2 Conventional celestial reference system and frame

The celestial reference system is based on a kinematical definition, yielding fixed axis directions with respect to the distant matter of the universe. The system is materialized by a celestial reference frame consisting of the precise coordinates of extragalactic objects, mostly quasars, BL Lacertae (BL Lac) sources and a few active galactic nuclei (AGNs), on the grounds that these sources are that far away that their expected proper motions should be negligibly small. The current positions are known to better than a milliarcsecond, the ultimate accuracy being primarily limited by the structure instability of the sources in radio wavelengths. A large amount of imaging data is available at the USNO Radio Reference Frame Image Database <[1]> and at the Bordeaux VLBI Image Database <[2]>.

The IAU recommended in 1991 (21st IAU GA, Rec. VII, Resol. A4) that the origin of the celestial reference system is to be at the barycenter of the solar system and the directions of the axes should be fixed with respect to the quasars. This recommendation further stipulates 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 was adopted by the IAU General Assembly in 1997 (23rd IAU GA, Resol. B2) 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 the Hipparcos optical reference frame realizing the ICRS with an accuracy significantly better than the FK5. Responsibilities for the maintenance of the system, the frame and its link to the Hipparcos reference frame have been defined by the IAU in 2000 (24th IAU GA, Resol. B1.1)

2.1 The ICRS

The necessity of keeping 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 of the IERS celestial reference system have shown that there were small shifts of order 0.1 mas from year to year until the process converged to better than 0.02 mas for the relative orientation between successive realizations after 1992. 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).

The process of maintenance of the system and improvement of the frame since its first realization in 1995 resulted in an increase of the stability of the axes of the system. The comparison between the latest two realizations of the ICRS, ICRF2 and ICRF-Ext.2, indicates that the axes of the ICRS are stable within 10 μas (IERS, 2009).

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

[1] http://rorf.usno.navy.mil/RRFID
[2] http://www.obs.u-bordeaux1.fr/BVID/

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 MHB2000 nutation model (Mathews *et al.*, 2002). The direction of the mean pole at J2000.0 in the ICRS is +17.1 mas in the direction 12^{h} and +5.0 mas in the direction 18^{h} when the IERS (1996) model is used, and +16.6 mas in the direction 12^{h} and +6.8 mas in the direction 18^{h} when the MHB2000 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 (1) by considering 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 ascension 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 ($12^{\mathrm{h}}29^{\mathrm{m}}6.6997^{\mathrm{s}}$ 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 Section 2.1.1 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 catalog shows a systematic position error in FK5 of the order of 100 mas. This was also confirmed by Mignard and Froeschlé (2000) when linking the final Hipparcos catalog to the ICRS.

Analyses of LLR observations (Chapront *et al.*, 2002) indicate that the origin of right ascension 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 ascension of the IERS. These results indicate that the ICRS origin of right ascension complies with the requirements established in the IAU recommendations (21st IAU GA, Rec. VII, Resol. A4).

2.2 The ICRF

The ICRS is realized by the International Celestial Reference Frame (ICRF). A realization of the ICRF consists of a set of precise coordinates of compact extragalactic radio 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. The ICRF positions are independent of the equator, equinox, ecliptic, and epoch, but are made consistent with the previous stellar and dynamical realizations within their respective uncertainties.

The first realization of the ICRF (hereafter referred to as ICRF1) was constructed in 1995 by using the very long baseline interferometry (VLBI) positions of 212 "defining" compact extragalactic radio sources (IERS, 1997; Ma *et al.*, 1998). In addition to the defining sources, positions for 294 less observed "candidate" sources along with 102 less suitable "other" sources were given to densify the frame. The position formal uncertainties of the set of positions obtained by this analysis were calibrated to render their values more realistic. The 212 defining 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 set of positions obtained by this analysis was rotated to the ICRS. 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).

Following the maintenance process which characterizes the ICRS, two extensions of the frame were constructed: 1) ICRF-Ext.1 by using VLBI data available until April 1999 (IERS, 1999) and 2) ICRF-Ext.2 by using VLBI data available until May 2002 (Fey *et al.*, 2004). The positions and errors of defining sources are unchanged from ICRF1. For candidate and other sources, new positions and errors have been calculated. All of them are listed in the catalogs in order to have a larger, usable, consistent catalog. The total number of objects is 667 in ICRF-Ext.1 and 717 in ICRF-Ext.2.

