PART IV

IAU RESOLUTIONS AND DESCRIPTION OF ICRS

1 - IAU RESOLUTIONS

2 - ARIAS *et al.* (1995) paper

Buenos Aires, 1991

Resolution A4: Recommendations from the Working Group on Reference Systems

Recommendations I to IX

The XXIst General Assembly of the International Astronomical Union,

RECOMMENDATION I

considering,

that it is appropriate to define several systems of space-time coordinates within the framework of the General Theory of Relativity,

recommends,

that the four space-time coordinates ($x^0 = ct$, x^1, x^2, x^3) be selected in such a way that in each coordinate system centered at the barycenter of any ensemble of masses, the squared interval ds^2 be expressed with the minimum degree of approximation in the form:

$$ds^2 = -c^2 d\tau^2$$

$$= -\left(1 - \frac{2U}{c^2}\right)(dx^0)^2 + \left(1 + \frac{2U}{c^2}\right)[(dx^1)^2 + (dx^2)^2 + (dx^3)^2],$$

where c is the velocity of light, τ is proper time, and U is the sum of the gravitational potentials of the above mentioned ensemble of masses, and of a tidal potential generated by bodies external to the ensemble, the latter potential vanishing at the barycenter.

Notes for Recommendation I

1. *This recommendation explicitly introduces The General Theory of Relativity as the theoretical background for the definition of the celestial space-time reference frame.*

2. *This recommendation recognizes that space-time cannot be described by a single coordinate system because a good choice of coordinate system may significantly facilitate the treatment of the problem at hand, and elucidate the meaning of the relevant physical events. Far from the space origin, the potential of the ensemble of masses to which the coordinate system pertains becomes negligible, while the potential of external bodies manifests itself only by tidal terms which vanish at the space origin.*

3. *The ds^2 as proposed gives only those terms required at the present level of observational accuracy. Higher order terms may be added as deemed necessary by users. If the IAU should find it generally necessary, more terms will be added. Such terms may be added without changing the rest of the recommendation.*

4. *The algebraic sign of the potential in the formula giving ds^2 is to be taken as positive.*

5. *At the level of approximation given in this recommendation, the tidal potential consists of all terms at least quadratic in the local space coordinates in the expansion of the Newtonian potential generated by external bodies.*

RECOMMENDATION II

considering,

a) the need to define a barycentric coordinate system with spatial origin at the center of mass of the solar system and a geocentric coordinate system with spatial origin at the center of mass of the Earth, and the desirability of defining analogous coordinate systems for other planets and for the Moon,

b) that the coordinate systems should be related to the best realization of reference systems in space and time, and,

c) that the same physical units should be used in all coordinate systems,

recommends that,

1. the space coordinate grids with origins at the solar system barycenter and at the center of mass of the Earth show no global rotation with respect to a set of distant extragalactic objects,

2. the time coordinates be derived from a time scale realized by atomic clocks operating on the Earth,

3. the basic physical units of space-time in all coordinate systems be the second of the International System of Units (SI) for proper time, and the SI meter for proper length, connected to the SI second by the value of the velocity of light $c = 299792458\ ms^{-1}$.

Notes for Recommendation II

1. *This recommendation gives the actual physical structures and quantities that will be used to establish the reference frames and time scales based upon the ideal definition of the system given by Recommendation I.*

2. *The kinematic constraint for the rate of rotation of both the geocentric and barycentric reference systems cannot be perfectly realized. It is assumed that the average rotation of a large number of extragalactic objects can be considered to represent the rotation of the universe which is assumed to be zero.*

3. *If the barycentric reference system as defined by this recommendation is used for studies of dynamics within the solar system, the kinematic effects of the galactic geodesic precession may have to be taken into account.*

4. *In addition, the kinematic constraint for the state of rotation of the geocentric reference system as defined by this recommendation implies that when the system is used for dynamics (e.g., motions of the Moon and Earth satellites), the time dependent geodesic precession of the geocentric frame relative to the barycentric frame must be taken into account by introducing corresponding inertial terms into the equations of motion.*

5. *Astronomical constants and quantities are expressed in SI units without conversion factors depending upon the coordinate systems in which they are measured.*

RECOMMENDATION III

considering,

the desirability of the standardization of the units and origins of coordinate times used in astronomy,

recommends that,

1. the units of measurement of the coordinate times of all coordinate systems centered at the barycenters of ensembles of masses be chosen so that they are consistent with the proper unit of time, the SI second,

2. the reading of these coordinate times be 1977 January 1, $0^h\ 0^m\ 32.184^s$ exactly, on 1977 January 1, $0^h\ 0^m\ 0^s$ TAI exactly (JD = 2443144.5, TAI), at the geocenter,

3. coordinate times in coordinate systems having their spatial origins respectively at the center of mass of the Earth and at the solar system barycenter, and established in conformity with the above sections (1) and (2), be designated as Geocentric Coordinate Time (TCG) and Barycentric Coordinate Time (TCB).

