3.5.4 ICRS Centre

Introduction

The IAU has charged the IERS with the responsibility of monitoring the International Celestial Reference System (ICRS), maintaining its current realization, the International Celestial Reference Frame (ICRF), and maintaining and improving the links with other celestial reference frames. Starting in 2001, these activities are run jointly by the ICRS Centre (US Naval Observatory and Observatoire de Paris) of the IERS and the International VLBI Service for Geodesy and Astrometry (IVS), in coordination with the IAU. The present report was jointly prepared by the U.S. Naval Observatory and Paris Observatory components of the ICRS Centre. The ICRS Centre web site <http://hpiers.obspm.fr/icrs-pc> provides information on the characterization and construction of the ICRF (radio source nomenclature, physical characteristics of radio sources, astrometric behaviour of a set of sources, radio source structure). This information is also available by anonymous ftp (<hpiers.obspm.fr/icrs-pc>), and on request to the ICRS Centre (<icrspc@ hpopa.obspm.fr>).

Maintenance and extension of the ICRF: validation of individual VLBI reference frames

Seven individual celestial reference frames obtained from VLBI analysis by three different laboratories have been validated by comparison to ICRF-Ext. 2 (Fey et al., 2004).

The reference frames analysed

Two solutions calculated at Geoscience Australia with the OCCAM 6.1 software are included in this report. In both solutions the orientation of the celestial frame has been defined by applying a no-net-rotation constraint to the positions of 207 defining sources in ICRF-Ext.2. The a priori models are IERS 1996 for the precession, MHB2000 (Mathews et al., 2002) for the nutation and tropospheric gradients have been adjusted. The solutions differ in the time span of the observations and in the tropospheric delay model used: VLBI observations analysed for RSC (AUS) 05 R 01 span over the period November 1979 – October 2004 and the IMF mapping function (Niell, 2001) has been applied for the troposphere modelling; the celestial frame RSC (AUS) 05 R 03 includes one more year of data (November 1979 – November 2005) and applied the VMF mapping function (Böhm and Schuh, 2004).

Four individual frames at the Federal Agency for Cartography and Geodesy and the Geodetic Institute of the University of Bonn (Germany) have been evaluated using CALC 9.13 / SOLVE release 2004.03.18. In all solutions the celestial reference frame has been oriented by a no-net-rotation constraint imposed to the positions of the 212 defining sources as in ICRF-Ext.1 (IERS 1999). The a priori precession and nutation models are IERS 1996. Tropospheric gradients have been adjusted in the solutions. The solutions differ only in the time span of the observations: RSC (BKGI) 05 R 01 data ranging January 1984 – February 2005; RSC (BKGI) 05 R 02 data has been acquired between January 1984 and June 2005; observations used to evaluate RSC (BKGI) 05 R 03 range the period January 1984 – October 2005; solution RSC (BKGI) 06 R 01 is based on data obtained from January 1984 to February 2006.

RSC (CGS) 05 R 01 is the extragalactic frame produced by the Space Geodesy Centre in Matera, Italy from observations in the period April 1980 – December 2004. The software used is CALC 9.12 / SOLVE release 2001.01.19, revision 2001.04.27. The celestial frame has been oriented by a no-net-rotation imposed to the positions of 179 defining sources in ICRF-Ext.1. The a priori precession and nutation models are both IERS 1996. Tropospheric gradients have been adjusted in the solution.

Table 1 gives the characteristics of the analysed frames. Four categories of sources appear in the table: defining, candidate and other sources correspond to the classification of ICRF sources (IERS, 1997; Ma et al., 1998); new are the sources added in ICRF-Ext.2; additional represents sources observed in VLBI programmes and not present in ICRF-Ext.2. The values of the median of the coordinate uncertainties indicate that all frames are of similar quality.

