the Hipparcos Catalogue that are not tagged as presenting a possible bias in proper motion (IAU 2001). There exists, in addition, another class of problematic stars, that show up by their discordant proper motions as determined by the Hipparcos mission on the one hand and by ground based observations on the other (so-called $\Delta\mu$ binaries). These stars should also not be considered as candidates for representing the ICRF. Information on these stars is given in the catalog ARIHIP (2001). A finding list of these stars are provided by Wielen et al. (2000). The conformity to the ICRS is secured with an uncertainty of 0.25 mas/yr in rotation and 0.60 mas in the position of the origin at epoch 1991.25 (Kovalevsky et al. 1997).

The IAU introduced in 2000 two "space fixed systems". The Barycentric Celestial Reference System (BCRS) and the

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Geocentric Celestial Reference System (GCRS), which have been defined in terms of metric tensors and the generalized Lorentz transformation between them, that contains the acceleration of the geocenter and the gravitational potential (IAU 2001 and Soffel 2000). The ICRS is to be understood as defining the orientation of the axes of both these systems for each of the origins. These axes show no kinematical rotation between them, but they are related by a scale factor and have different time-coordinates (TCB and TCG). The ICRF is the observed realization of the ICRS for practical applications. It can similarly be geocentric and barycentric. The VLBI observations that were used to define the ICRF were reduced following this model. Coordinates in this frame should be designated "*right ascension*" and "*declination*" without any further qualification except for designating the epoch of observations and to further apply proper motions.

To transform from the fixed frame to that of date, the position of the pole of the moving equator and the location of a fiducial point on that equator must be defined. The IAU has recommended that the origin of right ascensions on the true celestial equator is no longer the equinox, but a point called the Celestial Ephemeris Origin (CEO), which does not depend on the position of the ecliptic. The corresponding true reference frame is called in the 2001 IAU resolution the Celestial Intermediate Frame, and its pole, the Celestial Intermediate Pole (CIP, IAU 2001). In this frame the right ascensions and declinations should be designated as *true right ascensions* and *true declinations*, although the expressions "intermediate right ascensions", and "intermediate declinations" are also used. In the new system, the rotation of the Earth from the CEO is measured by the Earth rotation angle, or stellar angle, in place of the sidereal time measured from the equinox. The IAU resolution stated that the new system should be introduced on January 2003, and provision should be made that the IERS provide the necessary data to use the equinox as the fiducial point for right ascensions and sidereal time during an unspecified transition period. Right ascensions measured from the equinox should be designated as "*equinox right ascensions*". But only one of these options for a fiducial point should be used in an application.

New precession-nutation models were adopted, designated IAU 2000A and IAU 2000B, depending on precision, for accuracies better than a milliarcsecond. Precession-nutation models are applied together, thus eliminating the distinction between a "mean" and "true" equator and equinox. The link between new and old apparent places is dependent upon where the different precession/nutation models put the pole and the choice of the origin on the moving equatorial plane. Due to the increased accuracies and frequency of observations of the Earth orientation, particularly by VLBI and Global Positioning System (GPS) observations, sub-daily polar motion and nutation periods can be determined. Thus, the separation of nutation and polar motion terms became arbitrary, and the choice was made to designate all terms with periods less than 2 days as polar motion. The pole of the ICRS does not coincide with the mean pole of J2000.0 and there is a difference between the origin of the x axis in the ITRS and the equinox of J2000.0. These shifts have been included in the precession-nutation models. The numerical developments of the precession-nutation models, including the pole offsets, are changing as additional observations become available.

2. The old and the new systems

The objective of the sections that follow is to demystify the changes presented in the Introduction. Independent of the manner in which the axes of coordinates are fixed, their use is in strict conformity with what astronomers have done for decades. It is just as simple (or complicated) as before. In this paper, we propose to use the same names as before for those new concepts that replace old ones.

In the past, as in the future, one needs two reference systems: a fixed one and a current epoch moving one. Reduced and published observations are given with respect to a fixed reference frame, and current observations are made with respect to the moving equator.

2.1. Fixed reference frames

In the past, the fixed reference frame was defined in terms of a moving equator and a moving equinox corresponding to a certain date (B1950.0, J2000.0). The practical difficulty was that the definition of the motions was theory-dependent, and sometimes replaced by extrapolation of observations (FK5 and dynamical equinoxes). When observations of different stars from various epochs have been reduced to a fixed reference frame using precession values with errors, the resulting positions on this fixed frame contain systematic errors; these errors cause a rotation in catalogs based upon these stars. The observational realization of the fixed frame was based on nearby bright stars with proper motions.

In the new system, the ICRS is realized by the ICRF, based on distant radio sources, with its fixed coordinate axes and fiducial point. It is independent of the solar system dynamics. Thus it is truly a kinematically fixed frame. It is aligned to the FK5 at J2000.0 within the FK5 errors.

In both cases, the time-dependent reference frames do not coincide with the fixed ones, so one has to apply a rotation matrix to go from the fixed to the moving frame or the reverse. The new theoretical precession-nutation formula (IERS 2002) may be applied, but the precession-nutation quantities can also be directly derived from VLBI observations of Earth rotation. They are provided by the IERS and put in the same form as the values derived from the theoretical precession-nutation formulae.

2.2. Moving reference frames

In the past, the time-dependent reference frame was described by the *true* pole whose definition was actually modified at least twice. In 1960, the true or actual pole was defined via precession and nutation (Explanatory Supplement 1960). Then came the Celestial Ephemeris Pole (CEP), and now the Celestial Intermediate Pole (CIP) (IAU 2001). The changes were made necessary by the improvement of the nutation theory and by the requirement to clearly separate nutation from polar motion, but the basic idea remained the same, and there were generally no changes in notation. Similarly, the origin on the celestial equator defined by these poles was the *mean equinox of date*, whose position depended on the theory of the motion of the Earth and on the precession constant. The important feature is that both the pole and origin were time-dependent.

In the new system, rather than a theoretically defined equinox of date, the origin is a point called the Celestial Ephemeris Origin (CEO) on the *true* equatorial plane, perpendicular to the CIP, and the origin is determined by a formula based uniquely on observations of the CIP motion. The origin does not move along the equator at the precession rate. Thus, the new system is based on the kinematics of the Earth, rather than the dynamics of the solar system.