The generation of a second realization of the International Celestial Reference Frame (ICRF2) was constructed in 2009 by using positions of 295 new "defining" compact extragalactic radio sources selected on the basis of positional stability and the lack of extensive intrinsic source structure (IERS, 2009). Future maintenance of the ICRS will be made using this new set of 295 sources. ICRF2 contains accurate positions of an additional 3119 compact extragalactic radio sources; in total the ICRF2 contains more than five times the number of sources as in ICRF1. The position formal uncertainties of the set of positions obtained by this analysis were calibrated to render their values more realistic. The noise floor of ICRF2 is found to be only ≈ 40 μas, some $5-6$ times better than ICRF1. Alignment of ICRF2 with the ICRS was made using 138 stable sources common to both ICRF2 and ICRF-Ext.2. The stability of the system axes was tested by estimating the relative orientation between ICRF2 and ICRF-Ext.2 on the basis of various subsets of sources. The scatter of the rotation parameters obtained in the different comparisons indicate that the axes are stable to within 10 μas, nearly twice as stable as for ICRF1. The position stability of the 295 ICRF2 defining sources, and their more uniform sky distribution, eliminates the two largest weaknesses of ICRF1.

The Resol. B3 of the XXVII IAU GA resolved that from 1 January 2010 the fundamental realization of the ICRS is the Second Realization of the International Celestial Reference Frame (ICRF2) as constructed by the IERS/IVS Working Group on the ICRF in conjunction with the IAU Division I Working Group on the Second Realization of the ICRF.

The most precise direct access to the extragalactic objects in ICRF2 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 Optical realization of the ICRF

In 1997, the IAU decided to replace the optical FK5 reference frame, which was based on transit circle observations, with the Hipparcos Catalogue (ESA, 1997; IAU, 1997).

The Hipparcos Catalogue provides the equatorial coordinates for 117,955 stars on the ICRS at epoch 1991.25 along with their proper motions, their parallaxes and their magnitudes in the wide band Hipparcos system. The median uncertainties 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.

The alignment of the Hipparcos Catalogue to the ICRF was realized with a standard error of 0.6 mas for the orientation at epoch 1991.25 and 0.25 mas/yr for the spin (Kovalevsky *et al.*, 1997). This was obtained by a variety of methods, with VLBI observations of a dozen radio stars having the largest weight.

However, due to the short epoch span of Hipparcos observations (less than 4 years) the proper motions of many stars affected by multiplicity are unreliable in the Hipparcos Catalogue. Therefore, the 24th IAU General Assembly adopted resolution B1.2 which defines the Hipparcos Celestial Reference Frame (HCRF) by excluding the stars of the Hipparcos Catalogue with C, G, O, V and X flags for the optical realization of the ICRS (IAU, 2000).

A new reduction of the Hipparcos data (van Leeuwen 2007) resulted in significant improvements mainly for the parallaxes of bright stars (magnitude ≤ 7). However, the coordinate system remained unchanged. Both the original and the new reductions of the Hipparcos data are on the ICRS to within the limits specified above.

Absolute proper motions (and parallaxes) from optical data can be obtained without the HCRF by observing extragalactic sources like galaxies and quasars at multiple epochs. This has been achieved for example through the Northern Proper Motion (NPM) program (Klemola *et al.*, 1987) and its southern counterpart, SPM (Girard *et al.*, 1998). These proper motion data are on an inertial system, thus also on the ICRS.

To obtain absolute positions with this approach is much more difficult. Optical counterparts of ICRF sources would need to be utilized in wide-field imaging of overlapping observations to be able to bridge the large gaps between ICRF sources. This has not yet been accomplished in a practical application, thus all current optical position observations rely on a set of reference stars beginning with the HCRF as primary realization of the ICRS at optical wavelengths and the densification catalogs derived from the HCRF.

The first step of the densification of the optical reference frame is the Tycho-2 Catalogue (Høg *et al.*, 2000) for about 2.5 million stars. The Hipparcos satellite star tracker observations (Tycho) provide the late epoch data, very well tied into the Hipparcos Catalogue. The early epoch data of Tycho-2 and thus its proper motions are derived from many ground-based catalogs which have been reduced to the HCRF with Hipparcos reference stars. The Astrographic Catalogue (AC) (Urban *et al.*, 1998) provided the highest weight of the early observations for the Tycho-2 proper motions.

Recently the limitations of the Tycho-2 Catalogue seem to have become noticeable. Systematic errors as a function of magnitude and declination zones found in the UCAC3 (Zacharias *et al.*, 2010, Finch *et al.*, 2010) may be caused by the Tycho-2 itself. Similarly, systematic errors on the 2 degree scale were found in reductions of SPM data (Girard, priv. comm.). These systematic errors are on the $1-2$ mas/yr level, plausible with estimates of residual magnitude equations in the AC data (S. Urban, priv. comm.).