Table 1: Individual VLBI celestial reference frames analysed. n is the number of sources, m is the median of the coordinate uncertainties (unit: mas)

Frame	Total	Defining		Candidate		Other		New		Addit.		
	N	n	m	n	m	n	m	n	m	n	m	(°)
RSC (AUS) 05 R 01	639	202	0.04	251	0.17	4	0.23	58	0.19	124	0.30	–81;+84
RSC (AUS) 05 R 03	640	205	0.04	248	0.14	4	0.22	58	0.17	125	0.29	–81;+84
RSC (BKGI) 05 R 01	779	207	0.05	218	0.06	101	0.03	45	0.10	208	0.30	–81;+84
RSC (BKGI) 05 R 02	779	207	0.05	218	0.06	101	0.03	45	0.10	208	0.30	–81;+84
RSC (BKGI) 05 R 03	781	207	0.05	218	0.06	101	0.03	45	0.10	210	0.30	–81;+84
RSC (BKGI) 06 R 01	782	207	0.05	218	0.06	101	0.03	45	0.10	211	0.30	–81;+84
RSC (CGS) 05 R 01	537	179	0.05	186	0.05	98	0.02	42	0.08	32	0.10	–80;+84

Comparison of individual celestial frames to ICRF-Ext.2

The catalogues listed in Table 1 have been compared to ICRF-Ext.2. The algorithm of comparison is the one developed and currently used at the ICRS Centre in Paris Observatory. The coordinate differences between two frames are modelled by a global rotation of the axes, represented by the angles A_1, A_2, A_3, and by deformations represented by three parameters: D_α is a slope in right ascension as a function of the declination, D_δ is a slope in declination as a function of the declination, B_δ is a bias between the principal planes of the frame relative to that of ICRF-Ext.2.

$$A_1 \operatorname{tg}\delta\cos\alpha + A_2 \operatorname{tg}\delta\sin\alpha - A_3 + D_\alpha(\delta-\delta_0) = \Delta\alpha$$
$$-A_1\sin\alpha + A_2\cos\alpha + D_\delta(\delta-\delta_0) + B_\delta = \Delta\delta$$

Under the hypothesis that ICRF-Ext.2 is free from deformations, the systematic effects detected in the comparisons should be interpreted as deformations in the individual frames.

The defining sources in ICRF-Ext.2, as well as their respective coordinates have been kept identical to those in ICRF (Fey et al., 2004). Defining sources common to each individual frame and ICRF-Ext.2 (or ICRF) have been used for the comparisons. The six parameters have been evaluated by a weighted least squares fit; the equations have been weighted using the inverse of the variance of the coordinate differences.

Formal uncertainties of radio source positions smaller than 0.01 mas in the individual frames were set to this value for the assignation of weights. The fitted parameters allow the transformation of coordinates in the individual frames into ICRS. Equations of observation with post-fit residuals higher than 2.5 times the rms residual of the fit are deweighted. By doing this, the respective source coordinate is considered as an outlier and is consequently eliminated from the fit.

Results

The results of the comparisons are shown in Tables 2 to 4. Table 2 gives the global orientation between the axes of the individual frames analysed and those of the ICRS. Table 3 gives the values of the deformation parameters representing systematic effects in the individual frames. Table 4 gives the values of the post-fit weighted mean residuals and the rms residuals.

Table 2: Relative orientation between individual frames and ICRF-Ext.2. N is the number of the common defining sources in each individual frame used for the comparison. Unit: µas.

Frame	N	A_1	A_2	A_3
RSC (AUS) 05 R 01 (*)	202	+12.50±*20.55*	+17.18±*20.29*	-40.98±*25.97*
RSC (AUS) 05 R 03 (*)	205	+8.09±*19.72*	+16.26±*19.51*	-37.48±*25.00*
RSC (BKGI) 05 R 01	207	+5.66±*17.55*	-19.12±*17.46*	-31.56±*22.54*
RSC (BKGI) 05 R 02	207	+3.95±*17.50*	-19.94±*17.40*	-32.21±*22.46*
RSC (BKGI) 05 R 03	207	+0.91±*17.56*	-22.57±*17.47*	-32.71±*22.55*
RSC (BKGI) 06 R 01	207	-0.11±*17.52*	-24.02±*17.43*	-35.43±*22.50*
RSC (CGS) 05 R 01 (*)	179	+29.06±*23.46*	+7.89±*23.01*	+10.14±*32.49*

(*): some source coordinates have been deweighted

Table 3: Slopes and biases evaluated in the comparisons between VLBI individual reference frames and ICRF-Ext.2. D_α, D_δ are the slopes in right ascension and declination respectively, B_δ is thebias in declination; units are µas/deg for the slopes, µas for the bias.