There is a new expression for the relation between the UT1 and the Stellar Angle, (or Earth Rotation Angle), which replaces the Greenwich Mean Sidereal Time (GMST) in the new CEO-based system. The new expression is linear (Sect. 7.3).

3. Positions in the ICRS

The International Celestial Reference Frame (ICRF) coordinates are right ascensions and declinations referred to a fixed equator without index or subscript. They are barycentric and, because the system has no rotation, and thus no epoch (like J2000.0) attached to the reference frame, it is compulsory to use ICRF coordinates when comparing the positions of stars at different times. ICRF coordinates have the role played earlier by mean places referred to the mean equator and equinox at a standard epoch. Similar to what was done previously, an ICRF place is determined by removing the effects of refraction, parallaxes, diurnal and stellar aberration, light deflection, etc., from the directly observed position, and then applying the transformation matrix, based on precession-nutation, geodesic precession, polar motion, and Earth rotation between the reference frame of the observation and the ICRF.

The fact that ICRF is timeless, but the stars still have proper motions, means that the epochs of the observed positions of a star must always be mentioned (e.g. α, δ are ICRF positions for epoch T). The epoch of a catalogue represents either the mean epoch of observations, or some rounded date. In both cases, the positions of stars should be corrected for proper motions, if known, to be reduced to that epoch. For instance, the epoch of the Hipparcos catalogue, the realization of the ICRF in optical wavelengths, is 1991.25. In order to get the position in the ICRF of a Hipparcos star at time T, one must correct the coordinates by the effect of the proper motions for time $T - 1991.25$. The consequence is that, if the position of a star S is measured with respect to Hipparcos stars at time T, one must first compute the positions of the reference stars for this time T. Then, the position of S will indeed be in ICRF for epoch T. This difficulty does not exist for observations made with respect to ICRF radio-sources. The latter being fixed, whatever the epoch T of observations, the positions obtained are theoretically strictly referred to the ICRF. However, apparent proper motions of some radio sources due to changes in their structure have been found. It is possible that, in the future, this might have to be taken into account.

Since observations are generally made from the Earth, they refer to the GCRS. Since the GCRS is in motion around the barycenter, but has fixed directions with respect to extragalactic sources, there is a Coriolis-like effect from the relativistic theory of the transformation if referred to the BCRS. This transformation must be applied (IAU 2001). In practice, it is the geodesic precession/nutation, which is a very different effect from the precession and nutation proper. However, it is generally included in the precession-nutation model, specifically in the IAU-2000 A and B, so that it is automatically applied when computing the positions in the ICRS from Earth-based observations. Its value, a circular-orbit average, is

$$\psi_G = 19.194 \text{ mas per year.} \tag{1}$$

There are also periodic terms in this transformation, sometimes called geodesic nutation, along the ecliptic, whose largest terms are in mas:

$$\Delta\psi_G = -0.153 \sin l - 0.002 \sin 2l, \tag{2}$$

where l is the mean anomaly of the Sun (Fukushima 1991).

4. Ecliptic coordinates

The ICRF provides a fixed coordinate system for computing solar system ephemerides. In some cases it may be convenient to use a coordinate system based on a principal plane of the solar system, e.g. a fixed ecliptic, as used in the past. To be consistent with ICRS and its origin, a fixed ecliptic could be defined as a fixed plane through the origin of the ICRS with a fixed inclination ε_0 equal to the mean obliquity at J2000.0. Its value is $\varepsilon_0 = 23°26'21''.4059 \pm 0''.0003$ (Fukushima 2001). Each new ephemeris should define its own ecliptic and mean obliquity on the ICRS axes. The transformation from the ICRS (x, y, z) coordinates to the ecliptic fixed coordinates (X, Y, Z) is:

$$\begin{aligned} X &= x \\ Y &= y \cos\varepsilon_0 + z \sin\varepsilon_0 \\ Z &= -y \sin\varepsilon_0 + z \cos\varepsilon_0. \end{aligned} \tag{3}$$

The ecliptic remains a convenient basis for a coordinate system for theories of motion in the solar system and its position as a function of time is to be given as the longitude of the node and inclination on the ICRF equator from the ephemerides being used (each might have its own ecliptic). An equinox, as the intersection of the actual moving ecliptic with the intermediate moving equator (see below), can be defined to compute the times of phenomena.

5. Rotation of the Earth

The rotation of the Earth is ideally represented in geocentric coordinates by a transformation matrix $\mathcal{M}$ between a terrestrial reference system and the celestial reference system. In practice, the terrestrial system is the International Terrestrial Reference System (ITRS) defined by the International Union for Geodesy and Geophysics (IUGG 1992) and represented physically by the International Terrestrial Reference Frame (ITRF), which is a catalogue of positions and velocities of point marks on the Earth. The latest version is ITRF-2000 (Altamimi et al. 2002). The celestial system is, of course, the ICRS.

Now, just as was traditionally done, the transformation is made in two steps. First, the correction for polar motion is described by a matrix $\mathcal{R}$ transforming ITRS into an *Intermediate Reference System* defined by the Celestial Intermediate Pole (CIP), the corresponding celestial equator, and the Celestial Ephemeris Origin (CEO). Then, a precession-nutation matrix $\mathcal{N}$ transforms the intermediate system into the ICRS. The difference with the previous procedure lies only in the definition of the intermediate system. One has, as before:

$$\mathcal{M} = \mathcal{N} \times \mathcal{R}.$$

The pole is no longer the CEP, but the CIP. The difference is how the separation is done between polar motion and nutation. The CIP is defined in such a way that all nutation terms with periods smaller than 2 days are included in the polar motion. In addition, the subdiurnal tidal polar motion is taken into account by a model. In practice, the change that will occur on January 1, 2003, will be transparent to the user: the nutation theory and the published polar motion will conform to this change. The true equator, which was defined with respect to the CEP, will now be defined with respect to the CIP. Actually, the difference is of the order of a few tens of microarcseconds (Souchay 2000).

The other difference is in the choice of the CEO instead of the mean equinox on the equator. This choice has at least three advantages:

1. the difficulties with the equinox, already mentioned in the Introduction, are removed;
2. the CEO is defined in such a way that its motion on a fixed celestial sphere has no component along the equator. This means that the instantaneous movement of the CEO is always at right-angles to the instantaneous equator (Guinot 1979); and
3. the angle θ (called Stellar Angle or Earth Rotation Angle) measured on the equator between the CEO and the longitude origin in the ITRF is such that it yields UT1 through a strictly linear relationship.

