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 have been run jointly by the ICRS Centre (Observatoire de Paris and US Naval Observatory) 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 Paris Observatory and US Naval 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 and investigation of future realizations of the ICRS

The International Celestial Reference System (ICRS), adopted by the International Astronomical Union (IAU) in 1997, forms the underlying basis for all astrometry by defining the reference directions of a quasi-inertial celestial coordinate system that are fixed with respect to the most distant objects in the universe. Since 1 January 1998, the ICRS has been realized by the International Celestial Reference Frame (ICRF), which is based on the radio wavelength astrometric positions of compact extragalactic objects determined by the technique of very long baseline interferometry (VLBI).

At the XXVII General Assembly of the IAU held in Rio de Janeiro, Brazil, a second realization of the International Celestial Reference Frame (ICRF2; Fey, Gordon and Jacobs 2009) was adopted as the fundamental celestial reference frame as of 1 January 2010. ICRF2 is again based on the radio wavelength astrometric positions of compact extragalactic objects determined by the technique of VLBI. Significant developments and improvements in geodetic/astrometric VLBI observing and analysis have been made since the initial generation of the ICRF, hereafter ICRF1. Sensitivity of VLBI observing systems to weaker sources and overall data quality have improved significantly due to advances in VLBI receiver and recording systems and due to better observing strategies coordinated by the International VLBI Service for Geodesy and Astrometry (IVS). The use of newer and more modern radio telescopes, such as the 10 station Very Long Baseline Array (VLBA) of the National Radio Astronomy Observatory, has also greatly improved the sensitivity and quality of recent data. Further, enhan-

ced geophysical modeling and computers with faster processors have allowed significant improvements in data analysis techniques and astrometric position estimation.

ICRF2 contains precise positions of 3414 compact extragalactic sources, more than five times the number as in ICRF1. The ICRF2 has a noise floor of approximately 40 micro-arcseconds, some 5–6 times better than ICRF1, and an axis stability of approximately 10 micro-arcseconds, nearly twice as stable as ICRF1. Alignment of ICRF2 with the ICRS was made using 138 stable sources common to both ICRF2 and ICRF1. Future maintenance of ICRF2 will be made using a set of 295 new "defining" sources selected on the basis of positional stability and the lack of extensive intrinsic source structure. The stability of these 295 defining sources, and their more uniform sky distribution eliminates the two largest weaknesses of ICRF1.

ICRS Center personnel are involved in a program to extend the ICRF to higher radio frequencies than those currently used. At these higher radio frequencies, e.g., K-band (24 GHz) and Q-band (43 GHz), contributions to source position uncertainties from intrinsic source structure and from the Earth's Ionosphere will be less than that at the radio frequencies currently used for astrometric/geodetic VLBI. VLBA observations to extend the ICRF to K-band and Q-band continued in 2010. 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. Results of these high frequency reference frame observations can be found in Charlot et al. (2010) and Lanyi et al. (2010). Ongoing observations to determine the position stability of four ICRF2 quasars continued in 2010. Results of these observations can be found in Fomalont et al. (2011).

In the coming decades, there will be significant advances in the area of space-based optical astrometry. Proposed and scheduled missions such as the European Space Agency's (ESA) Gaia mission will achieve astrometric positional accuracies well beyond that presently obtained by any ground-based radio interferometric measurements. In 2010, ICRS Center personnel worked on development of a micro-satellite based astrometric mission, called the Joint Milli-Arcsecond Pathfinder Survey (J-MAPS), to produce milliarcsecond level astrometry for all of the bright stars up to 12th magnitude (limiting magnitude ~15–16) (see Gaume et al. 2009)

Monitor source structure to assess astrometric quality

VLBA RDV observations and analysis

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 2010. 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 2010, a total of six VLBA RDV experiments were observed.

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. In 2010, ICRS Center personnel imaged sources from three VLBA RDV experiments and from one high frequency (K-band) VLBA experiment. The RRFID currently contains 7279 Very Long Baseline Array (VLBA) images of 782 sources at radio frequencies of 2.3 GHz and 8.4 GHz. Additionally, the RRFID contains 1706 images of 282 sources at frequencies of 24 GHz and 43 GHz. The RRFID can be accessed from the Analysis Center web page or directly at <http://rorf.usno.navy.mil/rrfid.shtml>.

