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, enhanced 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 2012. 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. Preliminary 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).

At the IAU General Assembly in Beijing in August 2012, ICRS Center personnel organized an effort to establish an IAU Working Group on ICRF-3. The effort was well received by the IAU. A steering committee was established which met in Beijing and subsequently in October 2012 in Bordeaux. The steering committee wrote a charter for the working group, established Working Group membership, and selected a Working Group chair. The IAU subsequently accepted all these, and formally established the Working Group. The ICRF-3 Working Group will immediately pursue new observations that will fill gaps and improve weaknesses of ICRF2, present a progress report to the IAU General Assembly in 2015, and pursue the completion of ICRF-3 in 2018.

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 2012, 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, toward the end of 2011 the U.S. Navy cancelled the JMAPS program however, funding was allocated for two additional years (2012 and 2013) to complete the JMAPS instrument. Whether or not the JMAPS instrument will be utilized astrometrically, was unresolved at the end of 2012.

Assessment of VLBI Realisations of the ICRF

In 2012, new celestial reference frames were produced at different IVS analysis centers by the reanalysis of the full VLBI observational database and submitted to the IVS data center. The aus2012b catalog was produced at Geoscience Australia (Canberra), using the OCCAM geodetic VLBI analysis software package. Both bkg2012a and opa2012a were produced with the NASA Goddard Space Flight Center's package SOLVE, 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. The VLBI group of the NASA Goddard Space Flight Center also provided a catalog along with the gsf2012a solution.

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

Table 1: The characteristics and transformation parameters relevant to the four catalogs submitted to the IVS in 2012.

	No. Sources		Difference to ICRF2				Transformation parameters			
			Mean		Rms					
	All	Def.	α cos δ µas	δ µas	α cos δ µas	δ µas	A1 µas	A2 µas	A3 µas	Bδ µas
aus2012b	2895	288	4	-7	78	84	-23	4	3	-14
±							*5*	*5*	*5*	*5*
bkg2012a	3253	287	-1	22	51	66	7	15	1	18
±							*5*	*5*	*4*	*4*
gsf2012a	3708	295	2	-8	46	54	-2	7	-3	-14
±							*5*	*5*	*4*	*4*
opa2012a	3526	295	6	10	53	52	-4	12	-7	10
±							*5*	*5*	*4*	*4*

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 Table 1. The 6 parameters were fitted to the coordinate difference of the defining sources present in the catalogs. The drifts in right ascension and declination (noted Dα and Dδ, respectively) have been omitted in the Table 1 since they do not exceed 0.6 µas with formal error of 0.2 µas. Figures 1–4 below represent the residual (i.e., after alignment onto the ICRS) differences between each catalog and the ICRF2.