The position of the CEO on the equator is defined by an integral that involves only the path followed by the precessing-nutating pole since the reference epoch (Capitaine et al. 1986). This can be computed from the precession-nutation model and/or observations. Either numerical integration or an approximate formula given by Capitaine et al. (2000) can be used (see Sect. 7.1). The CEO motion depends only very slightly upon the pole used as the input

Stellar Angle, or Earth Rotation Angle, is the replacement for Greenwich Apparent Sidereal Time (GAST). The GAST origin was the equinox, which, in contrast to the CEO, had components of motion along the equator; these arose because the equator and ecliptic are moving relative to one another. Consequently, the relationship between GAST and UT1 included terms due to precession and nutation. The precession terms appeared in the formula that links Greenwich Mean Sidereal Time (GMST) and UT1, while the nutation terms appear in the formula GAST= GMST $+\Delta\psi\cos\varepsilon$ as the *equation of the equinoxes*. Now, the Stellar Angle does not depend on precession or nutation (see Sect. 7.3).

Remarks:

1. When introduced by Guinot (1979), the CEO was called a non-rotating origin. This term is potentially confusing given that the CEO is moving, simply because the equator, on which it is located, is itself moving. The "non-rotating" description refers to the absence of a component of motion along the equator; the instantaneous motion of the CEO is defined to be about an axis in the equatorial plane, such that there is no rotation about the z-axis. Note that this is a kinematical definition. It can be hard to visualize because there is no geometrical definition and, hence, a diagram defining where the CEO is at any given time cannot be drawn. The kinematical definition states how the CEO moves, not where it is. This motion does not depend on the choice of the system in which the coordinates of the pole of rotation are expressed.
2. As pointed out by Fukushima (2001), the position of the CEO has a zig-zag secular motion across the ICRF sky over long periods of time (tens of thousands of years). However, it is the only choice of origin that gives an Earth rotation angle formula free from precession-nutation terms; all the other options listed by Fukushima contain such "crosstalk" effects to a greater or lesser degree. The small motion of the CEO is due to the choice of the constant of integration and the x-axis of the ICRF being near the equinox of J2000.0. Moreover, the slow secular motion of the CEO has no obvious unfavorable consequences. Note that the quantity s (formula 8), analogous to the precession in right ascension, has a secular component mainly due to a t^3 term, which reaches only 40 mas in 2100, and that the CEO is independent of the celestial reference system adopted.

6. Computing true celestial coordinates

The coordinates α and δ in the intermediate or true system described in the previous section have the same definition as true coordinates in the equinox-based system. They are positions with respect to the true, or intermediate, equator and either the CEO or the equinox, depending upon which system is used. Thus, precession-nutation has been applied to ICRF positions. This is an extension of the use of the intermediary frame to astrometry and it is legitimate to call the resulting α and δ, the true geocentric coordinates and to call the frame, true celestial frame. Their determination from raw observations corrected for instrumental parameters, stellar aberration, and refraction, and reduced, if significant, to the geocenter, is analogous to the following procedure, described by Lieske et al. (1977).

For the old system, let us consider a set of three-dimensional reference Cartesian coordinate axes R_0 $(0\,x\,y\,z)$ at epoch t_0, centered at the center of the celestial sphere. The X-axis points to the fixed equinox γ_0. The Y-axis is 90° away in an easterly direction along the equator, and the Z-axis points toward the mean pole P_0 (Fig. 1). Let P be the pole of the instantaneous (true geocentric) reference frame $R(t)$ $(O\,x\,y\,z)$ at time t and, on its equator, the mean equinox of date, γ, is the

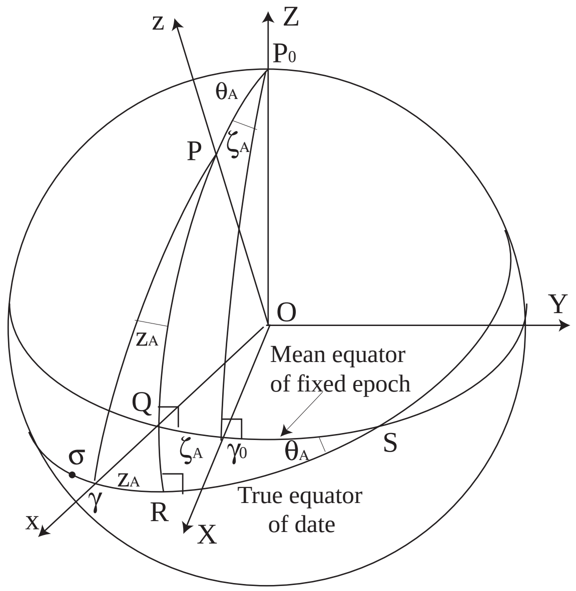

Fig. 1. The precession angles ζ_A, z_A, and θ_A. The Ox axis points towards γ in the old system, towards σ in the new.

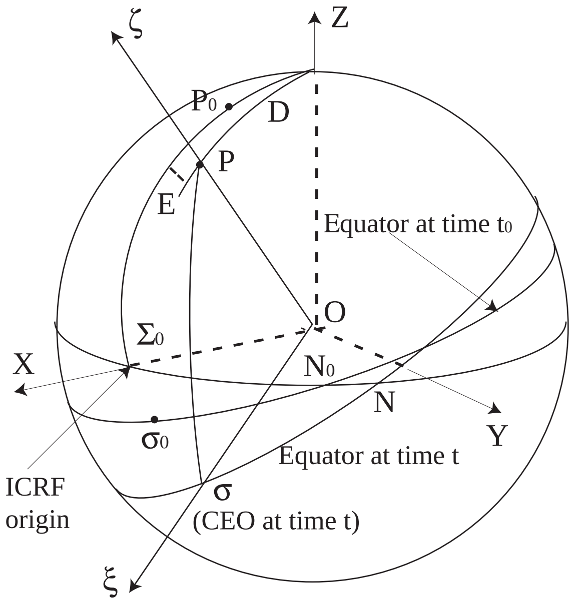

Fig. 2. Definition of the CEO on ICRF with motion of the pole from t_0 (P_0) to t (P).

origin of right ascensions. The transformation from R_0 to $R(t)$ consists of three rotations.

