2 Conventional Celestial Reference System and Frame

The celestial reference system is based on a kinematical definition, making the axis directions fixed with respect to the distant matter of the universe. The system is materialized by a celestial reference frame defined by the precise coordinates of extragalactic objects, mostly quasars, BL Lac sources and few active galactic nuclei (AGNs), on the grounds that these sources are so far away that their expected proper motions should be negligibly small. The current positions are known to better that a milliarcsecond, the ultimate accuracy being primarily limited by the structure instability of the sources in radio wavelengths. The USNO Special Analysis Center for Source Structure has a web site at <[1]>.

The related IAU recommendations (see McCarthy, 1992) specify that the origin is to be at the barycenter of the solar system and the directions of the axes should be fixed with respect to the quasars. These recommendations further stipulate that the celestial reference system should have its principal plane as close as possible to the mean equator at J2000.0 and that the origin of this principal plane should be as close as possible to the dynamical equinox of J2000.0. This system was prepared by the IERS and has been adopted by the IAU General Assembly of 1997 under the name of the International Celestial Reference System (ICRS). It officially replaced the FK5 system on January 1, 1998, considering that all the conditions set up by the 1991 resolutions were fulfilled, including the availability of an optical reference frame realizing the ICRS with an accuracy significantly better than the FK5.

2.1 The ICRS

The necessity of maintaining the reference directions fixed and the continuing improvement in the source coordinates requires regular maintenance of the frame. Realizations of the IERS celestial reference frame have been computed every year between 1989 and 1995 (see the IERS annual reports) keeping the same IERS extragalactic celestial reference system. The number of defining sources has progressively grown from 23 in 1988 to 212 in 1995. Comparisons between successive realizations have shown that there were small shifts from year to year until the process converged to better than 0.1 mas and to 0.02 mas for the relative orientation between successive realizations. The IERS proposed that the 1995 version of the IERS system be taken as the International Celestial Reference System (ICRS). This was formally accepted by the IAU in 1997 and is described in Arias *et al.* (1995).

2.1.1 Equator

The IAU recommendations call for the principal plane of the conventional reference system to be close to the mean equator at J2000.0. The VLBI observations used to establish the extragalactic reference frame are also used to monitor the motion of the celestial pole in the sky (precession and nutation). In this way, the VLBI analyses provide corrections to the conventional IAU models for precession and nutation (Lieske *et al.*, 1977; Seidelmann, 1982) and accurate estimation of the shift of the mean pole at J2000.0 relative to the Conventional Reference Pole of the ICRS. Based on the VLBI solutions submitted to the IERS in 2001, the shift of the pole at J2000.0 relative to the ICRS celestial pole has been estimated by using (a) the updated nutation model IERS(1996) and (b) the new MBH2000 nutation model (Mathews *et al.*, 2002). The direction of the mean pole at J2000.0 in the ICRS is +17.1mas in the direction 12^h and +5.0mas in the direction 18^h when the IERS(1996) model is used, and

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[1]http://rorf.usno.navy.mil/ivs_saac

+16.6mas in the direction 12^h and +6.8mas in the direction 18^h when the MBH2000 model is adopted (IERS, 2001).

The IAU recommendations stipulate that the direction of the Conventional Reference Pole should be consistent with that of the FK5. The uncertainty in the direction of the FK5 pole can be estimated by considering (1) that the systematic part is dominated by a correction of about $-0.30''/c$ to the precession constant used in the construction of the FK5 System, and (2) by adopting Fricke's (1982) estimation of the accuracy of the FK5 equator ($\pm 0.02''$), and Schwan's (1988) estimation of the limit of the residual rotation ($\pm 0.07''/c$), 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 in the FK5 pole position relative to the mean pole at J2000.0 estimated in this way is ± 50 mas. The ICRS celestial pole is therefore consistent with that of the FK5 within the uncertainty of the latter.

2.1.2 Origin of Right Ascension

The IAU recommends that the origin of right ascensions of the ICRS be close to the dynamical equinox at J2000.0. The x axis of the IERS celestial system was implicitly defined in its initial realization (Arias *et al.*, 1988) by adopting the mean right ascension of 23 radio sources in a group of catalogs that were compiled by fixing the right ascension of the quasar 3C 273B to the usual (Hazard *et al.*, 1971) conventional FK5 value ($12^h29^m6.6997^s$ at J2000.0) (Kaplan *et al.*, 1982).

The uncertainty of the determination of the FK5 origin of right ascensions can be derived from the quadratic sum of the accuracies given by Fricke (1982) and Schwan (1988), considering a mean epoch of 1955 for the proper motions in right ascension (see last paragraph of the previous section for further details). The uncertainty thus obtained is ± 80 mas. This was confirmed by Lindegren *et al.* (1995) who found that the comparison of FK5 positions with those of the Hipparcos preliminary catalogue shows a systematic position error in FK5 of the order of 100 mas. This was confirmed by Mignard and Froeschlé (2000) when linking the final Hipparcos catalog to the ICRS.

Analyses of LLR observations (Chapront *et al.*, 2002; IERS, 2000) indicate that the origin of right ascensions in the ICRS is shifted from the inertial mean equinox at J2000.0 on the ICRS reference plane by -55.4 ± 0.1 mas (direct rotation around the polar axis). Note that this shift of -55.4 mas on the ICRS equator corresponds to a shift of -14.6 mas on the mean equator of J2000.0, that is used in Chapter 5. The equinox of the FK5 was found by Mignard and Froeschlé (2000) to be at -22.9 ± 2.3 mas from the origin of the right ascensions of the IERS. These results indicate that the ICRS origin of right ascension complies with the IAU recommendations.