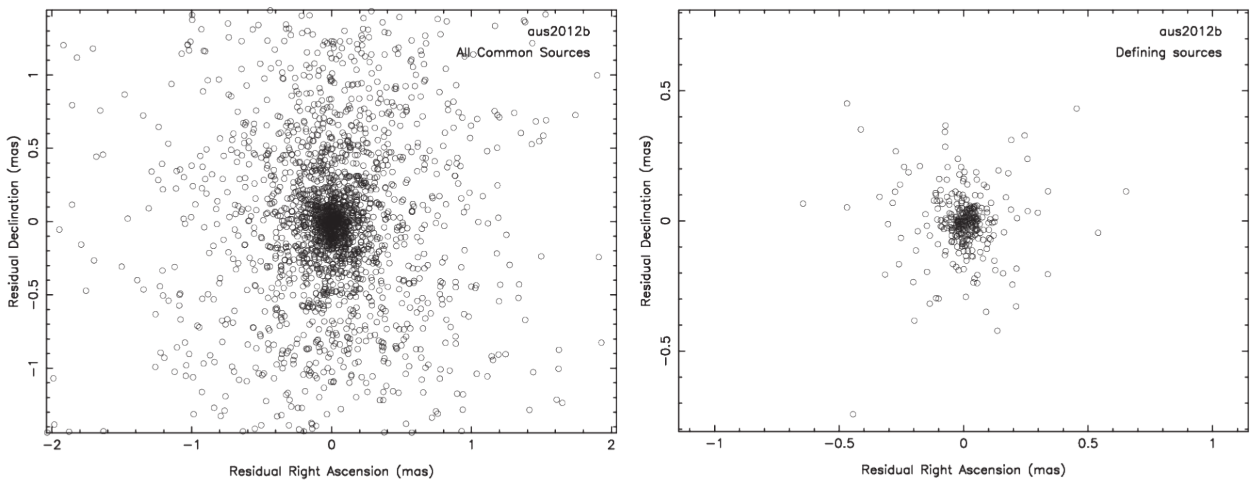

Fig. 1: The residual difference between the aus2012a catalog and the ICRF2 for all sources (Left) and defining sources only (Right).

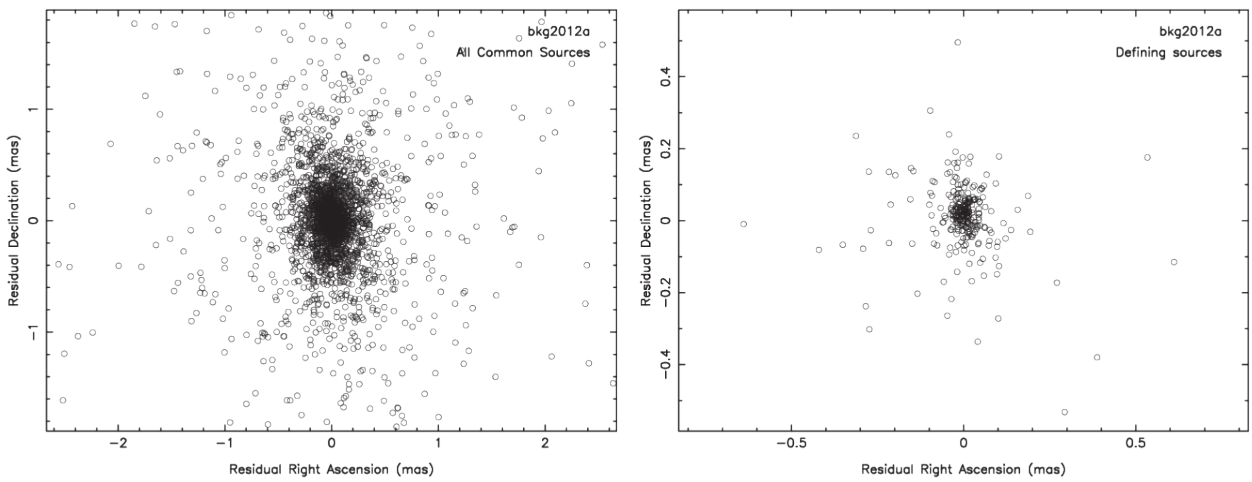

Fig. 2: The residual difference between the bkg2012a catalog and the ICRF2 for all sources (Left) and defining sources only (Right).