1. A rotation of $-\zeta_A$ about the Z-axis makes $P_0\gamma$ pass through P. This great circle meets the mean equator of epoch at right angles at point Q and the mean equator of date at right angles at R. The new x-axis is now in the direction Q and the y-axis points toward the node S, where the two equators cross;
2. a rotation of $+\theta_A$ equal to the angular separation of P from P_0 about the new y-axis brings the mean equator of epoch to the mean equator of date. The new z-axis points to the pole of date P, the y-axis to the node S, and the x-axis now points towards R in the plane of the equator of date;
3. a rotation of $-z_A$ equal to the angle $(\gamma - H)$ about the new z-axis brings H to γ, so that the x-axis points toward γ, the equinox of date, and still lies in the plane of the mean equator of date.

In the new system, the situation is technically similar. Now, in Fig. 1, the geocentric ICRF axes replace R_0, and γ_0 is the origin of right ascensions, while γ is replaced by the CEO σ. Thus, the first two rotations $-\zeta_A$ and $+\theta_A$ are similar. Only the third, $-z_A$, is changed, and is now equal to the angle $[\sigma, H]$.

As for z_A, $[\sigma, H]$ will be provided by the precession-nutation expressions (which include the geodesic precession-nutation). Actually, the transformation can be made in a much simpler manner. Now, continuous VLBI observations systematically provide the position of P in the ICRF, just as is the case for many years of the polar motion. So, just as one used to correct for polar motion using the positions of the terrestrial pole, similarly, one should compute the coordinates in the geocentric ICRF using the observed position of P ($-\zeta_A$ and $+\theta_A$) and of the CEO (σ). It is necessary that the method and values for the reduction of observations be documented and referenced.

7. UT1 and stellar angle

Let us now analyze in detail the concepts introduced above.

7.1. Celestial ephemeris origin

For the concept of the CEO, consider a rigid celestial sphere, with reference ICRF Cartesian axes $OXYZ$ with Σ_0 being the intersection of OX with the celestial sphere, as in Fig. 2. Let $P(t)$ be the instantaneous celestial pole, now called the Celestial Intermediate Pole (CIP) at time t with Cartesian coordinates $O\xi\eta\zeta$ such that $O\zeta$ is along OP and σ is the point on the equator of P where $O\xi$ pierces the sphere. The condition is imposed that for any infinitesimal displacement of P there is no rotation around $O\zeta$. Then σ would be the non-rotating origin on the moving equator of P.

The motion of point P between dates t_0 and t is determined by evaluating the quantity $s(t)$

$$s = [\sigma N] - [\Sigma_0 N] - ([\sigma_0 N_0] - [\Sigma_0 N_0]), \tag{4}$$

where quantities in brackets are arcs measured on inclined great circles shown in Fig. 2, $\sigma_0 = \sigma(t_0)$, N_0 and N are the ascending nodes of the equators at t_0 and t in the equator of the ICRS. Then s is given by Capitaine et al. (1986, Sect. 5.2):

$$s = -\int_{t_0}^{t} \frac{X\dot{Y} - Y\dot{X}}{1+Z} \mathrm{d}t - ([\sigma_0 N_0] - [\Sigma_0 N_0]), \tag{5}$$

where X, Y and Z are the coordinates of the pole and the dots denote their time derivative. In polar coordinates, if D is the angle $(\boldsymbol{OZ}, \boldsymbol{OP})$ and E is the angle of the plane $\boldsymbol{OZP}$ with respect to the principal plane $\boldsymbol{OZX}$, the equation is

$$s = \int_{t_0}^{t} (\cos D - 1)\dot{E}\mathrm{d}t - ([\sigma_0 N_0] - [\Sigma_0 N_0]). \tag{6}$$

Table 1. Additional terms in $\sigma(t)$ and $\Delta\sigma(t)$ for Eqs. (8) and (9) in μas units (Capitaine et al. 2002).

α_k	C_k	α_i	D_i
Ω	−2641	l'	−6
2Ω	−63	$l' + 2L$	+2
$\Omega + 2L$	−12	l	−3
$\Omega - 2L$	+11	$2L' + 2L$	+2
$2L$	+5	$L + 2L'$	+1
$\Omega + 2L'$	−2		
$\Omega - 2L'$	+2		
3Ω	+2		
$l' + \Omega$	+1		
$l' - \Omega$	+1		

The convention may be adopted that σ_0 is on the true equator at epoch t_0 and $[\sigma_0 N_0] = [\Sigma_0 N_0]$. Then $[\sigma_0 N_0]$ is the constant $s(t_0)$ in the integral. Then,

$$s = \int_{t_0}^{t} (\cos D - 1)\dot{E}\mathrm{d}t. \quad (7)$$

For the period 1975–2025, the development of $s(t)$ including all terms exceeding 0.5 μas is, in μas (Capitaine et al. 2000):

$$\begin{aligned} s(t) = & -\frac{XY}{2} + 2004 + 3812t - 121t^2 - 72\,574t^3 \\ & + \sum_k C_k \sin\alpha_k + 2t\sin\Omega + 4t\sin 2\Omega \\ & + 744t^2 \sin\Omega + 57t^2 \sin 2L \\ & + 10t^2 \sin 2L' - 9t^2 \sin 2\Omega \end{aligned} \quad (8)$$

where t is expressed in centuries since J2000.0 ($t_0 = 0$) and where α_k and C_k are given in Table 1. To extend the development for the periods 1900–1975 and 2025–2100 for terms exceeding 0.5 μas, add in μas:

$$\begin{aligned} \Delta s(t) = & +28t^4 + 15t^5 - 22t^3 \cos\Omega \\ & -t^3 \cos 2L + \sum_i D_i t^2 \sin\alpha_i, \end{aligned} \quad (9)$$

where α_i and D_i are given in Table 1. In this table and in Eqs. (8) and (9), the notations, referred to the ICRF axes and the corresponding fixed ecliptic are:

Ω: mean longitude of the node of the lunar orbit;
L: mean longitude of the Sun;
L': mean longitude of the Moon;
l: mean anomaly of the Sun ($l = L - \varpi$) where ϖ is the mean longitude of the Sun's perigee;
l': mean anomaly of the Moon ($l' = L' - \varpi'$), ϖ' being the mean longitude of the Moon's perigee.