Frame	N	D_α	D_δ	B_δ
RSC (AUS) 05 R 01 (*)	202	-0.88±*0.83*	-0.78±*0.44*	+51.50±*21.95*
RSC (AUS) 05 R 03 (*)	205	-0.85±*0.80*	-1.05±*0.41*	+58.78±*20.58*
RSC (BKGI) 05 R 01	207	-1.02±*0.72*	-0.57±*0.37*	+11.73±*18.31*
RSC (BKGI) 05 R 02	207	-1.00±*0.72*	-0.64±*0.37*	+13.94±*18.24*
RSC (BKGI) 05 R 03	207	-0.94±*0.72*	-0.68±*0.37*	+15.46±*18.31*
RSC (BKGI) 06 R 01	207	-1.11±*0.72*	-0.65±*0.37*	+12.93±*18.26*
RSC (CGS) 05 R 01 (*)	179	-0.63±*1.07*	-1.16±*0.60*	+62.27±*28.82*

(*): some source coordinates have been deweighted

Table 4: Weighted mean residuals r_α and r_δ, and rms residual after fitting the global rotations and the deformation parameters between individual frames and ICRF; unit is µas.

Frame	r_α	r_δ	rms
RSC (AUS) 05 R 01	-6.57	-0.52	271.54
RSC (AUS) 05 R 03	-7.40	-0.49	262.97
RSC (BKGI) 05 R 01	-4.95	+4.76	235.16
RSC (BKGI) 05 R 02	-5.72	+4.71	234.42
RSC (BKGI) 05 R 03	-6.36	+4.73	235.32
RSC (BKGI) 06 R 01	-7.06	+4.61	234.82
RSC (CGS) 05 R 01	-8.73	+7.28	284.57

The values of the angles A_1, A_2, A_3 in Table 2 show that the individual reference frames realize the axes of the ICRF better than 40 µas, and their uncertainties indicate that, after rotation, the inconsistency between the directions of the axes is at most 30 µas.

The parameters listed in Table 3 represent deformations of the individual frames relative to ICRS. The values of D_α and D_δ indicate that any of the frames present small deformations in the coordinates depending on the declination. The B_δ parameter quantifies the bias between the principal planes of the individual frames and that of the ICRS. For the solutions computed by AUS and CGS the biases are significant, between 50 to 60 µas. On the contrary, the principal planes of the BKGI frames are aligned to that of ICRS at the level of 10 to 15 µas. The values of the weighted mean residuals r_α and r_δ in Table 4 indicate that the model represents well the inconsistencies between the orientations of frames at a level of 10 µas or better.

Investigation of future realizations of the ICRS

Involvement by ICRS Centre personnel in the celestial reference frame VLBI program continued in 2005, increasing the number of observations of ICRF quasars in the southern celestial hemisphere and continuing an extensive observing program in the northern hemisphere. This observing program will eventually result in a future extension and potentially a new realization of the ICRS, tentatively called ICRF 2. Plans for the formulation of ICRF 2 will be discussed at XXVIth General Assembly of the International Astronomical Union (IAU) to be held in Prague, Czech Republic in August 2006. In the Southern Hemisphere, the USNO and the Australia Telescope National Facility (ATNF) are collaborating in a continuing VLBI research program in Southern Hemisphere source imaging and astrometry using USNO, ATNF and ATNF-accessible facilities. These observations are aimed specifically toward improvement of the ICRF in the Southern Hemisphere by a) increasing the reference source density with additional S/X-band bandwidth-synthesis astrometric VLBI observations, and b) VLBI imaging at 8.4 GHz of ICRF sources south of $\delta = -20^{\circ}$. In the Northern Hemisphere a major source of VLBI data continues to be the series of RDV experiments, which consist of observations of International Celestial Reference Frame (ICRF) sources at radio frequencies of 2.3 GHz and 8.4 GHz using the Very Long Baseline Array (VLBA), together with up to 10 geodetic antennas. These VLBA RDV observations constitute a joint program between the U.S. Naval Observatory (USNO), Goddard Space Flight Center (GSFC) and the National Radio Astronomy Observatory (NRAO) for maintenance of the celestial and terrestrial reference frames. During calendar year 2005, six VLBA RDV experiments were observed. In addition VLBA observations to extend the ICRF to K-band (24 GHz) and Q-band (43 GHz) continued in 2005. These observations are part of a joint program between the National Aeronautics and Space Administration, the USNO, the National Radio Astronomy Observatory (NRAO) and Bordeaux Observatory.

