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LETTER

Letter to the Editor

The adoption of ICRS on 1 January 1998: meaning and consequences

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Abstract. As of 1 January 1998, the celestial reference system adopted by the IAU will be based on a set of extragalactic directions, replacing the Fundamental Katalog No 5 (FK5) that gave star coordinates in a reference system (referred to as equator and equinox J2000) based primarily on the dynamics of the solar system. This change is deeper than a mere replacement of a reference system by a better one. It implies a drastic modification in the underlying concepts and has practical consequences at various levels for the users needing the best astrometric accuracy. The IAU decision begins a new era in the definition of reference systems and marks a sharp break with the practice of the last three hundred years characterized by the long series of fundamental star catalogues.

1. Historical background

1.1. The quasi-inertial frame

Adopting extragalactic directions as primary celestial references instead of star positions has been envisioned for over a decade by the International Astronomical Union (IAU). A series of Working Groups was organized jointly by several IAU commissions mainly to establish lists of objects appropriate for observation by Very Long Baseline radio Interferometry (VLBI) at wavelengths of 13 and 3.6 cm. VLBI is the technique that measures most efficiently directions of compact extragalactic radio sources, reaching sub-milliarsecond (mas) accuracy.

A decisive breakthrough was the formulation by the Working Group on Reference Systems (1988-1991) of a comprehensive group of recommendations that dealt with both the fundamental concepts of space-time references and their actual realizations. During the 1991-1994 term, the IAU Working Group on Reference Frames (WGRF) produced a list of about 600 radio sources that could be used to realize an extragalactic celestial reference system, provided that careful observations could tie them together into a consistent system. Meanwhile the International Earth Rotation Service (IERS) had initiated and developed operational procedures to maintain the celestial reference system. During the 1994-1997 term, the WGRF concluded this preparatory phase by recommending that the 1997 IAU General Assembly adopt the IERS celestial reference system under the name International Celestial Reference System (ICRS) and to charge the IERS to maintain its realization, the ICRF (International Celestial Reference Frame), in cooperation with an IAU working group on reference frames.

The fixed directions underlying the FK5 (Fricke et al. 1988) and the preceding fundamental star catalogues of positions and proper motions were defined by the mean equator and equinox at a reference epoch (J2000.0 for the FK5, B1950 for the FK4), which implied dynamical modelling of the Earth's orbital motion (ecliptic, equinox) for the realization of the reference frame and its subsequent access. In the past, these fundamental directions were considered conventional for some decades; they were changed from time to time, in particular to take advantage of advances in modelling of the motion of solar system objects. As was originally proposed by Guinot (1979), the IAU, in its 1991 Recommendations on Reference Systems (Bergeron 1992), decided to select distant extragalactic objects as the basis of its new celestial reference system and to adopt directions that would remain fixed with respect to a selected set of these objects. Continuity between the old and new system was mandatory so that these directions would be consistent with their previous realizations, i.e., the pole and origin of right ascensions in the new reference system should be close to the FK5 pole and right ascension origin, within the uncertainties of the FK5. A fundamental advantage of selecting extragalactic objects is that they are so distant that their proper motions are currently undetectable, even by the most precise techniques. More quantitatively, if we assume that the tangential velocity of a distant extragalactic object is comparable to its recession speed, the angular motion would be given by the Hubble constant, or about 0.01 mas/a.

According to the new rules adopted in the 1991 IAU Recommendations, the fundamental directions of the celestial reference system will remain fixed in space, as long as the directions of the distant extragalactic sources can be regarded as fixed directions. They will no longer be dependent on precise modelling

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of the motion of solar system objects and on the definition of the equinox by means of the celestial equator and the ecliptic.

The adopted positions of the defining sources may be re-estimated when improved information is available, but the direction of the coordinate axes will be maintained by implementing the statistical condition that the new coordinates of selected sources show no global rotation with respect to the old set. It is also foreseen that some sources may be deleted or new ones could be added in the future. This will be done by adhering strictly to a predefined procedure.

In order that the use of this new reference system should not be detrimental to the analysis of the highly accurate astrometric techniques, the IAU explicitly introduced the Theory of General Relativity as the background for all theoretical and data analysis problems related to time and space.

1.2. The IAU Resolutions

At its 23rd General Assembly in August 1997, the IAU decided (Appenzeller 1998),

- That, as from 1 January 1998, the IAU celestial reference system shall be the International Celestial Reference System (ICRS) as specified in the 1991 IAU Resolution on Reference Systems and as defined by the International Earth Rotation Service (IERS);
- That the corresponding fundamental reference frame shall be the International Celestial Reference Frame (ICRF) constructed by the IAU Working Group on Reference Frames;
- That the Hipparcos Catalogue shall be the primary realization of the ICRS at optical wavelengths;
- That IERS should take appropriate measures, in conjunction with the IAU Working Group on Reference Frames, to maintain the ICRF and its ties to the reference frames at other wavelengths.