The Bordeaux VLBI Image Database

The Bordeaux VLBI Image Database (BVID) is a web accessible database of radio frequency images of ICRF sources. The BVID currently contains 1898 Very Long Baseline Array (VLBA) images of 824 sources at radio frequencies of 2.3 GHz and 8.4 GHz. The BVID can be accessed from the Analysis Center web page or directly at <http://www.obs.u-bordeaux1.fr/BVID/>.

Investigation on the QSO optical/ radio centroid reconciliation

This issue is central to the representation of the ICRF in the optical band. It has being the object of several early investigations (e.g., Silva Neto et al., 2002) and it is actively revised for the onset of the Gaia Celestial Reference Frame (GCRF) as optical materialization of the ICRS (Bourda et al., 2010, 2011). A space astrometric mission of the Space Agency (ESA) Gaia will be launched in October 2013. It is anticipated that 500 000 QSOs would be detected. Optical positions will be determined with Gaia with an unprecedented accuracy, ranging from a few tens of μas at magnitude 15−18 to about 200 μas at magnitude 20. Simulations show that the residual spin of the Gaia frame can be determined to 0.5 μas/yr with a “clean sample” of at least 10 000 of these sources (Mignard, 2002). A preliminary Gaia catalog is expected to be available by 2015 with the final version released by 2020. In the future, aligning the Gaia frame and the VLBI frame (i.e. the ICRF2, or any successor introduced by 2015) will be crucial for ensuring consistency between measured radio and optical positions. This alignment will be important not only for guaranteeing a proper transition if the fundamental reference frame is moved from the radio to the optical domain, but also for registering the radio and optical images of any celestial target with the highest accuracy. Such a registration will allow one, for example, to pinpoint the relative location of the optical and radio emission in active galactic nuclei (AGN) to a few tens of μas, placing constraints on

the overall AGN geometry. Gaia will permit the realization of the extragalactic reference frame directly at optical bands, based on the QSOs which have the most accurate positions; possibly those with magnitudes brighter than 18, but also the aspects of variability and pointlikeness in the optical band must be considered. For the reconciliation between the ICRF and the GCRF, given the limited number of sources that are anticipated to be suitable to this end, the question of individual coincidence of the optical and radio centroids must be addressed on a case by case basis whenever possible. One such investigation was conducted by Camargo et al. observing 22 ICRF sources with the wide field CCD imager of the SOAR telescope.

Observations at OHP

In 2010 QSO observations began with a 1.2m telescope located in France (OHP). The goal of these observations is to monitor the magnitude of sources in order to have information about the physical processes that could produce displacements of their optical photocenter. Such displacements, if they exist, would be of critical importance in the framework of the link of reference systems (ICRF and the future Gaia Celestial Reference Frame). The T120 (telescope of 1.2m) of the OHP (Observatoire de Haute Provence, <http://www.obs-hp.fr/guide/t120.shtml>) is located in the South East of France. It was used from March 2010 to February 2011 during 17 nights. It is equipped with a 1.2m mirror of 7.2m focal length. It uses a 1024x1024 px2 CCD camera with a pixel scale in the focal plane of 0.69 arcsec/px given a field of view of 10 arcmin^2. The seeing during the observations was relatively poor, with a mean value of 3.4 arcsec. The filters used were the V and R Cousins filters. A first list of targets that could be used for the link between ICRF and the future Gaia Celestial Reference Frame has been given by Bourda et al. (2008). First preliminary observations of these targets have been done with the T120 to verify that all of them are observable by small aperture telescopes. They are the basis to other extended programs (in term of the frequency of observations) that are scheduled to begin in February 2011 with small robotic telescopes. The figure below gives an example of the data obtained.

Maintenance of the time stability of the ICRF

The astrometric position time series of quasars as derived from VLBI delays at OPAR IVS analysis center were used in two research projects which involved persons of the ICRS Center.