In the coming decades, there will be significant advances in the area of space-based optical astrometry. Proposed and scheduled missions such as the National Aeronautics and Space Administration's (NASA) *Space Interferometry Mission* (SIM-PlanetQuest) and the European Space Agency's (ESA) *Gaia* mission will achieve positional accuracies well beyond that presently obtained by any ground-based radio interferometric measurements. In 2005, ICRS Centre personnel continued their participation in the NASA SIM mission, through direct involvement in one of the SIM key science projects: *Astrophysics of Reference Frame Tie Objects*. In addition, during 2005 ICRS Centre personnel were funded by NASA to lead and execute a concept study for the *Origins Billions Star Survey (OBSS)* mission, a unique astrometric and astrophysical Galactic Exploration mission that will leave as a legacy the measurement of over two billion stellar positions, parallaxes, and proper motions, along with a scientifically rich database of extrasolar planet detections, binarity determinations, stellar photometry and variability, and low resolution spectrometry. ICRS Center personnel concluded the 8 month OBSS concept study in April 2005 and submitted a concept study report for the OBSS mission to NASA in May 2005. In addition, ICRS Centre personnel have been working on concept development for a microsatellite based astrometric mission, called the Milli-Arcsecond Pathfinder Survey (MAPS), to produce milliarcsecond level astrometry for all of the bright stars up to 12^{th} magnitude (limiting magnitude ~15–16). Together with several industrial partners, in 2005 ICRS Centre personnel conducted a preliminary concept study with the goal of better understanding mission related costs, schedule, and risks.

Monitor source structure to assess astrometric quality

VLBA RDV Imaging

Observations of International Celestial Reference Frame (ICRF) sources at radio frequencies of 2.3 GHz and 8.4 GHz using the Very Long Baseline Array (VLBA), together with up to 10 geodetic antennas, continued in 2005. These VLBA RDV observations constitute a joint program between the U.S. Naval Observatory (USNO), Goddard Space Flight Center (GSFC) and the National Radio Astronomy Observatory (NRAO) for maintenance of the celestial and terrestrial reference frames. During the calendar year 2005, six VLBA RDV experiments were observed.

VLBA High Frequency Imaging

VLBA observations to extend the ICRF to K-band (24 GHz) and Q-band (43 GHz) continued in 2005. These observations are part of a joint program between the National Aeronautics and Space Administration, the USNO, the National Radio Astronomy Observatory (NRAO) and Bordeaux Observatory. During the calendar year 2005, two VLBA high frequency experiments (BL122A and BL122B) were calibrated, imaged and added to the Radio Reference Frame Image Database.

ICRF Maintenance in the Southern Hemisphere

The USNO and the Australia Telescope National Facility (ATNF) are collaborating in a continuing VLBI research program in Southern Hemisphere source imaging and astrometry using USNO, ATNF and ATNF-accessible facilities. These observations are aimed specifically toward improvement of the ICRF in the Southern Hemisphere by a) increasing the reference source density with additional S/X-band bandwidth-synthesis astrometric VLBI observations, and b) VLBI imaging at 8.4 GHz of ICRF sources south of declination –20 deg.

VLBI images for a total of 48 Southern Hemisphere ICRF sources at a frequency of 8.4 GHz using the Australian Long Baseline Array were published by Ojha et al. (2005). These data, together with previously published data, were used to quantify the magnitude of the expected effect of intrinsic source structure on astrometric bandwidth synthesis VLBI observations by calculating a “structure index” for a total of 111 southern hemisphere sources; the structure index yields an estimate of their astrometric quality. Approximately 35 % of the sources were found to have a structure index indicative of compact or very compact structures. The remaining two-thirds of the sources are less compact and should probably be avoided in astrometric and geodetic VLBI experiments requiring the highest accuracy unless intrinsic source structure can be accounted for in the astrometric/geodetic analysis.

The Radio Reference Frame Image Database

The Radio Reference Frame Image Database (RRFID) is a web accessible database of radio frequency images of ICRF sources. The RRFID currently contains 3632 VLBA images of 502 sources at radio frequencies of 2.3 GHz and 8.4 GHz. Additionally, the RRFID contains 976 images of 255 sources at frequencies of 24 GHz and 43 GHz. The RRFID can be accessed from the Analysis Centre web page or directly at <http://www.usno.navy.mil/RRFID/>.

