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-
icd 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 2011. 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). Results of observations to determine the position/structure stability of four ICRF2 quasars 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. Missions such as the European Space Agency’s (ESA) Gaia mission are expected to achieve astrometric positional accuracies beyond that presently obtained by ground-based radio interferometric measurements. In 2011, ICRS Center personnel worked on development of a micro-satellite based astrometric mission, called the Joint Milli-Arcsecond Pathfinder Survey (JMAPS), to produce milliarcsecond level astrometry for all of the bright stars up to 12th magnitude (limiting magnitude ~15–16) (see Gaume et al. 2009). Unfortunately, due to budget limitations the U.S. Navy cancelled the JMAPS program toward the end of 2011, although funding was allocated for 2012 to complete the JMAPS instrument.
In 2011, new celestial reference frames were produced at different IVS analysis centers by the re-analysis of the full VLBI observational database and submitted to the IVS data center. The aus2011a and aus2011b catalogs were produced at Geoscience Australia (Canberra), using the OCCAM geodetic VLBI analysis software package. Both bkg2011a and opa2011a were produced by the NASA Goddard Space Flight Center’s package SOLVE, respectively at the Federal Agency for Cartography and Geodesy (BKG Leipzig) and Institute of Geodesy and Geoinformation of the University of Bonn (IGGB), and at the OPAR IVS analysis center of the Paris Observatory, respectively. Technical descriptions of the solutions are available at the IVS data center.

We evaluate the consistency of the four catalogs with the ICRF2 by modelling the coordinate difference between the ICRF2 defining source coordinates in both the submitted catalog and the ICRF2. The coordinate difference was modelled by a 6-parameter transformation as used at the IERS in previous comparisons (see, IERS Annual Report 1995, p. II-32). The results are reported in the Table hereafter. The 6 parameters were estimated on the coordinate difference of the defining sources present in the catalogs. The drifts in right ascension and declination (noted $D_\alpha$ and $D_\delta$, respectively) have been omitted in the Table since they do not exceed 0.6 μas with formal error of 0.2 μas. Figures below represent the residual (i.e., after alignment onto the ICRS) differences between each catalog and the ICRF2.

Table 1: The characteristics and transformation parameters relevant to the four catalogs submitted to the IVS in 2011.

<table>
<thead>
<tr>
<th>Catalog</th>
<th>No. Sources</th>
<th>Difference to ICRF2</th>
<th>Transformation parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean Rms</td>
<td>A1 A2 A3 Bδ</td>
</tr>
<tr>
<td></td>
<td>All</td>
<td>Defining</td>
<td>$\alpha$</td>
</tr>
<tr>
<td>aus2011a</td>
<td>2848</td>
<td>280</td>
<td>47 9 19 138 183</td>
</tr>
<tr>
<td>±</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>aus2011b</td>
<td>2881</td>
<td>291</td>
<td>48 22 167 166</td>
</tr>
<tr>
<td>±</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>bkg2011a</td>
<td>3226</td>
<td>287</td>
<td>8 26 59 68</td>
</tr>
<tr>
<td>±</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>opa2011a</td>
<td>3720</td>
<td>295</td>
<td>9 9 46 50</td>
</tr>
<tr>
<td>±</td>
<td></td>
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</tr>
</tbody>
</table>
Fig. 1: The residual difference between the four catalogs and the ICRF2 for all sources (Left) and defining sources only (Right).

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 2011. 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 2011, a total of six VLBA RDV experiments were observed.
Monitor source structure to assess astrometric quality

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 2011, 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 1867 images of 285 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>.

Fig. 1 (continued)
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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 3517 Very Long Baseline Array (VLBA) images of 1100 sources mostly at radio frequencies of 2.3 GHz and 8.4 GHz, but includes images for some sources at 24 GHz and 42 GHz. The BVID can be accessed from the Analysis Center web page or directly at <http://www.obs.u-bordeaux1.fr/BVID/>.