At present, the uncertainty of these expressions is smaller than 1 μas and is insensitive to expected modifications of the nutation-precession theory to about this level. A maximum error of 3 μas could be reached in 2100 (Capitaine et al. 2002).

7.2. Terrestrial ephemeris origin

For Earth orientation, the concept of the CEO must be applied to both the celestial and the terrestrial reference systems.

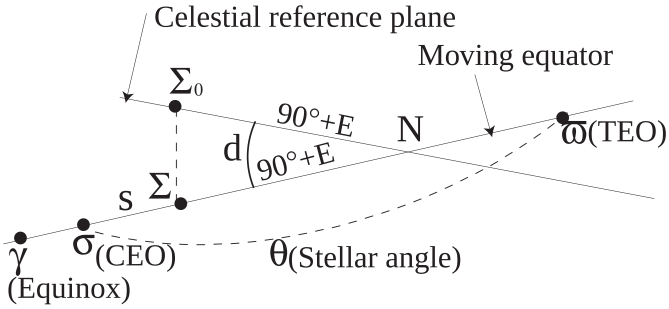

Fig. 3. Definition of the stellar angle.

So, a Terrestrial Ephemeris Origin (TEO) was introduced. The definitions are similar. The formula giving the shift of TEO is

$$s' = \int_{t_0}^{t} (\cos g - 1)\dot{F}\mathrm{d}t, \quad (10)$$

where F and g are the polar coordinates of the Earth's pole at time t, and $\dot{F}$ is the time derivative of F. Because of the very small magnitude of the polar displacements, this is a very small correction (smaller than 0.1 mas next century) that must however be evaluated from the measurement of the polar motion, when μas accuracies are sought.

7.3. Stellar angle

In the ICRS system the equivalent of sidereal time is the hour angle of the celestial ephemeris origin (CEO), and hence is subject only to the motions of that origin. It is called the *Stellar Angle* or *Earth Rotation Angle*.

The Stellar Angle in Fig. 3 is defined by the angle θ measured along the equator of the Celestial Intermediate Pole (CIP) between the TEO and the CEO positively in the retrograde direction. The definition of the CEO ensures that the derivative $\dot{\theta}$ is strictly equal to the instantaneous angular velocity ω of the Earth around the CIP. Thus, θ represents rigorously the sidereal rotation of the Earth around its axis and is such that UT1 is linearly proportional to the angle. The definition of UT1 by its relationship with mean sidereal time is proportional to θ, but has additional terms that take account of precession. Thus, with the CEO the definition of UT1 is such that the time derivative of UT1 is proportional to ω.

The numerical relationship between the Stellar Angle and UT1 has been derived (Capitaine et al. 2000) to be consistent with the conventional relationship between GMST and UT1. This provides the definition of UT1 for the ICRF. To an accuracy of 1 μas the relationship is

$$\begin{aligned} \theta(T_\mathrm{u}) = & \; 2\pi(0.779\,057\,273\,2640 \\ & +1.002\,737\,811\,911\,354\,48\, T_\mathrm{u}), \end{aligned} \quad (11)$$

where

T_u = (Julian UT1 date − 2 451 545.0).

7.4. ITRS to ICRS matrix

The coordinate transformation from a unit vector $\boldsymbol{G}_\mathrm{T}$ of the ITRS to a unit vector $\boldsymbol{G}_\mathrm{S}$ of the GCRS at date t can be given as

$$\boldsymbol{G}_\mathrm{S} = \mathcal{PN}(t) \times \mathcal{R}(t) \times \mathcal{W}(t) \times \boldsymbol{G}_\mathrm{T}. \tag{12}$$

In this equation, the fundamental components ($\mathcal{PN}(t), \mathcal{R}(t)$, and $\mathcal{W}(t)$) are the transformation matrices arising from the motion of the CIP in the ICRF due to precession-nutation expressions, from the rotation of the Earth around the CIP, and from polar motion, respectively. They are given in the similar manner to that given in the IERS Conventions 1996 (McCarthy 1996):

$$\mathcal{W}(t) = \mathcal{R}_3(-s') \times \mathcal{R}_1(-v) \times \mathcal{R}_2(u),$$

$$\mathcal{R}(t) = \mathcal{R}_3(-\theta),$$

$$\mathcal{PN}(t) = \mathcal{R}_3(-E) \times \mathcal{R}_2(-D)\mathcal{R}_3(E) \times \mathcal{R}_3(s). \tag{13}$$

In these equations, u and v are the coordinates of the CIP in the ITRF, s' is the shift of TEO defined by Eq. (10), and θ is the Stellar Angle. The quantities D, E and s are defined in Sect. 7.1. We have used the notation $\mathcal{R}_i$, $i = 1, 2, 3$ for the matrix rotation respectively around the axes x, y, z.

$\mathcal{PN}(t)$ can also be given in an equivalent form directly from the coordinates X and Y as:

$$\mathcal{PN}(t) = \begin{pmatrix} 1 - aX^2 & aXY & X \\ -aXY & 1 - aY^2 & Y \\ -X & -Y & 1 - a(X^2 + Y^2) \end{pmatrix} \mathcal{R}_3(s). \tag{14}$$

with

$$X = \sin D \cos E$$

$$Y = \sin D \sin E$$

$$a = \frac{1}{(1 + \cos D)}. \tag{15}$$

The latter can also be written with sufficient accuracy as

$$a = \frac{1}{2} + \frac{1}{8}(X^2 + Y^2).$$

7.5. The IAU 2000 precession-nutation series

In addition to the new definitions presented in the previous sections, the IAU has adopted a new model for precession and nutation based on the work of Mathews et al. (2002). It is presented in the form of series for nutation in longitude $\Delta\psi$ and obliquity $\Delta\epsilon$. There are two versions: the IAU 2000A series provides the position of the CIP in the GCRF with an accuracy of 0.1 mas (IERS 2002). A shorter version, accurate to 1 mas, is the IAU 2000B series.