Extension of the list of stable

One of the tasks of the ICRS Centre is the identification of those of the radio sources observed by the International VLBI Service program that are most suitable for the maintenance of the ICRF axes. Based on the analysis of time series of source coordinates, Feissel-Vernier (2003) had proposed a list of 199 well observed radio sources considered stable, and 163 sources considered unstable, based on the statistical analysis of time series of source directions. Using slightly modified selection scheme, Feissel-Vernier et al. (2006) extended the list to 71 new sources and downgraded 18 of the sources initially considered as stable, leading to a revised list of 247 sources. The new analysis is described hereafter.

A first extension concerns the sources with a relatively poor observation history. The Feissel-Vernier (2003) stability detection scheme, referred to MFV hereafter, is based on time series statistics of yearly averaged source coordinates. It has therefore the limitation of requiring time-density of observation. Over the 1990–2002 time span, 358 sources, i.e. about half of the total, were too sparsely observed to be submitted to the scheme. In order to learn more about their possible stability, a simplified selection scheme was applied to them. For sources observed in more than three sessions over more than two years, we assume that, in both $\alpha \cos \delta$ and δ, a standard deviation of the weighted mean position smaller than 0.5 μas and a linear drift smaller than 50 μas/year are an indication that the source might be stable. We thus select a set of 22 additional sources.

The second extension is based on a re-iterated computation of time series of coordinates provided by C. Ma (GSFC). The MFV scheme was applied to time series of source coordinates that were derived taking subsets of the ICRF *defining* sources as the background reference. As a sizeable part of those were detected as unstable, one could not rule out the possibility that the intrinsic instability of the set of reference sources create spurious instabilities in the sources under study. A slightly modified scheme was therefore applied to time series of source coordinates derived from a global analysis where the original 199 stable sources where held fixed relative to the ICRF through a No-Net-Rotation condition. The modified selection scheme includes the additionally rejecting sources with apparent drifts in $\alpha \cos \delta$ or δ larger than 10 mas/year, at a 5-σ significance. A set of 44 sources were detected as stable by this modified scheme.

Finally, when the above additional stability condition is applied to the time series used by Feissel-Vernier (2003), 18 sources are found to be unstable. This is the third change in the source selection.

In summary, 247 sources considered stable are selected. They are listed at URL <http://hpiers.obspm.fr/icrs-pc/icrf/stable_2006 .txt>. Their observation history is illustrated by Figure 1.

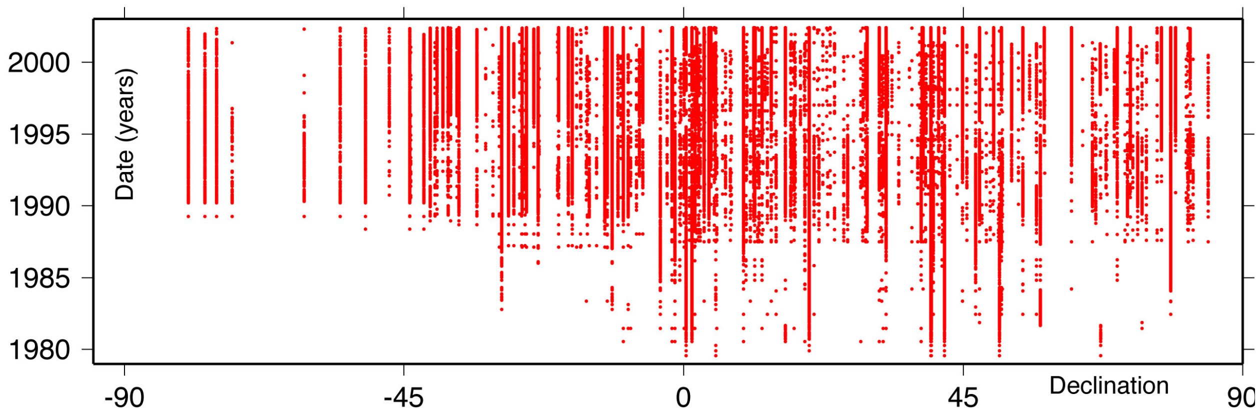

Fig. 1: 1979–2002 observations of the 252 most stable sources. Each dot represents a session in which the source was observed.

Maintenance of the link to the Hipparcos catalog

During the reporting period (2005) progress has been achieved in several areas related to the maintenance of the Hipparcos link: UCAC project (preparation for the final release), the extragalactic and galactic link to radio frame sources, and URAT.