Use of VLBI astrometric position time series for research

Titov, Lambert, & Gontier (2011) used position time series produced with a very loose constraint in order to detect the effect of the Solar System acceleration in the Universe in the distant body proper motion. They showed that the small systematic proper motion of ~5 microseconds of arc per year is indeed detectable in the VLBI observations. (The systematic shows up as a degree-2,

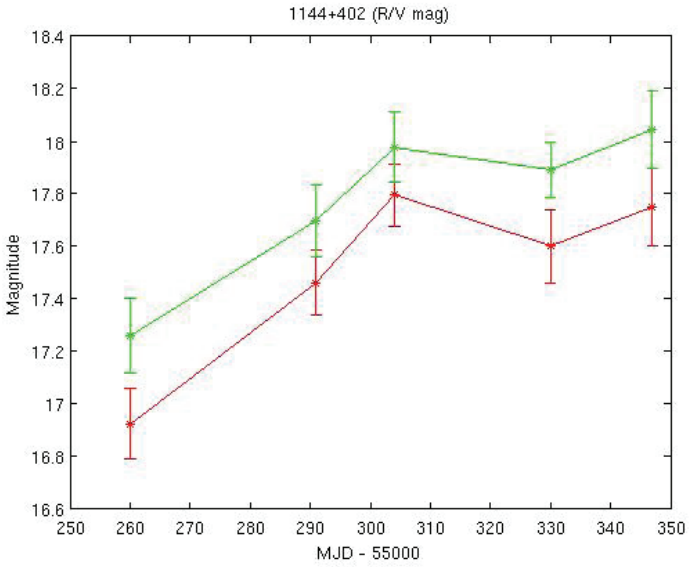

Fig. 1: Optical variability in V and R bands of a quasar observed at OHP

zero-order, deformation of the quasar velocity field, oriented towards the Galactic center. This confirms that the main component of the Solar System acceleration is due to the rotation around the Galactic center.) Higher order harmonics (quadrupolar deformation of the velocity field) were investigated, but the various systematics detected were not fully explained and need more research.

The time series used in this study are pretty different from those published on the IVS OPAR web site, obtained with a tighter constraint and aiming at describing mid-term (typically interannual) variations of the position of the centroid. However, it appears that the tight constraint biases significantly the slopes and impeaches the detection of the dipole.

Moór et al. (2011) assessed whether the direction of the centroid motion as derived from the time series was consistent with the relevant direction derived from source structure maps. On a sample of 62 sources, they compared the characteristic direction of the extended jet structure and the direction of the apparent proper motion. They concluded that there is indeed a correlation between the two characteristic directions. However, there are cases where the ~ 1–10 mas scale VLBI jet directions are significantly misaligned with respect to the apparent proper motion direction.

Linking the ICRF to frames at various wavelengths

The Large Quasar Astrometric Catalog

The Large Quasar Astrometric Catalog (LQAC) is a whole sky compilation of information on known QSOs. It complements the existing catalogues, which are dedicated on confined zones of the sky, wavelength, selection criteria, by providing the most precise astrometry and completeness of tabular data currently available. The LQAC presently contains entries for 113,666 objects (Souchay et al., 2009). Along the year it was introduced at several meetings

(e.g., Barache et al., 2009, 2010, at the ASPC and SF2A) to explain and discusses its contents and get comments and demands from the users.

The second version of the LQAC is being prepared. For this the database aspect will be emphasized, bringing in calculated quantities – namely absolute magnitudes, an additional set of coordinates to consistently represent the ICRF for all objects for which there is optical counterpart, and morphological indexes on the DSS optical bands. A coherent set of absolute magnitudes, computed according to rigorous relativistic space-time precepts, is a key point for astrophysics investigation, being a quantity free from theoretical modeling. It also provides elements to size up the accretion disk region in views of estimating optical variability likeness during the five years of the forthcoming Gaia mission. The morphological indexes have similar role in what concerns the signature of the host galaxy and the methodology will be that from the Gaia Initial QSO Catalog. The optical equatorial coordinates will follow the methodology used in the LQRF, by which both products can be embedded. The enlarged, second version of the LQAC in this way will also brings to the user the latest version of the Gaia Initial QSO Catalog.

Maintenance of the link to the Hipparcos catalog

During the reporting period (2010) USNO continued to make progress in the areas of astrometric star catalogs, the extragalactic link to radio frame sources, URAT, and JMAPS.