In the next two sections we briefly describe the ICRS, the ICRF and the Hipparcos catalogue, summarize the basic principles of the maintenance of the ICRF, and list the main consequences of the change.

2. ICRS and ICRF, Hipparcos, FK5, Equator and Equinox

By *Reference System* it is meant the set of prescriptions and conventions together with the modelling required to define, at any time, a triad of axes.

By *Reference Frame* it is meant a practical realization with given fiducial directions agreeing with the concepts introduced in the corresponding Reference System.

2.1. ICRS: The International Celestial Reference System

The ICRS (Arias et al. 1995) complies with the conditions specified by the 1991 IAU Recommendations. The origin of the ICRS axes is located at the barycentre of the solar system and the directions of its axes are fixed relative to distant extragalactic sources. For the sake of continuity with the FK5 pole, the ICRS pole is in the J2000.0 direction defined by the conventional IAU models for precession (Lieske et al. 1977) and nutation (Seidelmann 1982). The origin of right ascensions is also defined consistently with that of the FK5 by fixing the right ascension of 3C 273B to the Hazard et al. (1971) FK4 value transformed to the J2000(FK5) System (Kaplan et al. 1982).

The Hipparcos star positions and proper motions (ESA 1997) and the JPL solar system ephemerides (starting with DE403, see Standish 1997) are already expressed in the ICRS and several new catalogues (Urban et al. 1997a,b) in the visible have been aligned with the Hipparcos system, the latter being used as a secondary realization of the ICRS. The International Terrestrial Reference System (ITRS), also maintained and made available by the IERS as the International Terrestrial Reference Frame (ITRF), is connected to the ICRS at any time by the IERS Earth Orientation Parameters (EOP) with an accuracy equivalent to 1 cm at the surface of the Earth.

2.2. ICRF: The International Celestial Reference Frame

The choice of extragalactic objects to realize the fiducial directions was made possible by the availability of a mature and highly precise observing technique, Very Long Baseline radio Interferometry (VLBI). A detailed description of astrometric and geodetic VLBI analysis is given by Sovers and Jacobs (1996). The major sets of software in use for this modelling have been intensively tested and compared to each other. They are considered to be implemented consistently within one picosecond for the delay and one femtosecond/second for the delay rate, one order of magnitude better than the observations (Jacobs et al. 1997).

The ICRF consists of a catalogue of equatorial coordinates of 608 extragalactic radio sources derived from about 1.6 million observations accumulated by a worldwide network over 1979-1995. It was derived by a sub-group of the WGRF that agreed on an optimal data analysis strategy (Ma et al. 1998). It includes three lists of objects, with

1. the most compact and best observed 212 *defining* sources, with a median uncertainty of 0.4 mas on individual positions,
2. compact sources (294) whose positions are likely to be improved when more observations are accumulated in the future,
3. sources less appropriate for astrometric purposes (102), but which are provided for possible ties of reference frames at other wavelengths or for other objectives.

The accuracy of the ICRF realization of the ICRS axes is estimated to be 0.02 mas.

Extensive information on the ICRF is available in (Ma & Feissel 1997) and electronically (anonymous ftp and WWW site: hpiers.obspm.fr).

2.3. The Hipparcos Catalogue and the ICRF

The direct result of the data processing of the Hipparcos observations was a catalogue of astrometric positions for about 120 000

Table 1. Global orientation and spin between the FK5 and the ICRS at J2000.0. The Hipparcos Catalogue has been used as intermediate frame and the uncertainties propagated accordingly (Mignard & Froeschlé 1997).

	Orientation (mas)			Spin(mas/a)	
	J2000.0	σ			σ
ϵ_x:	-19.9	2.3	ω_x:	-0.30	0.27
ϵ_y:	- 9.1	2.3	ω_y:	0.60	0.27
ϵ_z:	22.9	2.3	ω_z:	0.70	0.27

stars of exceptionally good precision and free of regional error at the level of 0.1 mas. The intermediate frame in which these positions and proper motions were given was still arbitrary. A connection between the intermediate Hipparcos frame and the ICRS was carried out by using various data and methods (Lindegren & Kovalevsky 1975; Kovalevsky et al. 1997). The resulting alignment of the published Hipparcos Catalogue with the ICRS was eventually realized with standard errors for each axis of 0.6 mas for the orientation at J1991.25 and 0.25 mas/a for the spin. Consequently the Hipparcos Catalogue provides the master realization of the ICRS in the optical domain with the above uncertainties.