Linking the ICRF to frames at various wavelengths

The link between the ICRF and other celestial reference frames is fundamental to prepare the future ICRF as well the future connection between the ICRS and the GCRS (Gaia Celestial Reference System). In 2011 several actions were taken by the ICRS Center in order to facilitate and improve the link between the ICRF and other celestial frames.

Optical Representation of the ICRS

The astrometric precision for the observation of the constituent sources and maintenance of the ICRF is steadily increasing in VLBI observations, hand in hand with increasing sensitivity. In the optical domain a precision leap will be achieved by the European mission Gaia, perhaps shifting the ICRF dominion from the radio back to optical wavelengths. In the ground segment, large synoptic surveys as the SDSS and the forthcoming DES, Pan-STARRS, and LSST complement Gaia by deeper surveying, larger numbers, and multi-band observations. All this asks for a careful cataloguing of each object's astrometry and main outcomes from every observation. Such outcomes enable the relating of the astrometry to the photometry with astrophysics, in order to define the appropriateness or shortcomings of any given object as an element of the ICRF. To consider all these different aspects, that are progressively becoming relevant, a major meeting was held in 2011 in Porto, Portugal, sponsored by Gaia/Great.

The Large Quasar Astrometric Catalog

The ICRS Center is in charge of the LQAC, a whole sky compilation of information on known QSOs, as well as of its regular up-dates. The second version of the LQAC was published as a CDS catalog (Souchay et al., 2011). The LQAC2 now contains 187 504 quasars, observed optical and radio flux and redshift, original and consolidated equatorial coordinates, plus calculated absolute magnitudes and morphological indexes (see IERS Annual Report, 2010). A more precise description of the LQAC-2 will be given in the IERS Annual Report 2012.

Investigation on the QSO optical/radio centroid reconciliation

This issue is central to the representation of the ICRS in the optical band. It also is being actively revised for the onset of Gaia. For the reconciliation between the ICRF and the GCRF, given the limited number of sources that are anticipated to be suitable to this end,
Quasar Variability

Variability is a distinct feature of quasars, in all time, band, and regions domains. It hampers the astrometric precision which is signal-to-noise dependent, and may increase the photocenter jitter and detection of spurious proper motion. Taris et al. (2011) investigated photometric and astrometric variability of 41 quasars from the CFHT Deep Field 2, followed during 4.5 years.

Stellar Proper Motions

A milestone was reached with the publication of absolute proper motions (SPM4) of the southern proper motion program based on 2 epoch data (Girard et al. 2011). The positions were put on the Tycho2 system while the proper motion system is anchored by galaxies and QSOs.

UCAC 4

Data for the final USNO CCD Astrograph Catalog (UCAC4) was prepared and a beta version sent out to testers. All-sky plots of UCAC4 proper motion distribution look good, a significant improvement over UCAC3. First feedback from the testers was received and the catalog improved.

Quasar Position Shifts

Monitoring of a sample of 12 ICRF optical counterparts continued at the 1.55m telescope at NOFS to investigate possible centroid shifts as a function of time (photometric activity).

URAT

The entire dewar system and electronics of the USNO Robotic Astrometric Telescope (URAT) was delivered by Semiconductor Technology Associates (STA) and the telescope with its new focal plane array achieved first light on September 25, 2011 in Washington DC. The 4 monolithic CCDs with 10,560 by 10,560 pixels of 9 micron square size image 2.65 by 2.65 deg of sky each, with a total of 28 square degrees of sky coverage in a single exposure. All outputs are functional in 8 channel per CCD readout mode. The clocked anti-blooming mode is functional. The dewar almost got destroyed while sitting on a wooden box in preparation for mounting at the astrograph backend when an earthquake hit the Washington DC area.

Later in 2011 the telescope was prepared for shipment to the Naval Observatory Flagstaff Station (NOFS) while the camera and dewar was sent to STA for minor upgrades (e.g. removing the glow at the amplifiers, and obtaining a new neutral density spot on the dewar window). A status report was presented at the
3.5 Product Centres


Fig. 2: The URAT focal plane at STA: 4 big CCDs (95 mm by 95 mm each) and 3 guide CCDs.