Papers describing the details of the USNO CCD Astrograph Catalog 3rd release (UCAC3) were published (Finch et al. 2010, Zacharias, 2010) and work toward the final UCAC4 release begun. Detections on individual CCD frames were cleaned up, bugs in matching software fixed, and the conventional astrometric reduction of all applicable frames was repeated with improved modeling. Code was developed for an iterative overlap solution and simulations run, showing a slow convergence due to the only 2-fold pattern of UCAC observational data.

The new version of the Northern Proper Motion (NPM) plate reductions was obtained from T. Girard (Yale Univ.) which forms the basis for UCAC4 proper motions for the majority of stars north of Dec = –20 deg, with expected, formal errors of 3 to 5 mas/yr. The Brorfelde Schmidt CCD Catalog (BSCC) was published (Zacharias et al. 2010) as a joint effort between USNO and Copenhagen Observatory, giving precise positions of 13.7 million stars mainly north of 70 deg on the Tycho-2 reference system.

Monitoring a sample of 12 ICRF optical counterparts continued at the 1.55m telescope at NOFS, while the Space Interferometry Mission, SIMLite project was canceled by NASA.

Hardware construction of the USNO Robotic Astrometric Telescope (URAT) continued (Zacharias, Gaume 2010). See also

<www.usno.navy.mil/USNO/astrometry/optical-IR-prod/urat> . The URAT mount in Washington DC is now controlled by a computer. All 4 STA1600B CCD chips (10560 x 10560 pixels) were characterized and accepted. All 3 guide CCDs were produced, tested and accepted. The construction of the dewar is delayed and delivery of the complete 4-shooter camera will be in 2011.

The Joint Milli-arcsecond Pathfinder Survey (JMAPS) space mission was ramping up at USNO in 2010 including more detailed simulations and reduction code development. First hardware parts were built by contractors.

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

Lunar Laser Ranging (LLR) analyses provide scientific results in various domains (astronomy, gravitational physics, geodynamics, selenophysics). They contribute also to the positioning of the dynamical reference frame with respect to ICRS. The LLR technique is particularly sensitive to the orientation of the dynamical ecliptic materialized by the Earth's orbit. Figures LLR1 and LLR2 show the distribution of the LLR observations performed by the different