Notes for Recommendation III

1. *In the domain common to any two coordinate systems, the tensor transformation law applied to the metric tensor is valid without re-scaling the unit of time. Therefore, the various coordinate times under consideration exhibit secular differences. Recommendation 5 (1976) of IAU Commissions 4, 8 and 31, completed by Recommendation 5 (1979) of IAU Commissions 4, 19 and 31, stated that Terrestrial Dynamical Time (TDT) and Barycentric Dynamical Time (TDB) should differ only by periodic variations. Therefore, TDB and TCB differ in rate. The relationship between these time scales in seconds is given by:*

$$TCB - TDB = L_B \times (JD - 2443144.5) \times 86400.$$

The present estimate of the value of L_B *is* 1.550505×10^{-8} $(\pm 1 \times 10^{-14})$ *(Fukushima et al., Celestial Mechanics, 38, 215, 1986).*

2. *The relation TCB - TCG involves a full 4-dimensional transformation*

$$TCB - TCG = c^{-2} \left[\int_{t_o}^{t} (v_e^2/2 + U_{ext}(x_e))dt + v_e.(x - x_e) \right],$$

x_e *and* v_e *denoting the barycentric position and velocity of the Earth's center of mass and* x *the barycentric position of the observer. The external potential* U_{ext} *is the Newtonian potential of all solar system bodies apart from the Earth. The external potential must be evaluated at the geocenter. In the integral,* t = *TCB and to is chosen to agree with the epoch of Note 3. As an approximation to TCB - TCG in seconds one might use:*

$$TCB - TCG = L_C \times (JD - 2443144.5) \times 86400 + c^{-2} v_e.(x - x_e) + P.$$

The present estimate of the value of L_C *is* 1.480813×10^{-8} $(\pm 1 \times 10^{-14})$ *(Fukushima et al., Celestial Mechanics, 38, 215, 1986). It may be written as* $[3GM/2c^2a] + \epsilon$ *where G is the gravitational constant, M is the mass of the Sun, a is the mean heliocentric distance of the Earth, and* ϵ *is a very small term (of order* 2×10^{-12}*) arising from the average potential of the planets at the Earth. The quantity P represents the periodic terms which can be evaluated using the analytical formula by Hirayama et al., ("Analytical Expression of* $TDB\text{-}TDT_o$*", in Proceedings of the IAG Symposia, IUGG XIX General Assembly, Vancouver, August 10-22, 1987). For observers on the surface of the Earth, the terms depending upon their terrestrial coordinates are diurnal, with a maximum amplitude of 2.1 μs.*

3. *The origins of coordinate times have been arbitrarily set so that these times all coincide with the Terrestrial Time (TT) of Recommendation IV at the geocenter on 1977 January 1,* $0^h\ 0^m\ 0^s$ *TAI. (See Note 3 of Recommendation IV.)*

4. *When realizations of TCB and TCG are needed, it is suggested that these realizations be designated by expressions such as TCB(xxx), where xxx indicates the source of the realized time scale (e.g., TAI) and the theory used for the transformation into TCB or TCG.*

RECOMMENDATION IV

considering,

a) that the time scales used for dating events observed from the surface of the Earth and for terrestrial metrology should have as the unit of measurement the SI second, as realized by terrestrial time standards,

b) the definition of the International Atomic Time, TAI, approved by the 14th Conférence Générale des Poids et Mesures (1971) and completed by a declaration of the 9th session of the Comité Consultatif pour la Définition de la Seconde (1980),

recommends that,

1) the time reference for apparent geocentric ephemerides be Terrestrial Time, TT,

2) TT be a time scale differing from TCG of Recommendation III by a constant rate, the unit of measurement of TT being chosen so that it agrees with the SI second on the geoid,

3) at instant 1977 January 1, $0^h\ 0^m\ 0^s$ TAI exactly, TT have the reading 1977 January 1, $0^h\ 0^m\ 32.184^s$ exactly.