All 4.5 TB compressed pixel data of the USNO CCD Astrograph Catalog (UCAC) project are now loaded from over 1200 tapes onto hard disk drives and software development started for the final reductions of the data. The goal is to achieve a much larger completeness for the final catalog, including solutions for "problem" sources, in particular double stars. Release of the UCAC3 will be in 2007.

As part of the UCAC project early epoch photographic plates are being measured on the StarScan machine at USNO to provide proper motions on the Hipparcos system. About 1500 Hamburg Zone Astrograph plates were measured in 2005.

Reduction of the deep CCD images taken of extragalactic, compact radio sources during the UCAC project continued. Results from the 2.1m KPNO run and a 0.9m CTIO run give optical-radio differences on the 15 mas level per source, the most accurate data of this kind ever taken. Systematic error analysis and optical to radio frame tie will be investigated after more runs are reduced.

Monitoring a sample of 12 ICRF optical counterparts continued at the 1.55m NOFS. This effort is part of the SIM preparatory science for the celestial reference frame key project (PI is K. Johnston).

As part of the preparatory science for the SIM PlanetQuest Key project Astrophysics of Reference Frame Tie Objects (K.J. Johnston, P.I.), investigations continued into the use of radio stars to link the optical frame to the ICRF. The Very Large Array (VLA), linked with the Pie Town Very Long Baseline Array antenna, was used to determine astrometric positions of 46 radio stars in the ICRF. Positions were obtained in the ICRF directly through phase referencing of the stars to nearby ICRF quasars. The derived radio star positions are estimated to be accurate at the 10 mas level, with position errors approaching a few milli-arcseconds for some of the stars observed. Measured positions were combined with previous measurements taken from as early as 1978 to obtain proper motion estimates for all 46 stars with average uncertainties of ~1.7 mas/yr. A comparison with the Hipparcos Catalogue data, shows consistency in the reference frames produced by each data set on the 1-sigma level, with errors of ~2.7 mas per axis for the reference frame orientation angles at our mean epoch of 2003.78. No significant spin was found between the radio data frame and the Hipparcos Celestial Reference Frame (HCRF). Results are consistent with a non-rotating Hipparcos frame with respect to the ICRF (Boboltz et al. 2006, AJ, submitted).

The optical design of the USNO Robotic Astrometric Telescope (URAT) was finalized. The field of view is now 4.5 degree in diameter obtained from the FASA2 design, consisting of 2 full-aperture and 2 sub-aperture lenses plus 2 mirrors. In July 2005 a contract was signed with EOST to procure the primary mirror for URAT. The detector development for URAT was funded by the Office of Naval Research (ONR) through a Small Business Innovation in Research (SBIR) phase 2 contract assigned in December 2005. A 10.5k by 10.5k monolithic CCD with test camera will be delivered by Semiconductor Technology Associates (STA) to USNO in 2006. URAT will provide a direct link between ICRF optical counterparts and the radio frame on the few mas per source, as part of an all-sky astrometric survey for the 13 to 21th magnitude range.

Linking the ICRF to frames at various wavelengths

The ICRF (International Celestial Reference Frame) was adopted as the fundamental celestial reference frame at the XXII General Assembly of the International Astronomical Union held in August 1997 in Kyoto. One of the interesting tasks which remained to be done by the ICRS Centre consisted in searching for the optical counterparts of the ICRF objects in catalogues already published. Souchay et al. (2006a) have done such a study starting from the largest optical catalogue of extra-galactic objects, that is to say the Véron-Cetty and Véron catalogue (Véron-Cetty and Véron, 2003), referred in the following as VV2003. The VV2003 catalogue contains 48 921 quasars, 876 BL LAC objects and 15 069 active galaxies (AGN). We have carried out the cross-identifications between the 717 extragalactic radio sources in ICRF-Ext.2 (Fey et al., 2004) and the VV2003 sources. For these cross-identifications we have chosen two different thresholds, respectively 2" and 4". We have shown that with a 2" threshold, 173 objects among the 212 objects of the defining sources of the ICRF were cross-identified (81.6%). The respective numbers are 205 among the 294 objects named as “candidate sources” (67.0 %) and 90 among the 102 objects named as “other sources” (88.2%). Therefore we can remark that a substantial amount of ICRF objects are not included in the VV2003 catalogues, which means that we have no real access to their optical characteristics.