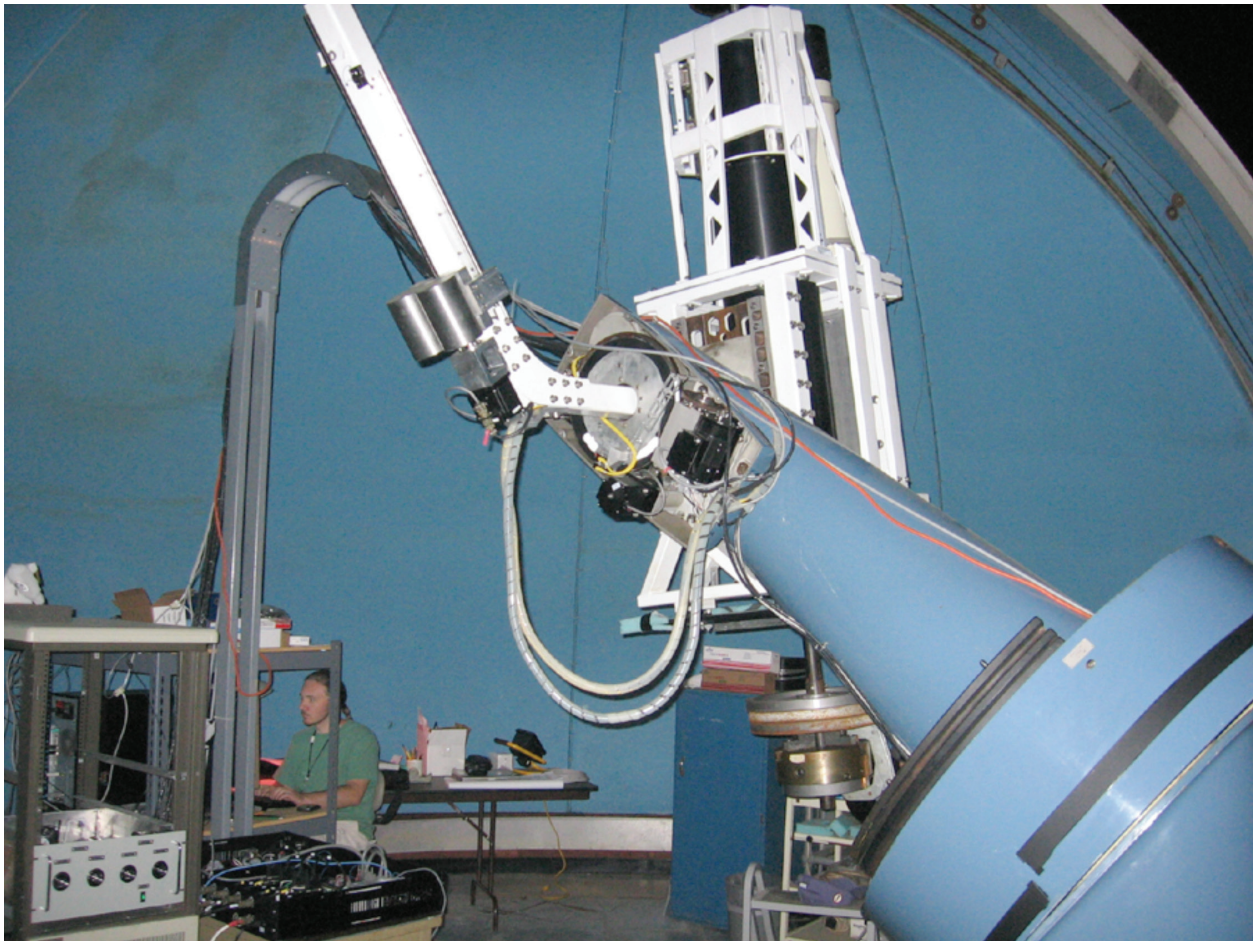

Fig. 2: The URAT telescope sans camera

terrestrial stations with the five retro-reflectors placed on the lunar ground. About 20000 LLR normal points have been taken by the tracking stations between 1969 and 2010.

At the Paris Observatory Lunar Analysis Center (POLAC), the dynamical reference frame of the solar system is defined as the dynamical mean ecliptic and equinox J2000 related to the orbit of the Moon given by the solution ELP (Chapront et al., 1999). Figure 5 shows the evolution of the residual between models and observations obtained by POLAC during the forty last years. The post-fit residuals are now around 300 picoseconds for the round-trip travel time of the light, that is to say less than 5 cm for the distance station–reflector.

The position of the inertial dynamical mean ecliptic of J2000.0 with respect to an equatorial frame chosen as reference is oriented by two angles: ε, the inclination of the ecliptic to the equator and φ, the angle between the origin of the right ascension (o) on the equator and the ascending node (γ^{I}_{2000}) of the ecliptic on the equator (Figure 6). Thus, the link with ICRS is defined by the angles $\varepsilon^{(ICRS)}$ and $\varphi^{(ICRS)}$. In the same way, the angles $\varepsilon^{(Eq2000)}$ and $\varphi^{(Eq2000)}$ define the link of the inertial dynamical mean ecliptic of J2000.0 with the mean equator of J2000.

The evaluations made by POLAC give the following values:

$\varepsilon^{(ICRS)}$ = 23º26'21".4110 ± 0.1 mas; $\varphi^{(ICRS)}$ = –55.4 ± 0.1 mas;

$\varepsilon^{(Eq2000)}$ = 23°26'21".4056 ± 0.1 mas; $\varphi^{(Eq2000)}$ = –14.6 ± 0.1 mas,

and the arc between $\gamma^{I}_{2000}{}^{(ICRS)}$ and $\gamma^{I}_{2000}{}^{(Eq2000)}$ on the ecliptic is estimated at 44.5 ± 0.3 mas.

These results have some applications for the astronomical community.

In the IAU 2009 System of Astronomical Constants (IAU, 2009), the obliquity at J2000.0 (given under the notation ε_{J2000}) is equal to the value of $\varepsilon^{(Eq2000)}$ (8.4381406 x 10^4"). It is a component of the IAU 2006 precession model.