Further steps in densifications of the optical reference frame use the Tycho-2 Catalogue for reference stars. The UCAC3 (Zacharias *et al.*, 2010) is an example of a recent all-sky, astrometric catalog based on CCD observations, providing positions and proper motions for about 100 million stars. The PPMXL (Roeser *et al.*, 2010) is a very deep, compiled catalog giving positions and proper motions on the ICRS for over 900 million stars. Extending beyond the visual wavelengths, the 2MASS near-IR catalog (<[3]>) provides accurate positions of over 470 million stars at individual mean epochs (around 2000), however, without proper motions. An overview of other current and future, ground- and space-based densification projects is given at <[4]>.

[3] http://www.ipac.caltech.edu/2mass/releases/allsky/
[4] http://www.astro.yale.edu/astrom/dens_wg/astrom-survey-index.html

2.2.2 Availability of the frame

The second realization of the international celestial reference frame ICRF2 (IERS, 2009) provides the most precise access to the ICRS in radio wavelengths. ICRF2 contains 3414 compact extragalactic radio sources, almost five times the number of sources in ICRF-Ext.2 (Fey *et al.*, 2004). The maintenance of the ICRS requires the monitoring of the source's coordinate stability based on new observations and new analyses. Programs of observations have been established by different organizations (United States Naval Observatory (USNO), Goddard Space Flight Center (GSFC), National Radio Astronomy Observatory (NRAO), National Aeronautics and Space Administration (NASA), Bordeaux Observatory) for monitoring and extending the frame. Observations in the southern hemisphere organized under the auspices of the IVS make use of the USNO and the Australia Telescope National Facility (ATNF) for contributing to a program of source imaging and astrometry.

The IERS Earth Orientation Parameters provide the permanent tie of the ICRF to the ITRF. They describe the orientation of the Celestial Intermediate Pole (CIP) 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 ± 0.1 mas in the IERS publications. The principles on which the ITRF is established and maintained are described in Chapter 4.

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 ephemeris of the Jet Propulsion Laboratory (JPL) is described by Standish *et al.* (1997). The later JPL ephemerides (DE421) is aligned to the ICRS with an accuracy of better than 1 mas (Folkner *et al.*, 2008, see also Chapter 3).

The lunar laser ranging (LLR) observations contribute to the link of the planetary dynamical system to the ICRS. The position of the dynamical mean ecliptic with respect to the ICRS resulting from LLR analysis is defined by the inclination of the dynamical mean ecliptic to the equator of the ICRS ($\epsilon^{(ICRS)}$) and by the angle between the origin of the right ascension on the equator of the ICRS and the ascending node of the dynamical mean ecliptic on the equator of the ICRS ($\phi^{(ICRS)}$). Evaluations of $\epsilon^{(ICRS)}$ and $\phi^{(ICRS)}$ made by the Paris Observatory Lunar Analysis Centre (Chapront *et al.*, 2002, Zerhouni *et al.*, 2007) give the following values for these angles at the epoch J2000:

$$\begin{aligned} \epsilon^{(\mathrm{ICRS})} &= 23^\circ 26' 21.411'' \pm 0.1 \text{ mas}; \\ \phi^{(\mathrm{ICRS})} &= -0.055'' \pm 0.1 \text{ mas}; \\ d\alpha_0 &= (-0.01460 \pm 0.00050)''. \end{aligned}$$

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

References

Arias, E. F., Feissel, M., and Lestrade, J.-F., 1988, "An extragalactic celestial reference frame consistent with the BIH Terrestrial System (1987)," *BIH Annual Rep. for 1987*, pp. D-113–D-121.

Arias, E. F., Charlot, P., Feissel, M., Lestrade, J.-F., 1995, "The extragalactic reference system of the International Earth Rotation Service, ICRS," *Astron. Astrophys.*, **303**, pp. 604–608.

Chapront, J., Chapront-Touzé, M., and Francou, G., 2002, "A new determination of lunar orbital parameters, precession constant and tidal acceleration from LLR measurements," *Astron. Astrophys.*, **387(2)**, pp. 700–709. doi: 10.1051/0004-6361:20020420.

ESA, 1997, "The Hipparcos and Tycho catalogues," *European Space Agency Publication*, Noordwijk, SP–1200, June 1997, 19 volumes.

Eubanks, T. M., Matsakis, D. N., Josties, F. J., Archinal, B. A., Kingham, K. A., Martin, J. O., McCarthy, D. D., Klioner, S. A., Herring, T. A., 1994, "Secular motions of extragalactic radio sources and the stability of the radio reference frame," *Proc. IAU Symposium 166*, E. Høg, P. K. Seidelmann (eds.), p. 283.