The sky coverage of ICRF-Ext.2 as well as the VV2003 catalogue were also studied separately and compared to each together. In the first case the zones of the celestial sphere for which the angular distance to the closest quasar is larger than 10° represent about 50% of the celestial sphere. In the second case the zones for which this closest distance is larger than 1° is restricted roughly to a thin band surrounding the galactic plane. Moreover comparative plots of the histograms of the photometric (V magnitude) and redshift characteristics of the quasars belonging to the two above catalogues, as well as the histograms related to their radio flux at 6cm and 11 cm show fundamentally different profiles and peaks. All the results above are analysed in detail by Souchay et al. (2006a).

Maintenance of the link to the solar system dynamical reference frame through close approaches between planets and quasars

Some optical observations enable one to relate the positions of moving bodies (such as the planets) with respect to a fixed quasi-inertial reference frame through stars recognized as astrometric standards, or extragalactic objects. After suitable reductions, these observations can be used to link the ICRS and the dynamical systems. One of the most promising experiments consists in determining the relative position between a planet and a quasar during close approaches between these two kinds of objects.

Toward this end we have carried out a systematic analysis of all the close approaches occurring between Jupiter and the quasars of the Veron-Cetty and Veron catalog (2003), during the time span from J2005.0 to J2015.0 (Souchay et al., 2006b). For instance we have found 24 close approaches between J2010.0 and J2012.0, which roughly corresponds to data taking phase of the Gaia astrometric space mission. For that we have chosen a 300 arcseconds threshold not to be exceeded for the shortest distance between the quasar and Jupiter's photocentre. These phenomena, which could be observed from ground-based telescopes as well as from Gaia, might play a significant role in the link between inertial directions supposed to be fixed, as given by the quasars, and the dynamical system. Notice that for this purpose, Jupiter's satellites photocentres might be chosen instead of the planet photocentre itself, because of its excessive brightness. In addition to these astrometric reductions, relativistic deflections of light due to Jupiter's mass and J2 dipole moment have been systematically modelled. Notice that the angular changes in the directions of the quasar concerned could be easily detected by Gaia measurements.

Maintenance of the link to the solar system dynamical reference frame using Lunar Laser Ranging (LLR) analyses

The solar system dynamical reference frame is materialized by the dynamical mean ecliptic and equinox (epoch J2000.0) related to the orbit of the Moon through the ephemerides of the semi-analytical lunar solution ELP (Chapront-Touzé M. and Chapront J., 1997). The analysis of the LLR observations enables one to define the orientation of dynamical mean ecliptic and equinox of J2000 with respect to ICRS. In the same time, the LLR analysis enables one to determine other parameters and to update the ELP theory (Chapront J. et al., 2002, 2003).

The position of the dynamical mean ecliptic with respect to the ICRS is defined by two angles: $\varepsilon^{(ICRS)}$, the inclination of the dynamical mean ecliptic to the equator of ICRS, and $\varphi^{(ICRS)}$, the angle between the origin $o^{(ICRS)}$ of right ascensions on the equator of ICRS and the ascending node $\gamma_I^{(ICRS)}$ of the dynamical mean ecliptic on the equator of ICRS.

The evaluation of these two angles is involved in the transformation of the rectangular coordinates of the LLR stations from the terrestrial reference frame to the celestial reference frame taking into account the polar motion, the Earth rotation and the orientation of the celestial pole. The precession-nutation matrix is computed with the IERS conventions using the daily corrections of the nutation in longitude and obliquity provided by IERS (Earth Orientation Centre series C04).

This transformation is realized according to the lunar solution ELP which results from weighted fits to the observations provided between 1970 and 2005 by the LLR stations: 10646 observations from Grasse (Observatoire de la Côte d'Azur, France), 7097 observations from Fort-Davis (McDonald Observatory, Texas) and 482 observations from Maui (Haleakala Observatory, Hawai). The last determination is:

$$\varepsilon^{(ICRS)} = 23°26'21.41112'' \pm 0.09 \text{ mas}$$

$$\varphi^{(ICRS)} = o^{(ICRS)}\gamma_I^{(ICRS)} = -0.05441 \text{ mas} \pm 0.09 \text{ mas}$$

The uncertainties mentioned here represent formal uncertainties resulting from the least square fitting. Realistic uncertainties can be estimated between five and ten times these values.

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