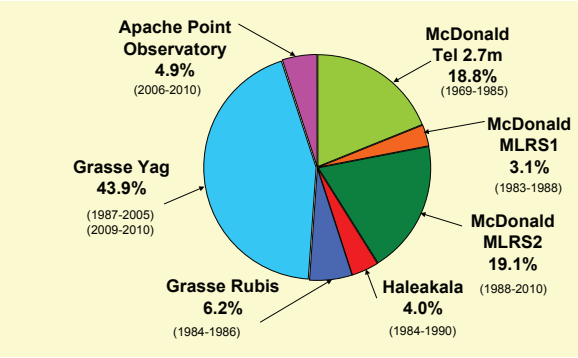

Fig. 3: Percentage of LLR normal points for each ground-based station during the 1969–2010 time interval

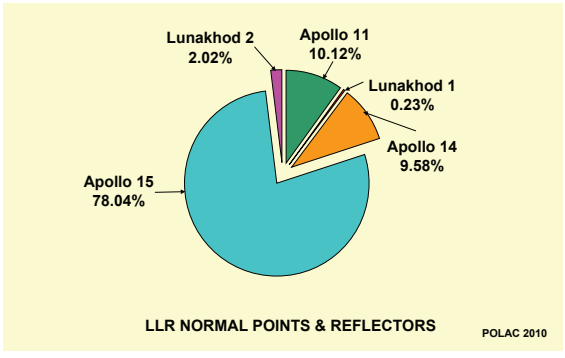

Fig. 4: Percentage of LLR normal points for each lunar reflector during the 1969–2010 time interval