Notes for Recommendation IV

1. *The basis of the measurement of time on the Earth is International Atomic Time (TAI) which is made available by the dissemination of corrections to be added to the readings of national time scales and clocks. The time scale TAI was defined by the 59th session of the Comité International des Poids et Mesures (1970) and approved by the 14th Conférence Générale des Poids et Mesures (1971) as a realized time scale. As the errors in the realization of TAI are not always negligible, it has been found necessary to define an ideal form of TAI, apart from the 32.184^s offset, now designated Terrestrial Time, TT.*

2. *The time scale TAI is established and disseminated according to the principle of coordinate synchronization, in the geocentric coordinate sytem, as explained in CCDS, 9th Session (1980) and in Reports of the CCIR, 1990, annex to Volume VII (1990).*

3. *In order to define TT it is necessary to define the coordinate system precisely, by the metric form, to which it belongs. To be consistent with the uncertainties of the frequency of the best standards, it is at present (1991) sufficient to use the relativistic metric given in Recommendation I.*

4. *For ensuring an approximate continuity with the previous time arguments of ephemerides, Ephemeris Time, ET, a time offset is introduced so that TT-TAI = 32.184^s exactly at 1977 January 1, 0^h TAI. This date corresponds to the implementation of a steering process of the TAI frequency, introduced so that the TAI unit of measurement remains in close agreement with the best realizations of the SI second on the geoid. TT can be considered as equivalent to TDT as defined by IAU Recommendation 5 (1976) of Commissions 4, 8 and 31, and Recommendation 5 (1979) of Commissions 4, 19 and 31.*

5. *The divergence between TAI and TT is a consequence of the physical defects of atomic time standards. In the interval 1977-1990, in addition to the constant offset of 32.184^s, the deviation probably remained within the approximate limits of ± 10μs. It is expected to increase more slowly in the future as a consequence of improvements in time standards. In many cases, especially for the publication of ephemerides, this deviation is negligible. In such cases, it can be stated that the argument of the ephemerides is TAI + 32.184^s.*

6. *Terrestrial Time differs from TCG of Recommendation III by a scaling factor, in seconds:*

$$TCG - TT = L_G \times (JD - 2443144.5) \times 86400.$$

The present estimate of the value of L_G is 6.969291×10^{-10} ($\pm 3 \times 10^{-16}$). The numerical value is derived from the latest estimate of gravitational potential on the geoid, W = 62636860 (± 30) m^2/s^2 (Chovitz, Bulletin Géodesique, 62, 359, 1988). The two time scales are distinguished by different names to avoid scaling errors. The relationship between L_B and L_C of Recommendation III, notes 1 and 2, and L_G is, $L_B = L_C + L_G$.

7. *The unit of measurement of TT is the SI second on the geoid. The usual multiples, such as the TT day of 86400 SI seconds on the geoid and the TT Julian century of 36525 TT days, can be used provided that the reference to TT be clearly indicated whenever ambiguity may arise. Corresponding time intervals of TAI are in agreement with the TT intervals within the uncertainties of the primary atomic standards (e.g., within ± 2 x 10^{-14} in relative value during 1990).*

8. *Markers of the TT scale can follow any date system based upon the second, e.g., the usual calendar date or the Julian Date, provided that the reference to TT be clearly indicated whenever ambiguity may arise.*

9. *It is suggested that realizations of TT be designated by TT(xxx) where xxx is an identifier. In most cases a convenient approximation is:*

$$TT(TAI) = TAI + 32.184^s.$$

However, in some applications it may be advantageous to use other realizations. The BIPM, for example, has issued time scales such as TT(BIPM90).

RECOMMENDATION V

considering,

that important work has already been performed using Barycentric Dynamical Time (TDB), defined by IAU Recommendation 5 (1976) of IAU Commissions 4, 8 and 31, and Recommendation 5 (1979) of IAU Commissions 4, 19 and 31,

recognizes,

that where discontinuity with previous work is deemed to be undesirable, TDB may be used.

Note to Recommendation V

Some astronomical constants and quantities have different numerical values depending upon the use of TDB or TCB. When giving these values, the time scale used must be specified.