Fey, A. L., Ma, C., Arias, E. F., Charlot, P., Feissel-Vernier, M., Gontier, A.-M., Jacobs, C. S., Li, J., and MacMillan, D. S., 2004. "The Second Extension of the International Celestial Reference Frame: ICRF-EXT.1," *Astron. J.*, **127(6)**, pp. 3587–3608. doi: 10.1086/420998.

Finch, C. T., Zacharias, N., and Wycoff, G. L., 2010, "UCAC3: Astrometric Reductions," *Astron. J.*, **139(6)**, pp. 2200–2207, doi: 10.1088/0004-6256/139/6/2200.

Folkner, W. M., Williams, J. G., and Boggs, D. H., 2009, "The Planetary and Lunar Ephemeris DE 421," IPN Progress Report 42-178, August 15, 2009, 34 pp., see http://ipnpr.jpl.nasa.gov/progress_report/42-178/178C.pdf.

Fricke, W., 1982, "Determination of the equinox and equator of the FK5," *Astron. Astrophys.*, **107(1)**, pp. L13–L16.

Fricke, W., Schwan, H., and Lederle, T., 1988, *Fifth Fundamental Catalogue, Part I. Veröff. Astron. Rechen-Inst.*, Heidelberg.

Girard, T. M., Platais, I., Kozhurina-Platais, V., van Altena, W. F., Lopez, C. E., 1998, "The Southern Proper Motion program. I. Magnitude equation correction," *Astron. J.*, **115(2)**, pp. 855–867, doi: 10.1086/300210.

Hazard, C., Sutton, J., Argue, A. N., Kenworthy, C. N., Morrison, L. V., and Murray, C. A., 1971, "Accurate radio and optical positions of 3C273B," *Nature Phys. Sci.*, **233**, pp. 89–91.

Høg, E., Fabricius, C., Makarov, V. V., Urban, S., Corbin, T., Wycoff, G., Bastian, U., Schwekendiek, P., and Wicenec, A., 2000, "The Tycho-2 Catalogue of the 2.5 million brightest stars," *Astron. Astrophys.*, **355**, pp. L27–L30.

IAU 1997 Resolution B2, "On the international celestial reference system (ICRS)," XXIIIrd IAU GA, Kyoto, 1997, http://www.iau.org/static/resolutions/IAU1997_French.pdf

IAU 2000 Resolution B1.2, "Hipparcos Celestial Reference Frame," XXIVth IAU GA, Manchester, 2000, http://syrte.obspm.fr/IAU_resolutions/Resol-UAI.htm

IERS, 1995, 1994 International Earth Rotation Service Annual Report, Observatoire de Paris, Paris.

IERS, 1997, *IERS Technical Note 23*, "Definition and realization of the International Celestial Reference System by VLBI Astrometry of Extragalactic Objects," Ma, C. and Feissel, M. (eds.), Observatoire de Paris, Paris, available at http://www.iers.org/TN23

IERS, 1999, 1998 International Earth Rotation Service Annual Report, Observatoire de Paris, Paris.

IERS, 2001, 2000 International Earth Rotation Service Annual Report, Observatoire de Paris, Paris.

IERS, 2009, *IERS Technical Note 35*, "The Second Realization of the International Celestial Reference Frame by Very Long Baseline Interferometry, " Presented on behalf of the IERS / IVS Working Group, Fey A. L., Gordon, D., and Jacobs, C. S. (eds.). Frankfurt am Main: Verlag des Bundesamts für Kartographie und Geodäsie, 2009. 204 p., available at http://www.iers.org/TN35

Kaplan, G. H., Josties, F. J., Angerhofer, P. E., Johnston, K. J., and Spencer, J. H., 1982, "Precise radio source positions from interferometric observations," *Astron. J.*, **87(3)**, pp. 570–576, doi: 10.1086/113131.

Klemola, A. R., Jones, B. F., and Hanson, R. B., 1987, "Lick Northern Proper Motion program. I. Goals, organization, and methods," *Astron. J.*, **94(2)**, pp. 501–515, doi: 10.1086/114489.

Kovalevsky, J., Lindegren, L., Perryman, M. A. C., Hemenway, P. D., Johnston, K. J., Kislyuk, V. S., Lestrade, J.-F., Morrison, L. V., Platais, I., Röser, S., Schilbach, E., Tucholke, H.-J., de Vegt, C., Vondrák, J., Arias, F., Gontier, A.-M., Arenou, F., Brosche, P., Florkowski, D. R., Garrington, S. T., Preston, R. A., Ron, C., Rybka, S. P., Scholz, R.-D., and Zacharias, N., 1997, "The Hipparcos Catalogue as a realization of the extragalactic reference system," *Astron. Astrophys.*, **323(2)**, pp. 620–633.