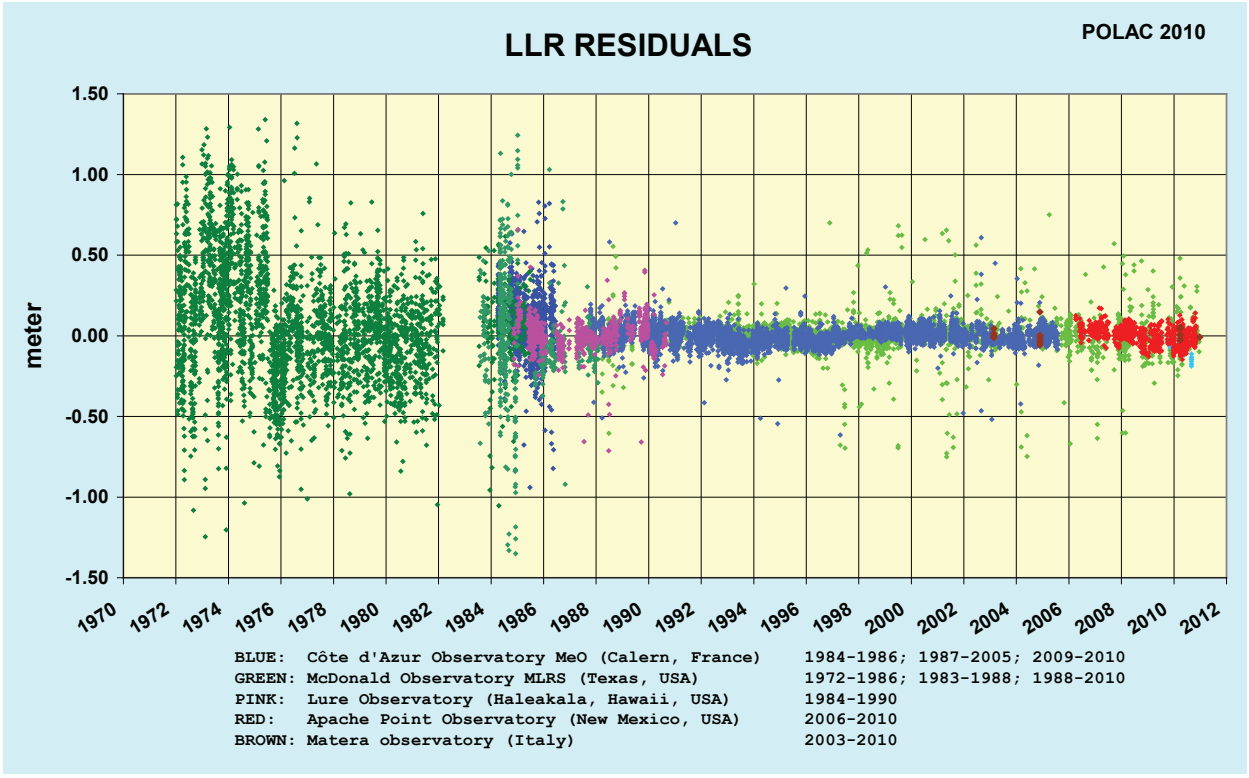

Fig. 5: Amplitude of LLR residuals from 1970 to 2010

The IAU recommends also that the origin of right ascension of the ICRS be close to the dynamical equinox at J2000.0. The shift $\varphi^{(ICRS)}$ of –55.4 mas (direct rotation around the polar axis) on the ICRS equator corresponds to the shift $\varphi^{(Eq2000)}$ of –14.6 mas on the mean equator of J2000.0 that is noted $d\alpha_0$ in the IERS Conventions (IERS, 2010).

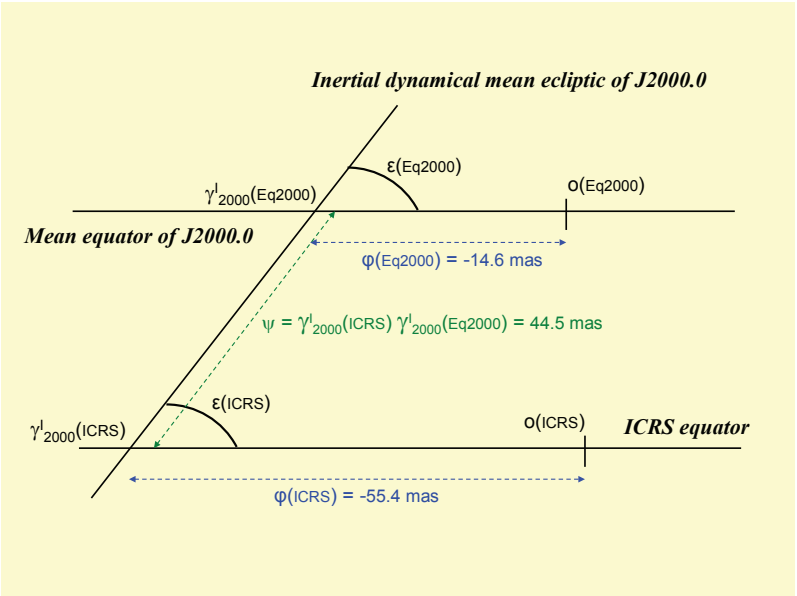

Fig. 6: Relative orientation of the fundamental planes (ecliptic, equator) from LLR observations

Maintenance of the link to the solar system dynamical reference frame using asteroid observations

The link between the ICRF and the dynamical reference frame realized by the ephemeris of the Solar System bodies is made simultaneous observations of the latter and QSOs. For the inner Solar System this link was directly investigated by VLBI observations of planet-orbiting spacecrafts and angularly nearby quasars (Newhall et al. 1986). In the case of the outer Solar System, simultaneous CCD observations of planets and quasars during apparent close approaches were obtained for Neptune and Uranus (da Silva Neto et al. 2005). In the framework of the forthcoming Gaia space mission, the close approaches of Jupiter with a large sample of quasars from the catalog were investigated in the time interval 2005–2015 (Souchay et al. 2007). Another approach was taken by Nedelcu et al. (2010) that determined between near Earth asteroids (NEAs), representing the dynamical reference frame by means of their ephemeris, and QSOs. Besides the large number these asteroids are generally bright and thus the astrometry is of good quality. Also, when planets are used, either there is a problem to define the center of an extended object, or satellites are used and the results must be later transported to the planet's ephemeris. This study, in the period 2010–2018, found respectively 2,924, 14,257, and 6,972 close approaches (within 10arcmin) between asteroids with a minimum solar elongation value of 60deg and quasars from the ICRF-Ext2, the Very Large Baseline Array Calibrator Survey (VLBA-CS), and the Very Large Array (VLA).