2.4. The FK5 and the ICRS

As the complete FK5 catalogue was observed by Hipparcos, the directions of the pole and origin of right ascensions of the FK5 relative to Hipparcos were determined, with an accuracy of 2.3 mas at the mean epoch J1991.25. The relative spin between the FK5 and Hipparcos frames was also assessed from the systematic deviations between the proper motions, with an accuracy of 0.1 mas/a. Eventually the directions of the FK5 axes in the ICRS were estimated (Table 1), taking into account the propagation of the uncertainty of the Hipparcos tie to the ICRS. The modelling of the FK5 non global deformations affect marginally the estimation of the orientation and spin.

The infinitesimal angles ϵ_x, ϵ_y, ϵ_z are defined as direct rotations around the ICRS axes pointing in the directions α = 0 h, α = 6 h, δ = 90° respectively; ω_x, ω_y, ω_z are defined as their corresponding time derivatives.

2.5. The mean pole and equinox at J2000.0 in the ICRS

According to their authors, the realizations of the mean pole and equinox at J2000.0 by means of the FK5 (Fricke et al. 1988) have respective uncertainties of 50 mas and 80 mas. VLBI and Lunar Laser Ranging (LLR) allow more accurate determination of these physical directions in the ICRS.

Using a state of the art precession-nutation model (McCarthy 1996), the analysis of long VLBI series of the observed motion of the celestial pole in the ICRS allows us to derive the coordinates of the mean pole at J2000.0 in the ICRS (IERS 1997). Combining VLBI and LLR Earth orientation and terrestrial reference frames and using the JPL planetary ephemeris

Table 2. ICRS coordinates of the mean celestial pole (ϵ_x, ϵ_y) and of the equinox (ϵ_z), see Fig. 1.

	Orientation (mas)	
	J2000.0	σ
ϵ_x:	- 5.1	0.01
ϵ_y:	17.2	0.01
ϵ_z:	-78	10

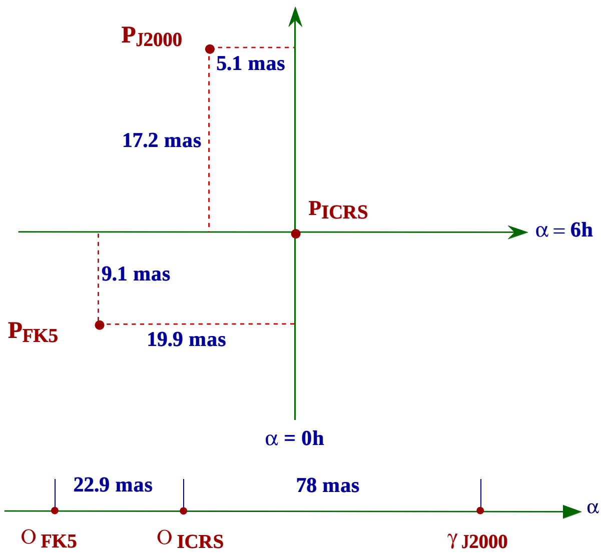

Fig. 1. Location of the poles and the origin of right ascensions of the FK5 and that of the celestial pole and equinox at J2000.0 with respect to the ICRS (values of Tables 1 & 2).

DE200, Folkner et al. (1994) derived the offset of the mean equinox at J2000.0 relative to the ICRS origin of right ascensions. Resulting values are summarized in Table 2.

The infinitesimal rotations of Tables 1 and 2 can be transformed into the coordinates of the poles on a plane tangent to the ICRS pole, as shown in Fig. 1. The position of the origins of right ascensions are also depicted along the equator.

3. Practical consequences of the adoption of the ICRS/ICRF

Kovalevsky & McCarthy (1997) have considered the various consequences of the change from the J2000 Reference System to ICRS, with particular emphasis on the conceptual aspects. We summarize hereafter the consequences in every-day life of the astronomers.

- For all uses with accuracy requirement less stringent than 50 mas, the adoption of ICRS has no significant effect.
- There is no epoch attached to the system, i.e., future updates of the ICRF will not change the ICRS origin and that of its defining directions.

- Changes of stellar positions between two epochs are derived by allowing for proper motion. The new positions are still referred to the ICRS.
- For precise applications, the IERS 1996 precession-nutation model (McCarthy 1996) or the celestial pole offsets published by the IERS should be used, rather than the less accurate IAU conventional models. The IERS 1996 model being referred to the mean pole at J2000.0 that is offset from the ICRS one, two additional constants must be used in order to refer the motion to the ICRS pole. Estimates of these constants corresponding to Fig. 1 are - 43.1 mas in longitude (-17.2 mas/sin ϵ) and - 5.1 mas in obliquity (IERS 1997).
- The direction of celestial objects in the ICRS are consistent with the terrestrial coordinates in the ITRS by the use of the IERS Earth orientation parameters (universal time, polar motion, precession-nutation).

The IAU Division 1 (Fundamental Astronomy) has set up an ICRS Working Group, in charge of studying all consequences of the adoption of the ICRS, and proposing solutions. This Working Group is chaired by François Mignard.

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