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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) conventional 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 orientation 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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