RECOMMENDATION VI

considering,

the desirability of implementing a conventional celestial barycentric reference system based upon the observed positions of extragalactic objects, and,

noting,

the existence of tentative reference frames constructed by various institutions and combined by the International Earth Rotation Service (IERS) into a frame used for Earth rotation series,

recommends,

1. that intercomparisons of these frames be extensively made in order to assess their systematic differences and accuracy,
2. that an IAU Working Group consisting of members of Commissions 4, 8, 19, 24, 31 and 40, the IERS, and other pertinent experts, in consultation with all the institutions producing catalogs of extragalactic radio sources, establish a list of candidates for primary sources defining the new conventional reference frame, together with a list of secondary sources that may later be added to or replace some of the primary sources, and,

requests,

1. that such a list be presented to the XXIInd General Assembly (1994) as a part of the definition of a new conventional reference system,

2. that the objects in this list be systematically observed by all VLBI and other appropriate astrometric programs.

Note for Recommendation VI

This recommendation essentially describes the first part of the work that must be done to prepare the realization of the reference system defined by Recommendations I and II. The choice of objects must be made in the first place by considering their observability by VLBI, but special care should be taken to include a large proportion of extragalactic radio sources with well identified optical counterparts.

RECOMMENDATION VII

considering,

a) that the new conventional celestial barycentric reference frame should be as close as possible to the existing FK5 equator and equinox and the dynamical equinox which are referred to J2000.0,

b) that it should be accessible to astrometry in visual as well as in radio wavelengths,

recommends,

1. that the principal plane of the new conventional celestial reference system be as near as possible to the mean equator at J2000.0 and that the origin in this principal plane be as near as possible to the dynamical equinox of J2000.0,

2. that the positions of the extragalactic objects selected in accordance with Recommendation VI and representing the reference frame be computed initially for the equator and equinox J2000.0 using the best available values of the celestial pole offset with respect to the IAU expressions for precession and nutation,

3. that a great effort be made to compare reference frames of all types, in particular the FK5, solar system and extragalactic reference frames,

4. that observing programs be undertaken or continued in order to relate planetary positions to radio and optical objects, and to determine the relationship between catalogs of extragalactic source positions and the best catalogs of star positions, in particular the FK5 and Hipparcos catalogs.

Notes for Recommendation VII

1. *This recommendation specifies the choice of the coordinate axes that will be adopted in the final reference frame and describes the work to be done before such a frame can be constructed. Although the considerations call for visual and radio wavelengths for the primary catalog, other observable wavelengths are not excluded. Positions of objects observed in other wavelengths should also be referred to the same system.*

2. *The objective set by this recommendation is that there should be no discontinuity in the positions of stars when the present FK5 frame is replaced by the extragalactic reference frame. This means that the position of the extragalactic objects should be in the FK5 system for J2000.0. It is acknowledged that the best values of precession and nutation must be used in order to avoid introducing spurious proper motions into the positions of extragalactic objects. The final transfer to the preferred equinox and principal plane will be done by applying a rotation at J2000.0.*

3. *The dynamical equinox in this recommendation is defined as the intersection of the mean equator and the ecliptic. The latter is defined as the uniformly rotating plane of the orbit of the Earth-Moon barycenter averaged over the entire period for which the ephemerides are valid. Since it is ephemeris dependent, the choice of the equinoctial point will be made using the most accurate and generally available ephemerides of the solar system at the time.*

4. *The definition given to the reference system by Recommendations I and II implies the stability in time of the system of coordinates realized by the celestial reference frame. The directions of the coordinate axes should not be changed even if at some later date the realization of the dynamical equinox or CEP are improved. Similarly, modifications to the set of extragalactic objects realizing the reference system should be made in such a way that the directions of the axes are not changed. This means that once the coordinate axes have been specified, in the way described in the first part of the recommendation, the connection between the definition of the conventional reference system and the peculiarities of the Earth's kinematics will have been severed.*

5. *As long as the relationship between the optical and the extragalactic radio frames is not sufficiently accurately determined, the FK5 catalog shall be considered as a provisional realization of the celestial reference system in optical wavelengths.*

RECOMMENDATION VIII

recognizing,

a) the importance to astronomy of adopting conventional values of astronomical and physical constants,

b) that values of these constants should be unchanged unless they differ significantly from their latest estimates,

c) that estimates of these constants should be improved frequently to represent the current status of knowledge,

d) the necessity of providing standard procedures using these numerical values, and,

noting,

a) that the MERIT Standards and IERS Standards have contributed significantly to the progress of astronomy and geodesy,

b) that numerical values in these standards have served as a system of constants in analyzing observations of high quality, and

considering,

that procedures in these standards do not cover the whole of fundamental astronomy,

recommends,

that a permanent working group be organized by Commissions 4, 5, 8, 19, 24 and 31, in consultation with the IAG and the IERS, in order to update and improve the system of astronomical units and constants, the list of estimates of fundamental astronomical quantities and standard procedures; this group shall:

1. prepare a draft report on the system of astronomical units and constants at least six months before the XXIInd General Assembly (1994),

2. prepare a draft list of best estimates of astronomical quantities at least six months before each following General Assembly,

3. prepare, at least six months before each following General Assembly, a draft report on standard procedures needed in fundamental astronomy, which,

   a) should have a maximum degree of compatibility with the IERS Standards,

b) should include the implementations of procedures in the form of tested software and/or test cases,

c) should be available not only in written form, but also in machine-readable form,

4. prepare a draft report on possible electronic access to these units, constants, quantities and procedures at least six months before the XXIInd General Assembly (1994).

RECOMMENDATION IX

recognizing,

that a generally accepted non-rigid Earth theory of nutation, including all known effects at the one tenth milliarcsecond level, is not yet available,

recommends,

1. that those satisfied with accuracy of the nutation angles (ϵ or $\psi \sin\epsilon_0$) numerically greater than $\pm$ 0.002" (one sigma rms) may continue to use the 1980 IAU Nutation Theory (P.K. Seidelmann, Celestial Mechanics, 27, 79, 1982),

2. that those requiring values of the nutation angles more accurate than $\pm$ 0.002" (one sigma rms) should make use of the Bulletins of the IERS which publish observations and predictions of the celestial pole offsets accurate to about $\pm$ 0.0006" (one sigma rms) for a period of up to six months in advance,

3. that the IUGG be encouraged to develop and adopt an appropriate Earth model to be used as the basis for a new IAU Theory of Nutation.

CCIR *International Radio Consultative Committee*

IAG *International Association of Geodesy*

IUGG *International Union of Geodesy & Geophysics*

IERS *International Earth Rotation Service*

Den Haag, August 1994

Resolution B5 on the Working Group on Reference Frames

The XXIInd General Assembly of the International Astronomical Union

Considering that the IAU Working Group on Reference Frames consisting of members of Commissions 4, 8, 19, 24 and 31, the International Rotation Service (IERS) and other pertinent experts has been formed to produce a list of candidate extragalactic radio sources for defining the new conventional reference frame and secondary sources that may later be added to the primary sources or replace some of the primary sources,

Noting that a list of sources which define the conventional reference frame together with list of candidate sources which may, at some future date, be added to or replace the defining sources has been made,

Recommends that this list of defining sources be adopted by the XXIInd General Assembly (1994) as the first stage in the definition of the new reference frame, and

Requests that the Working Group on Reference Frames be continued and its membership be reviewed by Commissions 4, 8, 19, 24 and 31 and the IERS to

1. define the positions of the radio sources on the list,

2. determine the relationship of this frame to an optical frame defined by stars, and

3. recommend to the XXIIIrd General Assembly (1997) that a way be found to organize the work for the maintenance and evolution of this frame and its extension to other frames at other wavelengths.

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ASTRONOMY
AND
ASTROPHYSICS

The extragalactic reference system of the International Earth Rotation Service, ICRS

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Abstract. The celestial reference system of the International Earth Rotation Service (IERS), ICRS, was recommended to the International Astronomical Union (IAU) for adoption as the conventional system, under the name of International Celestial Reference System, by the IAU working group on reference frames. This system agrees with the decisions taken by IAU in 1991 and it is consistent with the FK5 system at J2000.0. It is maintained on the basis of high-accuracy observations of extragalactic radio sources by very long baseline interferometry (VLBI). The maintenance algorithm ensures stable directions of its axes within ±20 microarcseconds. The typical accuracy of the source coordinates is ±300 microarcseconds. ICRS is accessible directly by the observation of extragalactic objects and indirectly through the major reference frames attached to the Galaxy, the Solar System and the Earth.

Key words: reference systems – astrometry – quasars:general

1. Introduction

The International Astronomical Union (IAU) decided in 1991 that its celestial reference system would be realized on the basis of precise coordinates of extragalactic radio sources. The corresponding IAU recommendations (Bergeron 1992) specify that its origin has to be at the barycentre of the Solar System and that its axes have to be fixed with respect to the extragalactic objects.

One of the missions of the International Earth Rotation Service (IERS) is to maintain a comprehensive reference system for application in astronomy, in space navigation and in global geodynamics. The IERS celestial reference system (ICRS), materialised by the J2000.0 equatorial coordinates of compact extragalactic radio sources measured by very long baseline interferometry (VLBI), fulfills the IAU recommendations.

