CHAPTER 1 CONVENTIONAL CELESTIAL REFERENCE SYSTEM

In 1991 the International Astronomical Union (IAU) decided that the IAU celestial reference system would be realized by a celestial reference frame defined by the precise coordinates of extragalactic radio sources. 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 are to be fixed with respect to the quasars. In compliance with this recommendation, the IERS Celestial Reference System (ICRS) is realized by the IERS Celestial Reference Frame (ICRF) defined by the J2000.0 equatorial coordinates of extragalactic objects determined from Very Long Baseline Interferometry (VLBI) observations. It is a frame whose directions are consistent with those of the FK5 (Fricke *et al.*, 1988). The origin is located at the barycenter of the solar system through appropriate modeling of observations in the framework of General Relativity (see Chapters 2 and 12). The rotational stability of the frame is based on the assumption that the sources have no proper motions. Checks are performed regularly to ensure the validity of this constraint (Ma and Shaffer, 1991; Eubanks *et al.*, 1994). The HIPPARCOS reference frame is planned to be linked astrometrically to the ICRF to unify the radio and optical coordinate systems at the level of $\pm 0\overset{''}{.}0005$ in direction and $\pm 0\overset{''}{.}0005$/year in rotation (Lindegren and Kovalevsky, 1995). The ICRS is recommended for the IAU conventional celestial system by the IAU Working Group on Reference Frames under the name "International Celestial Reference System." See Arias *et al.* (1995).

Equator

The IAU recommendations call for the principal plane of the conventional reference frame to be close to the mean equator at J2000.0. The VLBI observations which are used to establish the extragalactic reference frame also provide the monitoring of 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 the accurate estimation of the shift of the mean pole at J2000.0 relative to its conventional one, to which the pole of the ICRS is attached. Based on the VLBI observations available in early 1995 and the IERS correction model for precession and nutation (see Chapters 4 and 5), one can estimate the shift of the pole at J2000.0 relative to the IERS celestial pole to be 17.3 ± 0.2 mas in the direction 12^h and 5.1 ± 0.2 mas in the direction 18^h.

On the other hand, the IAU recommendations stipulate that the direction of the new conventional celestial pole 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 $-0\overset{''}{.}25$/cy to the precession constant imbedded in the FK5 System, and (2) by adopting Fricke's (1982) estimation of the accuracy of the FK5 equator ($\pm 0\overset{''}{.}02$), and Schwan's (1988) estimation of the limit of the residual rotation ($\pm 0\overset{''}{.}07$/cy), 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 IERS celestial pole is therefore consistent with that of the FK5 within the uncertainty of the latter.

Origin of Right Ascension

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 x axis of the IERS celestial system was implicitly defined in the 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 3C 273B to the usual (Hazard *et al.*, 1971) conventional FK5 value ($12^h29^m6^s\!.6997$ at J2000.0) (Kaplan *et al.*, 1982).

The uncertainty in 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. The uncertainty thus obtained is $\pm$ 80 mas. Folkner *et al.* (1994), comparing VLBI and LLR Earth orientation and terrestrial frames and the estimated frame tie of planetary ephemerides, show that the mean equinox of J2000.0 is shifted from the right ascension origin of the IERS system by 78 $\pm$ 10 mas (direct rotation around the polar axis). This shows that the ICRS origin of right ascension complies with the IAU recommendations.

Precision and Accuracy

The estimation of coordinates performed by the Central Bureau of the IERS is based on individual frames contributed by the IERS Analysis Centers. Several extragalactic frames are produced each year by independent VLBI groups. Selected realizations are used to form the ICRF. The algorithm used for the compilation is designed primarily to maintain the three directions of axes fixed for successive realizations while the precision of coordinates of individual sources is improved. Successive realizations produced up to now have maintained the initial definition of the axes within $\pm 0\farcs0001$.

The inaccuracy of the conventional IAU 1976 Precession and IAU 1980 Theory of Nutation 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, in the analysis of VLBI observations. Therefore, the usual practice in catalog work is to estimate additional parameters which describe the motion of the celestial pole relative to its conventional position (see Sovers, 1991). Another type of possible systematic error is related to low elevation observations in cases where the observing network has a modest north-south extension. This effect can 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, for recent global analyses these systematic differences are at the level of 0.001 mas per degree and 0.1 mas respectively (IERS, 1995). 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). After taking into account the small systematic errors mentioned above, the precision of the source coordinates is a white noise function of the number of observations, with a typical value of $\pm$ 0.2 mas for 100 observations (Arias *et al.*, 1995).

Availability of the Frame

The catalog of source coordinates published in the 1994 IERS Annual Report (July 1995) provides access to the ICRS. It includes a total of 608 objects, among which 236 with good observational histories attach the frame to the ICRS. In the future, based on new observations and new analyses, the stability of the source coordinates will be monitored, and the appropriate warnings and updates will appear in IERS publications.

The direct access to the quasars 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 the ICRF to the major practical reference frames may be obtained through use of the IERS Terrestrial Reference Frame (ITRF, see Chapter 3), the HIPPARCOS Galactic Reference Frame, and the JPL ephemerides of the solar system (see Chapter 2).

The principles on which the ITRF is established and maintained are described in Chapter 3. 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; nutation offsets $d\psi$, $d\epsilon$) and the orientation of the Earth around this axis (UT1-TAI), as a function of time. This tie is available daily with an accuracy of ± 0.5 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). The tie of the galactic frame to ICRS is a part of the HIPPARCOS project. It is described in some detail by Lindegren and Kovalevsky (1995). Its expected accuracy is ± 0.5 mas at the HIPPARCOS mean epoch of observation (1991.25) and ± 0.5 mas/year for the time evolution.

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