2.2 The ICRF

The ICRS is materialized by the International Celestial Reference Frame (ICRF). A realization of the ICRF consists of a set of precise coordinates of extragalactic radio sources. The objects in the frame are divided in three subsets: "defining," "candidate" and "other" sources. Defining sources should have a large number of observations over a sufficiently long data span to assess position stability; they maintain the axes of the ICRS. Sources with an insufficient number of observations or an observing time span too short to be considered as defining sources are designated as candidate; they could be potential defining sources in future realizations of the ICRF. The category of "other" sources includes those objects with poorly determined positions which are useful in deriving various frame links.

A first realization of the ICRF was constructed in 1995 by a reanalysis of the available VLBI observations. The set of positions obtained by this analysis was rotated to the ICRS; the position formal uncertainties were calibrated to render their values more realistic (IERS, 1997; Ma *et al.*, 1998). Following the maintenance process which characterizes the ICRS, an extension of the frame, ICRF-Ext.1 was constructed by using VLBI data available until April 1999 (IERS, 1999). For defining sources, the positions and errors are unchanged from the first realization of the ICRF. The 212 defining extragalactic radio sources are distributed over the sky with a median uncertainty of ± 0.35 mas in right ascension and of ± 0.40 mas in declination. The uncertainty from the representation of the ICRS is then established to be smaller than 0.01 mas. The scattering of rotation parameters of different comparisons performed, shows that these axes are stable to ± 0.02 mas. Note that this frame stability is based upon the assumption that the sources have no proper motion and that there is no global rotation of the universe. The assumption concerning proper motion was checked regularly on the successive IERS frames (Ma and Shaffer, 1991; Eubanks *et al.*, 1994) as well as the different subsets of the final data (IERS, 1997). For candidate and other sources, new positions and errors have been calculated. All of them are listed in the catalog in order to have a larger, usable, consistent catalog. The total number of objects in ICRF-Ext.1 is 667.

The most precise direct access to the quasars is done through VLBI observations, a technique which is not widely available to users. Therefore, while VLBI is used for the maintenance of the primary frame, the tie of the ICRF to the major practical reference frames may be obtained through the use of the IERS Terrestrial Reference Frame (ITRF, see Chapter 4), the HIPPARCOS Galactic Reference Frame, and the JPL ephemerides of the solar system (see Chapter 3).

2.2.1 HIPPARCOS Catalogue

The 1991 IAU recommendation stipulates that as long as the relationship between the optical and extragalactic radio frame is not sufficiently accurately determined, the FK5 catalog will be considered as a provisional realization of the celestial reference system. In 1997, the IAU decided that this condition was fulfilled by the Hipparcos Catalogue (ESA, 1997).

The Hipparcos Catalogue provides the equatorial coordinates of about 118000 stars in the ICRS at epoch 1991.25 along with their proper motions, their parallaxes and their magnitudes in the wide band Hipparcos system. Actually, the astrometric data concerns only 117,955 stars. The median uncertainty for bright stars (Hipparcos wide band magnitude <9) are ± 0.77 and ± 0.64 mas in right ascension and declination respectively. Similarly, the median uncertainties in annual proper motion are ± 0.88 and ± 0.74 mas/yr respectively.

The alignment of the Hipparcos Catalogue to the ICRF was realized with a standard error of of ± 0.6 mas for the orientation at epoch (1991.25) and ± 0.25 mas/year for the spin (Kovalevsky *et al.*, 1997). This was obtained by comparing positions and proper motions of Hipparcos stars with the same subset determined with respect to the ICRF and, for the spin, to optical galaxies.

2.2.2 Availability of the Frame

The catalogue of source coordinates published in IERS (1999) (see also Ma *et al.*, 1998) provides access to the ICRS. It includes a total of 667 objects. Maintenance of the ICRS requires the monotoring of the source coordinate stability based on new observations and new analyses; the appropriate warnings and updates appear in IERS publications.

The principles on which the ITRF is established and maintained are described in Chapter 4. The IERS Earth Orientation Parameters provide the permanent tie of the ICRF to the ITRF. They describe the orientation of the Celestial Ephemeris Pole in the terrestrial system and in the celestial system (polar coordinates x, y; celestial pole offsets $d\psi$, $d\epsilon$) and the orientation of the Earth around this axis (UT1−UTC), as a function of time. This tie is available daily with an accuracy of ±0.3 mas in the IERS publications.

The other ties to major celestial frames are established by differential VLBI observations of solar system probes, galactic stars relative to quasars and other ground- or space-based astrometry projects. The tie of the solar system ephemerides of the Jet Propulsion Laboratory (JPL) is described by Standish *et al.* (1995). Its estimated precision is ±3 mas, according to Folkner *et al.* (1994). Other links to the dynamical system are obtained using laser ranging to the Moon, with the ITRF as an intermediate frame (Chapront *et al.*, 2002; IERS, 2000; IERS, 2001).

Ties to the frames related to catalogs at other wavelengths will be available from the IERS as observational analyses permit.

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