The definition, the realization, the maintenance and the accessibility of ICRS are described in this paper.

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2. Definition of ICRS

The 1991 IAU recommendations on reference frames request that the future IAU celestial reference frame be based on a kinematical rather than dynamical definition by using quasars or active nuclei of galaxies for its materialisation. This new concept in the history of IAU celestial reference frames is expected to make coordinate axes fixed with respect to distant matter in the Universe. The earlier definitions adopted privileged axes in the dynamics of the Earth's motion in space, the mean equator and the dynamical equinox at some reference epoch (e.g. B1950, J2000.0). For the sake of continuity, the previous conventional directions at J2000.0 were retained in the new definition. As a result, the new coordinate axes are expected to be consistent with the previous ones, implicitly defined by the FK5 star catalogue (Fricke et al. 1988), within the uncertainty of the latter. We explain below how the definition of ICRS agrees with the IAU recommendations and we show its continuity with the FK5 system.

2.1. Origin of coordinate axes

According to the IAU recommendations, the origin of coordinate axes of the new celestial reference system should be at the barycentre of the Solar System.

This condition is fulfilled for ICRS through modelling of observations in the framework of General Relativity. Agreement has been reached among analysts on the appropriate corrections (see McCarthy 1992). Further intercomparison of the various models actually used is necessary to check the accuracy of the actual barycentric property of the coordinate axes.

2.2. Principal plane

The IAU recommends that the principal plane of the new celestial reference system be close to the mean equator at J2000.0.

The principal plane of the IERS system was defined by the equator plane implied by the IAU (1976) and IAU (1980) con-

ventional precession and nutation (Lieske et al. 1977; Seidelmann 1982). Since these models are now known to be in error by several milliarcseconds (mas), it is necessary to use more accurate precession and nutation models to locate the mean equator of J2000.0, relative to the IERS system. Such models can indeed be built from the same VLBI observations that serve to establish the extragalactic reference frame. For this purpose, Souchay et al. (1995) analysed the 1979–1994 VLBI estimates of the Earth's celestial pole offsets (Ma et al. 1994) and derived corrections to the conventional precession and to the largest nutation terms. Based on their corrections, the predicted shift of the Earth's mean pole at J2000.0, relative to the IERS celestial pole, is 18.0 ± 0.1 mas in the direction 12h and 5.3 ± 0.1 mas in the direction 18h. Another independent study combining 16 years of VLBI observations and 24 years of lunar laser ranging (LLR) observations (Charlot et al. 1995) concludes that these shifts are 17.5 ± 1.0 mas and 4.7 ± 1.0 mas, respectively. The two studies are consistent and show that the ICRS celestial pole is offset from the mean pole at J2000.0 by less than 20 mas.

The IAU recommendations also stipulate that the direction of the new conventional celestial pole be consistent with that of the FK5 system. The uncertainty of the FK5 pole direction can be estimated (i) by considering that the systematic part is dominated by a correction of −2.5 mas/a to the precession constant imbedded in the FK5 system, and (ii) by adopting Fricke's (1982) accuracy of the FK5 equator (±20 mas), and Schwan's (1988) limit to the residual rotation (±0.7 mas/a), taking the epochs of observations from Fricke et al. (1988). Assuming that the error in the precession rate is absorbed by the proper motions of stars, the uncertainty on the FK5 pole position relative to the mean pole at J2000.0 estimated in this way is ±50 mas. Thus the IERS celestial pole is consistent with that of the FK5 system within the uncertainty of the latter.

2.3. Origin of right ascensions

The IAU recommends that the origin of right ascensions of the new celestial reference system be close to the dynamical equinox at J2000.0.

The Ox axis of the IERS celestial system was implicitly defined in the initial realization (Arias et al. 1988) by adopting the right ascensions of 23 radio sources from catalogues obtained by the Goddard Space Flight Center (GSFC), the Jet Propulsion Laboratory (JPL), and the National Geodetic Survey (NGS). These catalogues were compiled by fixing the right ascension of 3C273B to the usual (Hazard et al. 1971) conventional FK5 value (12h 29m 6.6997s at J2000.0).

The uncertainty in the FK5 origin of right ascensions is estimated to be ±80 mas. This value was derived from the equator accuracy given by Fricke (1982) and from the residual rotation rate limit given by Schwan (1988), assuming a mean epoch of 1955 for the star proper motions and random errors in the FK5 positions. Studies by Morrison et al. (1990) and Lindegren et al. (1995) have shown that the FK5 catalogue has systematic position errors of the order of 100 mas. As a consequence the above uncertainty (±80 mas) is likely to be optimistic.