Maintenance of the link to the solar system dynamical reference frame using Pulsar Timing analyses

In 2010, activities related to VLBI observations of millisecond pulsars (MSP) and the link between dynamical reference frames and ICRF based on millisecond pulsar observations have been maintained and used with new planetary ephemerides, INPO10A (Fienga et al., 2010). As explained in the IERS Annual Report 2008–2009, radio timing and VLBI astrometry of millisecond pulsars is used to estimate rotation matrices between the reference frames of planetary ephemerides and ICRF. We used 18 MSP observed by radio timing at the NRT (Desvignes, 2009) and VLBI astrometry of 4 MSP extracted from Chaterjee et al. (2009) and Deller et al. (2009). More details about the used procedure as well as the MSP used to estimate the rotation matrixes can be found in Fienga et al. (2010) and Fienga et al. (2010b).

To check the procedure, we have estimated rotation matrices between planetary ephemerides reference frames themselves. Based only on radio timing observations, the angles presented in the left-hand side part of Table 1 and obtained in using the all sample of pulsars available with a good accuracy are quite compatible with previous determinations of rotation matrices between planetary frames or the estimation one can expect. For example, the rotation angles between DE405 and DE200 obtained with

the 18 most accurate TOAs give results consistent with Standish (1998). The accuracy of the presented results is a factor 10 better than this last paper.

Furthermore, DE405 and the other modern ephemerides (INPOPs, DE414) have rotation matrices quite stable indicating a very similar behavior between INPOP08, INPOP10A and DE414 in one hand and DE405 in the other hand. The rotations between these ephemerides are less than 2 mas which corresponds to the present mean accuracy of the VLBI tracking observations used to link the planetary ephemerides to ICRF (Folkner et al., 2008; Fienga et al., 2008).

In the right hand side of Table 1, one can find the rotation angles obtained between planetary ephemerides frames and the ICRF as deduced from pulsar timing and VLBI astrometry. The rotations obtained are more important than expected for all the ephemerides. However to get these rotation angles, only 4 pulsars were used in the fit with one pulsar (J2145-07) severally down-weighted due to its high uncertainties in timing and VLBI astrometry. Furthermore, the spatial distribution of the 4 MSPs is not optimized. One should wait for new VLBI observations of pulsars to obtain a more definitive conclusion. An important set of VLBI observations of MSP is now proceeded by Chatterjee et al. as a ground follow-up program to the FERMI mission. From this intensive VLBI program, 22 pulsars should be observed. Among them, at least 3 targets are tracked by the NRT regularly and can be used for reference frame ties.

Table 1: Angles of rotation deduced from adjustment of rotation matrices between ICRF and planetary reference frames obtained by comparisons of MSP positions deduced from radio timing and VLBI astrometry. The angles are given in milliarcseconds and the uncertainties are the formal 1-sigma deduced from the least squares.

	θ mas	η mas	ζ mas
18 MSPs with TOA $(\sigma_\alpha,\sigma_\delta) < 10$ mas			
DE405 → DE200	-0.4 ± 0.3	-13 ± 0.4	-13 ± 0.3
DE405 → DE200 [22]	-1 ± 2	-14 ± 3	-10 ± 3
DE414 → DE405	1.5 ± 0.3	-1.0 ± 0.4	-0.9 ± 0.3
INPOP08 → DE405	1.3 ± 0.3	-0.3 ± 0.4	-1.1 ± 0.3
INPOP10A → DE405	1.6 ± 0.3	-0.7 ± 0.4	-0.7 ± 0.3
Only 4 MSPs with TOA $(\sigma_\alpha,\sigma_\delta) < 10$ mas			
DE405 → DE200	-0.5 ± 0.2	-12 ± 0.3	-13 ± 0.18
INPOP08 → DE405	1.4 ± 0.03	-0.03 ± 0.05	-1.4 ± 0.03
INPOP10A → DE405	1.7 ± 0.01	-0.03 ± 0.02	-1.0 ± 0.01

	θ mas	η mas	ζ mas
Only 4 MSPs with TOA + VLBI $(\sigma_\alpha,\sigma_\delta) < 10$ mas			
DE405 → ICRF	6 ± 5	15 ± 11	-4 ± 6
INPOP08 → ICRF	4 ± 5	15 ± 11	-2.5 ± 6
INPOP10A → ICRF	4 ± 5	15 ± 11	-3.0 ± 6
DE200 → ICRF	6 ± 5	28 ± 11	9 ± 6
DE200 → ICRF [1]	2 ± 2	12 ± 3	6 ± 3
DE200 → ICRF [25]	-1 ± 3	10 ± 3	4 ± 5

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