To derive the position (X, Y, Z) of the CIP, the following procedure can be applied (IERS 2002). One has:

$$\begin{aligned} X &= \bar{X} + \xi_0 - \bar{Y} \mathrm{d}\alpha_0 \\ Y &= \bar{Y} + \eta_0 + \bar{X} \mathrm{d}\alpha_0 \end{aligned} \tag{16}$$

where $\xi_0 = -0''.016\,617$ and $\eta_0 = -0''.006\,819$ are the celestial pole offsets at the basic epoch (J2000.0) and $\mathrm{d}\alpha_0$ is the right ascension of the mean equinox, and where:

$$\begin{aligned} \bar{X} &= \sin\omega \sin\psi \\ \bar{Y} &= -\sin\varepsilon_0 \cos\omega + \cos\varepsilon_0 \sin\omega \cos\psi. \end{aligned} \tag{17}$$

In these equations, ε_0 is the obliquity of the ecliptic at J2000. One can compute ω and ψ from the precession-nutation series by:

$$\begin{aligned} \omega &= \omega_\mathrm{A} + \Delta\psi \sin\epsilon_\mathrm{A} \sin\chi_\mathrm{A} + \Delta\epsilon \cos\chi_\mathrm{A}, \\ \psi &= \psi_\mathrm{A} + \frac{\Delta\psi \sin\epsilon_\mathrm{A} \cos\chi_\mathrm{A} - \Delta\epsilon \sin\chi_\mathrm{A}}{\sin\omega_\mathrm{A}}. \end{aligned} \tag{18}$$

Here, ω_A, ψ_A, ϵ_A and χ_A are the precession quantities of the model given as polynomials of time.

8. Time scales

The observations from the Earth are generally referred to UTC, a time scale that is based on the International Atomic Time (TAI), but has the great disadvantage of not being continuous because from time to time steps of one second are introduced. Therefore, IAU (1992) recommends use of Terrestrial Time (TT), which is defined by its origin in 1977 with respect to TAI and the Système International (SI) second. Realizations of TT are designated as TT(x). For instance,

TT(TAI) = TAI + 32.184 s.

Other realizations may be achieved by analyses of the indications of very accurate time standards and their determinations of the SI second. The value of TT was exact at its origin but, at other times, uncertainties due to the realizations add up. In 2001 the uncertainty is about 20–30 microsec. TT is the time reference for apparent geocentric ephemerides.

But, when dealing with bodies outside the Earth, one must use the coordinate times that correspond to the space-time coordinate system. The IAU (1992) stated that the units of measurement of the coordinate times of all coordinate systems centered at the barycenters of ensembles of masses must be chosen so that they are consistent with the proper time, the SI second. The coordinate times are to be consistent with the relativistic transformations between the coordinate systems and such that the definitions of units of mass, length and time are consistent. As a consequence, two coordinate times were defined.

8.1. Geocentric Coordinate Time (TCG)

Around the Earth, the space-time coordinate is centered at the center of mass of the Earth. The corresponding time coordinate is the Geocentric Coordinate Time (TCG) whose scale unit is such that the relation between TCG and TT is linear and is:

$$\mathrm{TCG} - \mathrm{TT} = L_\mathrm{G} \times (\mathrm{JD} - 2\,443\,144.5) \times 86\,400\,\mathrm{s} \tag{19}$$

with $L_\mathrm{G} = 6.969\,290\,134 \times 10^{-10}$ and being a defining constant, not subject to change. JD is the Julian date. The bracket vanishes on January 1, 1977, 0h.TT. Note that TT replaces, since 1992 (IAU 1992), the Terrestrial Dynamical Time (TDT) previously in use.

8.2. Barycentric Coordinate Time (TCB)

For the space-time coordinates in the Solar system, the origin is the barycenter of the Solar system. The corresponding time coordinate is the Barycentric Coordinate Time (TCB). It is related to TCG by:

$$(\mathrm{TCB} - \mathrm{TCG})_{\mathrm{secular}} = L_{\mathrm{C}} \times (\mathrm{JD} - 2\,443\,144.5)\,86\,400\,\mathrm{s} \quad (20)$$

with $L_{\mathrm{C}} = 1.480\,826\,8457 \times 10^{-8}$. The uncertainty of L_{C} is of the order of 10^{-17}. In addition, the expression (20) has a nonlinear variation described by a number of periodic terms depending on the various periods present in the motion of planets. They are discussed in Fukushima (1995) who finds that there are 515 terms that are greater in amplitude than 0.1 ns. The most important periodic terms in TCB – TCG are, in seconds,

$$0.001\,658 \sin g + 0.000\,014 \sin 2g,$$

where $g = 357^{\circ}\!.53 + 0^{\circ}\!.985\,003$ (JD − 2451 545.0) represents essentially the mean anomaly of the Earth's orbit.

The change from the earlier coordinate time in the Solar system (Barycentric Dynamical Time, TDB) is that, while TDB–TDT were defined in such a way that they differed only by periodic terms, TCB–TCG have also a secular trend resulting from the full four-dimensional transformation between geocentric and the barycentric space-time coordinates. This makes the time scales consistent with relativistic transformations. The IAU (2001) gives the relations between the coordinate times very accurately in 2000.

9. Astrometry of observations and coordinates

9.1. Description of observations

Documented positions are described by their location, reference frame, and date. Thus, the locations can be topocentric, geocentric, selenocentric, barycentric, or satellitocentric. The reference frames can be ICRF, true position, which is the equator of date referred to the CIP, or mean position, which is the equator of date referred to the CIP for some convenient epoch (used primarily for artificial satellites). The time scales for observations are those appropriate for the location and reference frame. Thus, topocentric and satellitocentric observations would be on UTC or better on TT, which has no discontinuities (TT = TAI + 32.184 s). Geocentric observations would be on TCG, and barycentric observations on TCB. Sometimes TT will be retained as a convenience.

There are geometric observations that involve time delay measurements, such as are made by radar and laser measurements between the actual positions of two different bodies. Individual measurements are independent of the reference frame, but the series of observations become dependent on the motions of the bodies and, thus, on the reference frame and kinematics of the system.

9.2. Types of observations

Let us describe what corrections are to be made for different types of observations.