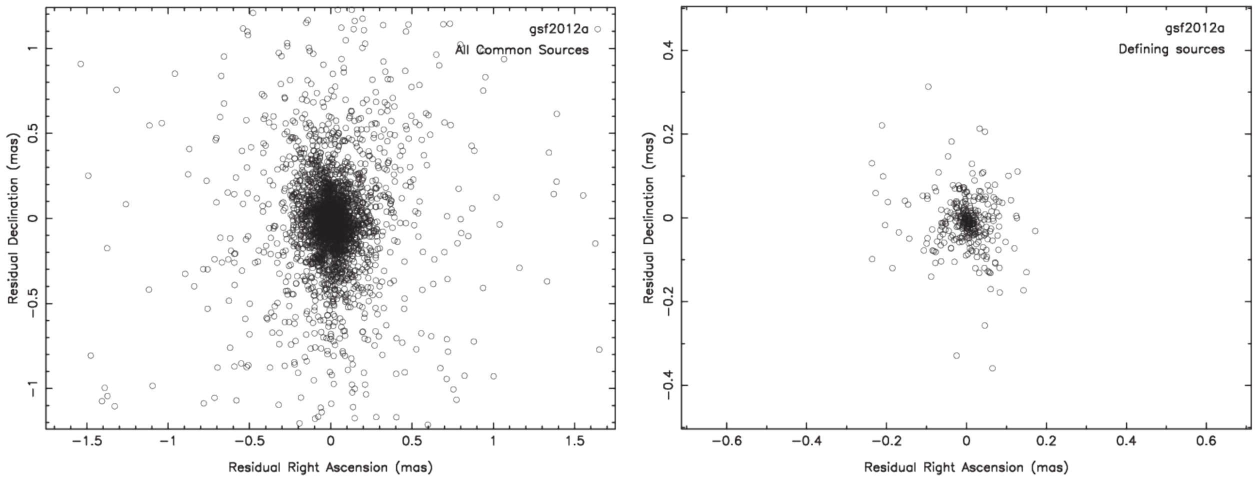

Fig. 3: The residual difference between the gsfc2012a catalog and the ICRF2 for all sources (Left) and defining sources only (Right).

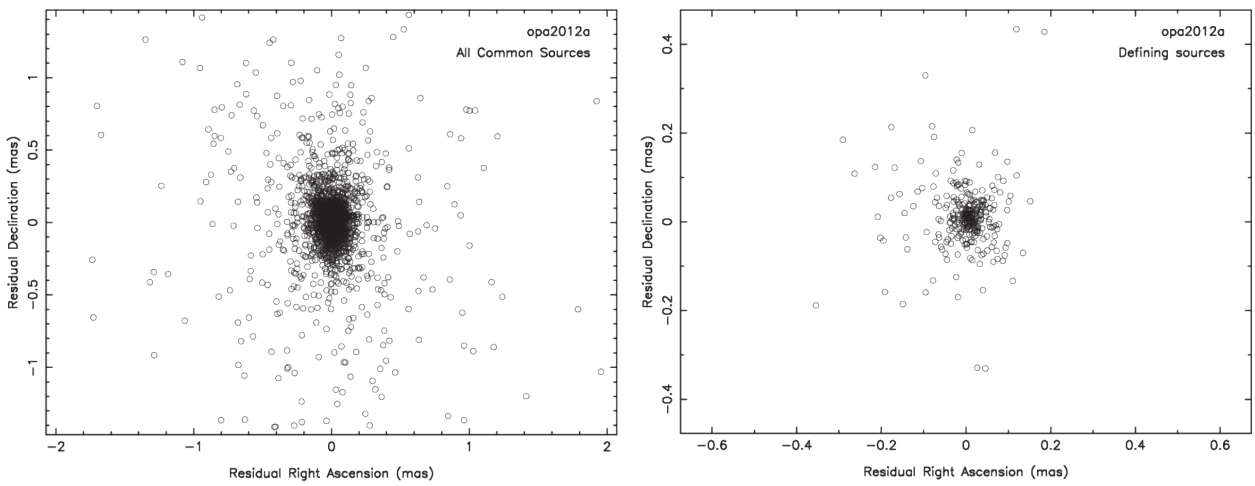

Fig. 4: The residual difference between the opa2012a catalog and the ICRF2 for all sources (Left) and defining sources only (Right).

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 2012. 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 2012, 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 2012, ICRS Center personnel imaged sources from two high frequency (K-band) VLBA experiments. 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>.

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 other 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). During the reporting period (2012) ICRS Center personnel continued to make progress with several astrometric star catalogs (e.g. UCAC and URAT), the extragalactic link to ICRF sources, and in preparation for the Gaia astrometric space mission.