Lieske, J. H., Lederle, T., Fricke, W., and Morando, B., 1977, "Expressions for the precession quantities based upon the IAU (1976) System of Astronomical Constants," *Astron. Astrophys.*, **58(1-2)**, pp. 1–16.

Lindegren, L., Röser, S., Schrijver, H., Lattanzi, M. G., van Leeuwen, F., Perryman, M. A. C., Bernacca, P. L., Falin, J. L., Froeschlé, M., Kovalevsky, J., Lenhardt, H., and Mignard, F., 1995, "A comparison of ground-based stellar positions and proper motions with provisional Hipparcos results," *Astron. Astrophys.*, **304**, pp. 44–51.

Ma, C., and Shaffer, D. B., 1991, "Stability of the extragalactic reference frame realized by VLBI," in *Reference Systems*, Hughes, J. A., Smith, C. A., and Kaplan, G. H. (eds.), Proceedings of IAU Colloquium 127, U. S. Naval Observatory, Washington, pp. 135–144.

Ma, C., Arias, E. F., Eubanks, T. M., Fey, A. L., Gontier, A.-M., Jacobs, C. S., Sovers, O. J., Archinal, B. A. and Charlot, P., 1998, "The International Celestial Reference Frame as realized by Very Long Baseline Interferometry," *Astron. J.*, **116(1)**, pp. 516–546, doi: 10.1086/300408.

Mathews, P. M., Herring T. A., and Buffett, B. A., 2002, "Modeling of nutation and precession: New nutation series for nonrigid Earth, and insights into the Earth's interior," *J. Geophys. Res.*, **107(B4)**, 10.1029/2001JB000390.

Mignard, F. and Froeschlé, M., 2000, "Global and local bias in the FK5 from the Hipparcos data," *Astron. Astrophys.*, **354**, pp. 732–739.

Roeser, S., Demleitner, M., and Schilbach, E., 2010, "The PPMXL Catalog of positions and proper motions on the ICRS. Combining USNO-B1.0 and the Two Micron All Sky Survey (2MASS)," *Astron. J.*, **139(6)**, pp. 2440–2447, doi: 10.1088/0004-6256/139/6/2440.

Schwan, H., 1988, "Precession and galactic rotation in the system of the FK5," *Astron. Astrophys.*, **198(1-2)**, pp. 116–124.

Seidelmann, P. K., 1982, "1980 IAU theory of nutation: The final report of the IAU Working Group on Nutation," *Celest. Mech.*, **27(1)**, pp. 79–106, doi: 10.1007/BF01228952.

Standish, E. M., Newhall, X X, Williams, J. G., and Folkner, W. M., 1997, "JPL Planetary and Lunar Ephemerides," Willmann-Bell Inc., Richmond, VA.

Urban, S. E., Corbin, T. E., Wycoff, G. L., Martin, J. C., Jackson, E. S., Zacharias, M. I., and Hall, D. M., 1998, "The AC 2000: The Astrographic Catalogue on the system defined by the Hipparcos Catalogue," *Astron. J.*, **115(3)**, pp. 1212–1223, doi: 10.1086/300264.

van Leeuwen, F. 2007, "Hipparcos, the new reduction of the raw data," ASPL series, Springer, doi: 10.1007/978-1-4020-6342-8.

Zacharias, N., Finch, C., Girard, T., Hambly, N., Wycoff, G., Zacharias, M. I., Castillo, D., Corbin, T., DiVittorio, M., Dutta, S., Gaume, R., Gauss, S., Germain, M., Hall, D., Hartkopf, W., Hsu, D., Holdenried, E., Makarov, V., Martines, M., Mason, B., Monet, D., Rafferty, T., Rhodes, A., Siemers, T., Smith, D., Tilleman, T., Urban, S., Wieder, G., Winter, L., and Young, A., 2010, "The Third US Naval Observatory CCD Astrograph Catalog (UCAC3)," *Astron. J.*, **139(6)**, pp. 2184–2199, doi: 10.1088/0004-6256/139/6/2184.

Zerhouni, W., Capitaine, N., and Francou, G., 2008, "The use of LLR observations (1969-2006) for the determination of the celestial coordinates of the pole," *Journées 2007 Systèmes de Référence Spatio-temporels*, N. Capitaine (ed.), Observatoire de Paris, pp. 123–124,
http://syrte.obspm.fr/journees2007/index.php?page=proceedings.pdf