1. *Narrow angle (topocentric observed positions)*: the observations of small fields of view with images at one exposure, are made by CCDs, either in stare mode or time delay integration, or by photographic plates and recorded in TT. These astrometric observations are made of program objects with respect to reference stars, whose positions are available from positional catalogs on the ICRF. So the resulting program object positions will be on the ICRF. The reference star positions must be corrected for their proper motions between the reference catalog epoch and the observational time with the correct time difference. It is also advisable to correct the reference stars for predicted refraction (including color effects), gravitational deflection, parallax, and differential aberration. Thus, the astrometry is done in observational coordinates and the plate constants will be partially free of the differential effects so that the magnitude of the unknown parameters will be smaller.
2. *Wide angle observations (topocentric observed positions)*: observations made independent of reference stars by means of interferometers, transit circles, and telescopes with positional readouts are topocentric apparent positions at a TT time. They require correction for instrumental parameters, refraction, diurnal aberration, Earth orientation, light bending, telescope location, and time correction (TCG-TT) to achieve a geocentric true position. Correction must then be made for precession-nutation, geodesic precession if not included in the latter, aberration, proper motion, radial velocity, parallax, and time difference (TCB-TCG) to reach barycentric ICRF positions. In practice, it is preferred to use the position and velocity of the observer with respect to the solar system barycenter and reduce the observation in one step, avoiding the use of the geocentric position.
3. *Radar and laser observations (time delay measurements)*: these are time delay measurements of geometric distances of bodies at specific times. The positions of the transmitting, reflecting, and receiving bodies are the actual geometric positions at specific times, which differ according to the transmission time between the bodies. Thus, an iterative solution is appropriate to determine the times and locations, and relativistic effects must be taken into account. For ephemeris determination the calculated ephemeris positions could best be fit to the observations to determine corrections to the computed positions. Alternatively, initial positions are topocentric in UTC and must be corrected to geocentric on TCG, based on Earth orientation parameters. Reductions should then be made to barycentric positions on TCB.
4. *Solar System observations*: solar system observations can be of various types, such as radar, laser, and optical, narrow, or wide, angle observations. Depending on the type, reference should be made to the appropriate sections above. Correction for the motion of the solar system body may be an additional correction to the above descriptions.
5. *Pulsar timing*: pulsar timings are topocentric, geometric measurements made on the observatory clock. Pulsar timings require the most accurate and careful relativistic reduction procedures, including correcting carefully for the time differences of the local clock and whatever atomic

time scale is used for analysis. Reduction for the physics of the source and the actual geometry of the solar system and the Earth orientation must be made to reach the barycentric position on the ICRF and TCB.

6. *VLBI observations*: Very Long Baseline Interferometer (VLBI) observations, made at radio frequencies, are similar to optical interferometer observations and are topocentric apparent positions at a TT time. They are an angular measurement with respect to the interferometer baseline and the true equator of date. They require correction for diurnal aberration, atmospheric effects, instrument locations, Earth orientation, and time correction (TCG–TT) to achieve geocentric positions. Then, they can be transformed to geocentric GCRF or barycentric ICRF positions by means of precession-nutation, geodesic precession, aberration, and time difference (TCB–TCG). In practice, since the VLBI observations of radio sources define the ICRF, the observations are used to solve for the corrections to precession-nutation, polar motion, Earth rotation, geodetic effects, and astronomical constants.
7. *Observations of artificial satellites*: observations of artificial satellites can be made by various techniques. These include radar and laser observations of category (3) above. Also, astrometric observations of (1) and (2) above may be made. The computed artificial satellite ephemerides should be transformed to the observational positions for the determination of observed minus computed positions for orbital parameter improvements, and the time argument should be TCG. The reference frame, here, is a dynamically non-rotating reference system. Hence, geodesic precession must not be applied in the reduction of data, but the complementary terms due to accelerations must be included in the equations.

9.3. Reduction steps

This section presents the reduction procedure going from the raw observation to the position on the ICRF system. While a number of possibilities are proposed, it is generally advisable to reduce observations directly to ICRF positions. Standardized software for reduction procedures is being developed by the IAU Working Group SOFA (chaired by Patrick Wallace, `ptw@star.rl.ac.uk`), the IMCCE at the Paris Observatory, and the USNO.

1. *Raw observation*: this is the observation as it is actually made with the recorded time in UTC. This should not be distributed or published as the observer is best able to make the appropriate corrections.
2. *Local place*: this is the observation corrected for refraction and instrument parameters and recorded in UTC. This is also not of use except to the observer.
3. *Topocentric apparent place*: this is the local place corrected for diurnal aberration and the time difference TT–UTC. It is on ITRF and TT.
4. *Geocentric apparent place*: this is the topocentric apparent place corrected for polar motion, irregularities of UT1 (via Stellar Angle), diurnal parallax and light bending. It is on the CEO and true equator and can be either on TT or TCG. Accurate Earth Orientation Parameters are available from the IERS.
5. *Barycentric catalog position*: the correction from geocentric apparent place to the barycentric ICRF involves precession-nutation including geodesic precession-nutation, stellar parallax (if known), stellar aberration, light deflection and light time. The positions are in ICRF and time can be TT or TCB. Right ascensions and declinations are equivalent to the old positions with respect to the mean equinox an the mean equator for the epoch J2000.0. Only the epoch of observation of moving objects and stars must be specified. There are no apparent positions in the fixed frame and the use of the word "mean" is no longer necessary. The standard model of precession-nutation IAU 2000A is accurate to 0.1 milliarcsec. More precise values are available weekly from the IERS.

10. Distribution of astronomical data

10.1. Observations

Observations should be recorded with information such that all reductions could be redone with improved constants and methods in the future. The observations should be in the form for combination with other similar observations from other sources. Observational star catalogs should be for the mean epoch of the observations as barycentric mean positions on ICRS and TCB. Compiled catalogs as reference star catalogs should be on the ICRS in TCB for the epoch J2000.0.

10.2. Almanacs

Almanacs should provide star catalog data in geocentric apparent positions for an epoch in the applicable year in TT or TCG. Solar system data should be provided as geocentric apparent positions for individual dates on GCRS and TT or TCG. For the transition, an ephemeris of the difference between the equinox and the CEO should be given. Thus, it would be possible to convert the Stellar Angle into GAST and CEO right ascensions into equinox right ascensions of both apparent and true positions.

10.3. Ephemerides

Ephemerides for solar system bodies should be calculated on the ICRS fixed reference frame and the TCB time scale. Satellite ephemerides should be done on planet-centered ICRF in TCB. These ephemerides can be transformed into true or apparent positions dependent on the observation type for determination of ephemerides corrections.