Optical Representation of the ICRS: Gaia

The ICRS/ICRF paradigm is based on a frame formed by very distant extragalactic sources which are thus assumed to have no global rotation. By definition this frame is considered to be kinematically non-rotating. To present date the versions of the ICRF (IERS Tech. Notes 23/1997 and 35/2009) were formed by VLBI positions of selected radio loud quasars. The ESA satellite Gaia, to be lauched on end 2013, astrometric solution will be referred to a kinematically non-rotating frame thanks to the global zero-proper motion constraint set on the clean subset of quasars detected by Gaia. The positional accuracy of the individual sources will depend on their magnitude, but at least for the (forecasted) 30,000 QSOs brighter than G=18 this would be better than 80 μas and 60 μas/yr. This astrometric solution should supersede the VLBI based versions of the ICRF, and bring the primary representation of the ICRS to the optical wavelength at the time of issuing of the Gaia final solution, to be published around 2020 (Mignard, 2012).

In preparation for what is currently called the Gaia Celestial Reference Frame (GCRF), the Gaia Initial QSO Catalog has been prepared (Andrei et al., 2012a).

Gaia Initial QSO Catalog (GIQC)

QSOs will define the GCRF, and accordingly on Gaia board means are capable of classifying them. The QSO classification will possess three major orientations: getting the cleanest QSO sample to determine the GCRF; deriving the most complete QSO sample based on the full Gaia data; and determining the astrophysical parameters for each QSO. The determination itself of a Gaia source as a QSO is planned to rely primarily on comparison of the photometric output against a template of spectral energy distributions (SED), and secondarily on astrometric observables, variability analysis and a reliable initial list of known QSOs. A sample as small as 10,0000 quasars can stabilize the GCRF to a residual rotation of less than 0.5 µas per year, provided they are well distributed over the sky. The relatively small number of points actually required to constitute a robust GCRF brings particular relevance for the initial list of known QSOs, the GIQC. It aims to obtain a clean sample of at least 10,000 quasars, distributed all-sky above |20deg| of galactic latitude, with magnitude brighter than V=20 and point-like PSF. This bona fide initial clean sample is useful both for the actual orientation of the GCRF and to enlarge the templates of the recognition scheme. For that, catalogue and published QSO determinations were inspected (Taris et al., 2012a). The 4th version of the GIQC, presented at the Gaia CU3 meeting (Coordination Unit 3, Core Processing) in Porto, Portugal (2012), contains 187,505 objects, divided in three categories – defining, candidates, and other (Andrei el al., 2012b). The defining objects are 136,643 well documented QSOs, being 103,422 from the SDSS/DR8 (Schneider et al., 2010). The catalog brings reliable redshift for 183,543 objects (97.87%), and there are reliable optical images for 159,701 objects (85.17%).

The morphology indexes

In the GIQC morphological indexes were assigned to each object on basis of the departure of the images from a purely stellar PSF, defined by the stars nearby to each quasar. A morphological departure indicates that the isophotes from the host galaxy must be considered in order to reach maximum precision in the determination of the centroid of the target. A pilot study compared 1,343 quasars in images from the SDSS (r images) and the DSS (R plates). The outcome has shown that the DSS images were able to detect quasars for which the host galaxy signature was sensed in the SDSS images, using the SHARP, SROUND, and GROUND, PSF parameters in IRAF's DAOFIND task. Thus the images of all quasars in the GIQC were searched for in the B, R, and I plates of the DSS. For each of the 3 DAOFIND parameters, in each of the 3 colors, a morphological index was produced as the z-ratio of the parameter value for the quasar to the mean parameter ratio for the surrounding stars, normalized by the standard deviation in that mean. Thus, in all, there are up to 9 morphological indexes for each quasar. Typically about 10% of the quasars are found with departures larger than 2 in the z-ratio. The departures are clearly more important in the R plates than in the B plates (Souchay et al., 2012).

The variability indexes

Variability is a prominent characteristic of quasars due to the violent processes of infall of matter to the massive central black hole (Taris et al., 2012b). As the objects that will materialize the GCRF will be those with the most accurate and stable positions (which are therefore critical, defining, properties), there is evidence that flux variations at different time scales correlate with variations of the astrometric location of their photocentres. Therefore, photocentre angular variations at different wavelengths are possibly the results of common phenomena occurring in the vicinity of the central engine of QSOs: the base of relativistic jets, the broad emission line regions, or accretion disks (Popovic et al., 2012).