The location of the dynamical equinox in the IERS system was recently determined within ±10 mas by Folkner et al. (1994). By using an indirect method comparing VLBI and LLR terrestrial frames and Earth orientation, they derived the frame tie between the IERS system and the JPL Solar System ephemeris frame. Their results show that the x-axis of the IERS system is offset from the mean equinox of epoch J2000 by 78 ± 10 mas. Thus, the ICRS origin of right ascensions is consistent with the FK5 origin, and complies with the IAU recommendations.

3. Realization and maintenance of ICRS

3.1. Accuracy and precision

The accuracy of the axes of ICRS could in principle be limited, either by inaccurate precession and nutation models, or by large-scale systematic errors in the source coordinates.

It is well known that, as a result of the inaccuracy of the conventional IAU (1976) precession and IAU (1980) theory of nutation, their direct use in the analysis of VLBI observations would give rise to systematic errors in the source positions and to misorientation of the axes of the frames, both at the level of a few milliarcseconds. Therefore the established practice in catalogue work is to estimate additional parameters which describe the motion of the celestial pole relative to its conventional position, either by estimating celestial pole offsets for each session, or by estimating corrections to the precession constant and to some of the largest nutation terms, as allowed by the length and density of the series of observations analysed. Sovers (1991) showed that these procedures have similar performances on the resulting source positions. The estimation of coordinates in ICRS is based on frames obtained at the IERS analysis centres by one of these techniques. Consequently they are free from systematic errors caused by inaccurate precession and nutation models. The small offsets between the poles of the catalogues, that are due to inconsistent fixing of the celestial pole offsets at some reference day, are accounted for by the adjustment of rotation angles; they have no influence on the consistency of source coordinates in the IERS frame.

Another type of possible systematic error is related to low elevation observations in the case of observing networks with a modest north-south extension. This effect may be modelled as a linear dependence of declination errors on declination which can reach 0.01 mas per degree and create a tilt of the frame equator of up to 0.6 mas (Feissel et al. 1995). However, considering recent global analyses based on complex observing networks, these systematic differences seem to be now at the level of 0.001 mas per degree and 0.1 mas respectively (IERS 1994). No other type of systematic differences can be found above this level in the present-day VLBI celestial reference frames (Feissel et al. 1995; Eubanks et al. 1994). This is confirmed by the fact that the residual coordinate differences, after taking into account the small systematic errors mentioned above, decrease as the square root of the number of observations, with a typical value of ±0.25 mas for 100 observations (Arias et al. 1993).

Table 1. Relative orientation of the successive realizations of ICRS (angles A_1, A_2, A_3 rotate the realization of year $n-1$ to that of year n based on the subset of primary sources of year $n-1$)

Year of realization	Number of sources total	primary	A_1 (mas)	A_2 (mas)	A_3 (mas)	References
1988	228	23	—	—	—	Arias et al. (1988)
1989	209	20	-0.15 ± 0.10	-0.24 ± 0.10	0.21 ± 0.07	IERS (1989)
1990	228	51	0.00 ± 0.12	0.07 ± 0.11	0.05 ± 0.10	IERS (1990)
1991	396	57	0.03 ± 0.05	0.06 ± 0.04	0.00 ± 0.04	IERS (1991)
1992	422	65	0.05 ± 0.09	0.03 ± 0.09	-0.09 ± 0.07	IERS (1992)
1993	504	153	0.00 ± 0.03	0.00 ± 0.03	0.00 ± 0.02	IERS (1993)
1994	531	209	0.00 ± 0.02	0.00 ± 0.02	0.00 ± 0.02	IERS (1994)

3.2. Maintenance

The new highly precise astrometric techniques and the possibility to re-analyse large numbers of observations whenever necessary raise the question of how one should understand the conventional character of the celestial frame. In practice, there are two possible interpretations:

(i) The source coordinates themselves are considered conventional, i.e., their numerical values are fixed for some time (years). This is the philosophy on which the series of FK catalogues is based.

(ii) The axes of the system are conventionally considered as fixed to their initial directions, but improved source coordinates available at the time of analysis are provided to users; this is required for space navigation, Earth orientation programs, geodetic applications, the link of celestial frames, etc. The maintenance method applied by IERS is along these lines; such a procedure is made possible by the high model standardization among the IERS analysis centres, and because the implementation of an extragalactic celestial frame implies less geophysical and astronomical modelling than does the series of FK catalogues. This approach was also adopted in the 1991 IAU resolutions on reference systems.