10.4. Artificial satellites

The most useful reference system and time system for calculating the motions of the artificial satellites and providing a catalog of the elements of their orbits would be a geocentric dynamically fixed reference frame on TT. This would provide the reference frame for computation of the ephemerides of the satellites. Thus, they should be reduced as indicated above (item 7 of Sect. 9.2). Artificial satellite catalogs should be given on the GCRF and TT or TCG (Seago & Vallado 2000).

11. Definitions

The new coordinate systems introduced by the IAU have direct consequences on the definition of concepts and quantities that are used, or should now be used, in fundamental and applied astrometry. As a service to the user, we provide here these definitions:

- *Astrometric position*: observed positions with respect to GCRF reference stars at some epoch. Positions have not been corrected for annual and planetary aberration.
- *Barycentric Celestial Reference System (BCRS)*: a global "space fixed" coordinate system centered at the barycenter, defined by the metric tensors of the IAU 2000 resolutions (Soffel 2000).
- *Catalog, or mean, positions*: positions on the ICRF.
- *Celestial Ephemeris Origin (CEO)*: origin for the right ascensions on the true equator of date. Its motion has no component along the true equator.
- *Celestial Intermediate Equator, or the true equator*: equatorial plane through the center of the Earth and perpendicular to the celestial intermediary pole (CIP) at some epoch.
- *Celestial Intermediate Pole (CIP)*: equatorial pole defined by the IAU 2000A precession-nutation model which is the transformation from the ICRF to the true equator.
- *Earth rotation angle*: see Stellar Angle.
- *Ecliptic*: mean plane of the Earth's orbit around the Sun as determined from and designated by an ephemeris of the Earth, (e.g. ecliptic of DE 405).
- *Ecliptic longitudes and latitudes*: coordinates measured from the equinox with respect to the ecliptic of date in TCB. They can be apparent geocentric, true, or mean.
- *Equinox*: either of the two points at which the ecliptic intersects the celestial intermediate equator; also the time at which the Sun passes through either of these intersection points; i.e. when the apparent longitude of the Sun is 0 or 180 degrees. When required the equinox can be designated by the ephemeris of the Earth from which it is obtained (e.g. vernal equinox of DE 405).
- *Equinox right ascensions*: right ascensions that are measured from the equinox, instead of from the CEO.
- *Fixed ecliptic*: ecliptic for any ephemeris at epoch J2000.0, which is orientated such that the equinox is aligned with the Ox origin of the ICRS.
- *Geocentric apparent right ascensions and declinations*: positions measured in the GTRF of specific time. They are topocentric positions that have been corrected for diurnal aberration and geocentric parallax (e.g. the geocentric apparent right ascension and declination at epoch 2002 June 15.312 on TCG or TT).
- *Geocentric Celestial Dynamical Reference System*: it is used for the representation of the motion of artificial satellites. It differs from the GCRS by subtracting the geodetic precession from the current precession-nutation series. The equations of motion should include the additional terms of acceleration of the axes due to the motion of the Earth.
- *Geocentric Celestial Reference System (GCRS)*: a geocentric "space fixed" coordinate system, defined by the metric tensors of the IAU 2000 resolutions and related to the BCRS by generalized Lorentz transformations (Soffel 2000). It has no kinematic rotation since it is based on extragalactic sources and its axes are parallel to those of the ICRS.
- *Geocentric ICRF positions*: defined by the ICRF origin and equator, but are centered at the geocenter.
- *Geocentric True Reference Frame (GTRF)*: geocentric reference frame defined by the true equator, CIP, and CEO at a specified date.
- *Geocentric true right ascensions and declinations*: coordinates given in GTRF at a specific time in TCG or TT. They are geocentric apparent positions corrected for annual aberration and gravitational deflection (e.g. the true geocentric right ascension and declination at time 2002 June 15.0 in TT).
- *Geometric position*: the position of an object in a three dimensional reference frame that can be either topocentric, geocentric, or barycentric with the $Oxyz$ axes parallel to the ICRF axes.
- *International Celestial Reference Frame (ICRF)*: radio realization of the barycentric fixed celestial reference system (ICRS). Other realizations have a specific name (e.g. HCRF: Hipparcos Celestial Reference Frame).
- *International Celestial Reference System (ICRS)*: the international reference system is a fixed epoch independent system with the assumption that the extragalactic sources do not show a global rotation. It assumes in addition a relativistic space-time.
- *International Terrestrial Reference Frame (ITRF)*: a realization by a set of coordinates and velocities of fiducial points on the Earth (e.g. ITRF-2000).
- *International Terrestrial Reference System (ITRS)*: the terrestrial reference system to which the positions on the Earth are referred. It is geocentric and has no global residual rotation with respect to horizontal motions at the Earth's surface.
- *Local positions*: the observed position only corrected for refraction and instrumental parameters.
- *Right Ascension α and Declination δ*: without qualification, right ascension and declination are measured in ICRF. The epoch of the positions must be specified. By extension, catalog or mean position in a barycentric reference system from the catalog right ascension fiducial point and from the catalog equator, respectively. They are designated with the catalog reference system as necessary (e.g. Hipparcos right ascension and declination at epoch 1991.25 on TCB).
- *Stellar Angle, or Earth Rotation Angle*: angle measured along the true equator between the TEO and the CEO positively in the retrograde direction.
- *Terrestrial Ephemeris Origin (TEO)* is the origin of the longitudes in the terrestrial reference system of date.

- *Topocentric apparent position*: position on the ITRF and TT where a local place has been corrected for diurnal aberration. Alternatively, a geocentric apparent position has been transformed for Earth rotation and polar motion and corrected for diurnal parallax and light bending.

12. Conclusion

The new system, based on the ICRS and related IAU resolutions, is defined and described in this paper and is a logical progression from the old system based on the solar system dynamics and nearby stars. The new system introduces greater rigor in the definitions and some simplifications. Among the simplifications are:

- A fixed, epoch-independent, reference frame based on distant non-moving sources.
- A reference frame independent of the dynamics of the solar system.
- An origin, or departure point, not precessing along the moving equator.
- Proportionality between the new Stellar Angle, or Earth Rotation Angle, and UT1.
- Microsecond accuracy predictability of the departure point for many decades, so it is not theory-dependent.
- Lack of interaction between expressions for the motions of reference frames.

The definitions and applications of the ICRS to astrometry should be formally adopted by the IAU in 2003.

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