Typically Gaia will take about 80 measurements of each quasar during the five years mission, a couple of times in successive fields (or slightly more if the quasar happens to occupy the nodus of a transit great circle), and then come back to the target after a month and a half. Such cadence is very well suited to single out the peculiar quasar variability in comparison to other variable sources (Kelly et al., 2009, Andrei et al., 2012c). At the same time, if an associated astrometric jitter is not accounted for, the error budget of the quasar increases beyond what can be attributed to photon noise.

Accordingly variability indexes were produced on basis of the mass of the central black hole and the absolute luminosity of the quasar. With these elements the radius of the accretion disk and of the dust torus region were calculated, as apparent angular sizes accounting for the cosmological redshift correction. Those two radii, the accretion disk one in micro-arcseconds and the torus one in milli-arcseconds, are given as the indexes to indicate the likeness of an astrometric jitter that would impact the stability of the centroid during the Gaia mission.

Optical monitoring of extragalactic radiosources to ensure the link between ICRF and the future Gaia celestial reference frame

After two years of observation, a huge amount of optical images of some AGN's selected to ensure the link between the ICRF and the future Gaia celestial reference frame have been gathered (without taking into account the data mining). They come from small robotic telescopes, medium size or large optical facilities spread all over the world.

In 2012 four large telescopes (CFHT, NOT, MPG 2.2 and Rozhen 2m) provided high resolution optical images dedicated to morphology analysis while four smaller ones (OHP, the two TAROT and Zadko) provided images dedicated to photometry. Work is also in progress to add three other medium size telescopes for the magnitude monitoring and the Subaru Telescope in collaboration with a Japanese team for the morphology studies (late 2012 early 2013).

The first results of the optical monitoring campaign have been submitted to “Astronomy and Astrophysics” (Fig. 5). A part of them have been also published in the proceedings of the GREAT ESF meeting held in Porto in June 2011 (Mem. S.A.It. Vol. 83-3, 986, 2012).

All the optical images will be made available to the astronomers by the mean of a database currently under construction in the frame of the ICRS Center. These observations will be also of interest in the frame of the Gaia Initial QSO Catalogue (GIQC) and for astrophysical studies (emission regions, gravitational lensing, photocenter scattering, constraints for binary black holes models).

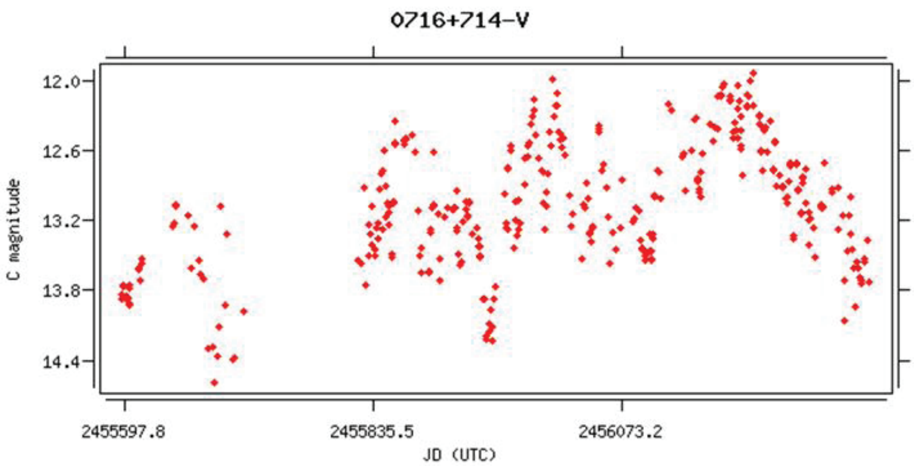

Fig. 5: The target ICRF J072153.4+712036 monitored by one of the TAROT telescope in the filter V

The Large Quasar Astrometric Catalog

The ICRS Center is in charge of the LQAC (Large Quasar Astrometric Catalog), a whole sky compilation of information on known QSOs, as well as of its regular up-dates. The second version of the LQAC, named as LQAC-2 (Souchay et al., 2012) was published as a CDS catalog. The LQAC-2 now contains 187 504 quasars. It delivers complete information (when available) as a set of optical magnitudes and radio fluxes, the redshift, original and consolidated equatorial coordinates, together with re-calculated absolute magnitudes and morphological indexes (see IERS Annual Report, 2010).