The initial definition of the IERS system and its maintenance process are described by Arias & Feissel (1990). As new information on source positions became available, new issues of the IERS celestial reference frame (ICRF) were introduced, applying every time a no rotation constraint with respect to the previous realization. In this process, the axes of the frame were maintained and the frame was progressively densified and made more precise. The maintenance of the axes is based on selected primary (or defining) sources, whose coordinates are stable and consistent. With the increasing quality of results since the start of this work, the number of primary sources increased from 23 in 1988 to 209 in 1994. Table 1 lists the issues of ICRF since 1988, with the successive rotation angles estimated on the basis of the subset of primary sources. The stability of axes is currently kept within ± 0.02 mas. The progressive refinement and densification of the frame was based on VLBI observation programs operated by the Jet Propulsion Laboratory, a consortium of geodetic institutes in the framework of IRIS (International Radio Interferometry Surveying), the Goddard Space Flight Center, the US Naval Observatory, and the Naval Research Laboratory.

The non-rotating character of the frame results from the assumption that the sources have undetectable proper motions; checks are regularly performed to ensure the validity of this constraint (Ma & Shaffer 1991; Eubanks et al. 1994). Apparent motions may be observed for some sources, but they are likely to be caused by variations in their mas-scale brightness distribution. For example, Charlot (1994) showed that the apparent change of position observed for the quasar 3C273 vanishes when its mas-scale structure is modelled in the VLBI analysis with its astrometric position referred to the central core of the source. When changes in the observed position are detected for some sources, a special treatment needs to be applied.

To conclude the preparation phase started by IERS in 1988, defining coordinates for the extragalactic objects selected by the IAU working group on reference frames (De Vegt & Johnston 1994) will be adopted in 1995. The typical accuracy of the source coordinates is ± 0.3 mas (IERS 1994). In the future, the IAU sources will be monitored, and IERS will continue to study the stability of their coordinates and publish the necessary updates (Arias & Gontier 1994).

4. Accessibility of ICRS

The direct access to the extragalactic objects is most precise through VLBI observations, a technique which is not widely available to users. Therefore, while VLBI is used for the maintenance of the frame, the tie of ICRS to the major practical reference frames (the Hipparcos galactic reference frame, the JPL ephemerides of the Solar System, and the IERS terrestrial reference system) is or will be secured.

The tie of the galactic frame to ICRS is a part of the Hipparcos project. It is described in some detail by Lindegren & Kovalevsky (1995). It will be based on a variety of approaches: observation of radio stars by VLBI (Lestrade et al. 1995) and by connected-element radio interferometry, Hubble Space Telescope astrometry, photographic astrometry, and Earth orienta-

tion observations. Its expected accuracy is ±0.5 mas at the Hipparcos mean epoch of observation (1991.25) and ±0.5 mas/a for the time evolution.

The Jet Propulsion Laboratory has announced (Standish 1994) that their future lunar and planetary ephemerides will be oriented onto the extragalactic celestial reference frame. The study by Folkner et al. (1994) shows that the tie between the two reference frames is known within ±3 mas.

The IERS Earth orientation parameters provide the permanent tie of ICRS to the IERS terrestrial reference system (ITRS). This tie is available daily with an accuracy of 0.5 mas (Feissel et al. 1993). The principles on which ITRS is established and maintained are described by Boucher & Altamimi (1990). It is geocentric, the centre of mass being defined for the whole Earth, including oceans and atmosphere. It is available worldwide at the ±1 cm level of accuracy by a reference frame consisting of coordinates for about 200 sites observed by VLBI, lunar and satellite laser ranging, and by the GPS and DORIS satellite-based radio positioning systems.

5. Conclusion

The IERS celestial reference system, ICRS, is defined in agreement with the 1991 IAU recommendations. Its realization is precise at the sub-milliarcsecond level. ICRS provides continuity with the old conventional celestial reference system (FK5) within the errors of the latter. It is accessible directly by VLBI observation of the extragalactic fiducial objets (compact radio sources), and indirectly via the Hipparcos stellar catalogue, the JPL ephemerides, and the IERS terrestrial reference frame through Earth orientation parameters. It is maintained on the basis of permanent VLBI observing programs in geodynamics and additional astrometric campaigns.

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