Fig. 3: Setup of the URAT telescope with the dewar and camera electronics in September 2011. From left to right: Norbert Zacharias, Charlie Finch, Ted Rafferty (retired, in the background), and Greg Bredthauer (STA).
3.5.4 ICRS Centre

Maintenance of the link to the solar system dynamical reference frame

*Using Planetary Ephemeris: the ASETEP database*

The link between the ICRS and the Dynamical System is one of the important tasks devoted to the ICRS Center. This can be done through the ephemerides of the planets and asteroids; each orbital motion of these bodies can be considered as a representation, a materialization of the Dynamical System, at least by defining implicitly the basic plane from which it is defined (generally the fixed ecliptic and equinox of the epoch J2000.0).

In that topic recent high precision ephemerides as INPOP (from Paris Observatory, cf. Fienga et al. (2010)), DE (from JPL, cf. Standish et al., 1998) and EPM (from IAA) compete to give the best determinations of the planetary motions. Nevertheless, their accuracy is limited by the lack of knowledge concerning the masses of the largest asteroids which exert significant gravitational perturbations.

In 2011, a database was constructed in order to give a clear view of the specific influence of a set of 43 asteroids whose mass is known with a relatively good accuracy (better than ±60% of relative uncertainty), on the terrestrial planets: Mercury, Venus, the Earth (in fact the EMB: Earth-Moon Barycentre) and Mars. This database is called ASETEP (Asteroidal Effects on the Terrestrial Planets).

In addition to basic tables where the masses of the 43 asteroids above are given, together with their nominal value, their uncertainty, the origin of their determination, the ASETEP database provides mainly three kinds of information:

- It gives the specific influence of each of the 43 selected asteroids on each of the 6 orbital elements of any of the 4 terrestrial planets (Mercury, Venus, the EMB and Mars), leading to the presentation of $43 \times 6 \times 4 = 1032$ curves.
- It gives the influence of each of the 43 selected asteroids on the geocentric coordinates ($\alpha, \delta, \text{distance}$) of the centre of mass of each of the 3 terrestrial planets (Mercury, Venus, Mars), leading to the presentation of $43 \times 3 \times 3 = 387$ curves.
- It presents information tables related to the asteroids (mass estimation with uncertainty, amplitude of the oscillations characterizing the perturbations etc...).

The ASETEP database will be up-dated regularly at each time a new and more precise estimation of the masses of the asteroids involved will be given. They will be also extended by including more and more asteroids, according to their mass uncertainty.

*Using Lunar Laser Ranging analyses*

Between 1969 and 2011, about 20,000 observations (LLR normal points) have been performed by the following LLR tracking stations:
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.

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).

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: \( \varepsilon \), the inclination of the ecliptic to the equator and \( \phi \), the angle between the origin of the right ascension (\( \alpha \)) on the equator and the ascending node (\( \gamma \)) of the ecliptic on the equator.

The link with ICRS is defined by the angles \( \varepsilon \)(ICRS) and \( \phi \)(ICRS) and the evaluations made by POLAC with the LLR observations, performed between 1969 and 2011, give the following values:

\[
\varepsilon \ (\text{ICRS}) = 23^\circ 26'21".411 \pm 0.001"
\[
\phi \ (\text{ICRS}) = -55.4 \pm 0.1 \text{ mas}
\]

**Using Pulsar Timing analyses**

In 2011 a large program of VLBI observations of pulsars organised by a large international consortium was launched. About 20 pulsars have been selected for a 4 year observational session in order to estimate their parallaxes but also the variability with time of their physical characteristics. This survey is also a complementary session of VLBI observations for objects observed by FERMI in X. Pulsars selected for their interest for linking reference frames such as J0751+1801, J1744-1134 and J0613+0200 were also included. These observations will help for the densification and the improvement of the VLBI pulsar observations when improvement in radio timing of these objects will be ensure by new analysis of the timing data sets.
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