Spectroscopic observations of ICRF sources

We continued in 2012 our program of optical spectroscopic observations of ICRF sources. The targets were selected from the International VLBI Service (IVS) candidate International Celestial Reference Catalogue which forms part of an observational VLBI program to strengthen the celestial reference frame. New redshifts of 120 objects were obtained with five telescopes: the 3.58m ESO New Technology Telescope (NTT), the two 8.2m Gemini telescopes (Chile and Hawaii), the 2.5m Nordic Optical Telescope (NOT), and the 6.0m Big Azimuthal Telescope (BTA) of the Special Astrophysical Observatory in Russia. We obtained spectra of the potential optical counterparts of more than 150 compact flat-spectrum radio sources, and measured redshifts of 120 emission-line objects, together with 19 BL Lac objects. These identifications add significantly to the precise radio-optical frame tie to be undertaken by Gaia, due to be launched in 2013. A few cases of close alignment of the reference radio sources and foreground galactic stars were reported. Fig. 6 shows two images of the quasar IVS B2300-307 obtained under different weather conditions with the 3.58-meter New Telescope Technology (NTT) in 2010 and 2011 years. Fig. 7 shows a sample of spectra of 12 quasars obtained with different telescopes.

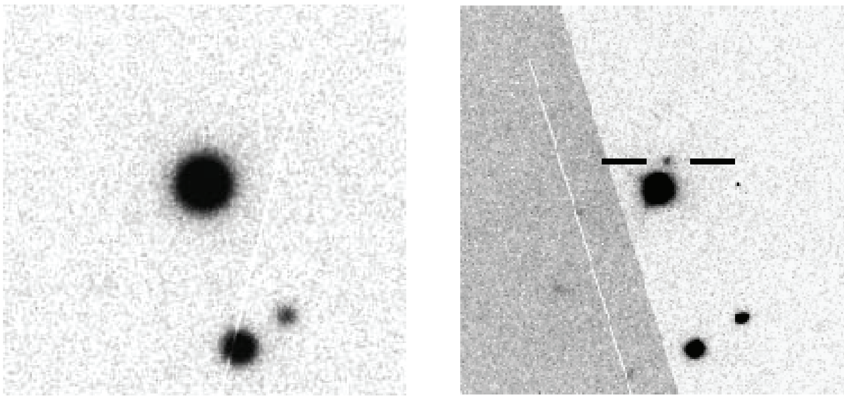

Fig. 6: Two acquisition images of the sky field around the quasar IVS B2300−307 made at the NTT in 2010 August (left: seeing 2”) and 2011 December (right: seeing 0”.6). Each image is 50” on a side; north is up and east to the left. The foreground star in the centre of the left image completely obscures the quasar due to its large seeing disk. In the right image the much better seeing reveals the faint quasar (marked between the bars), separated by 3”.7 from the star. (The diagonal step in contrast in the right image is an artifact of fast readout using two amplifiers for the acquisition image).

Link Between HCRS and Extragalactic Frame

Re-reductions of Cerro Tololo Interamerican Observatory (CTIO) 0.9m telescope data taken of over 400 ICRF optical counterparts between 1997 and 2001 were completed using UCAC4 type reductions of contemporary astrograph observations. The astrograph data provides a strong link between the Hipparcos/Tycho-2 primary reference stars of the Hipparcos Catalog Reference Frame (HCRF) and the faint QSO optical counterparts without impact of proper motion uncertainties of link stars in the 12 to 16 mag range.

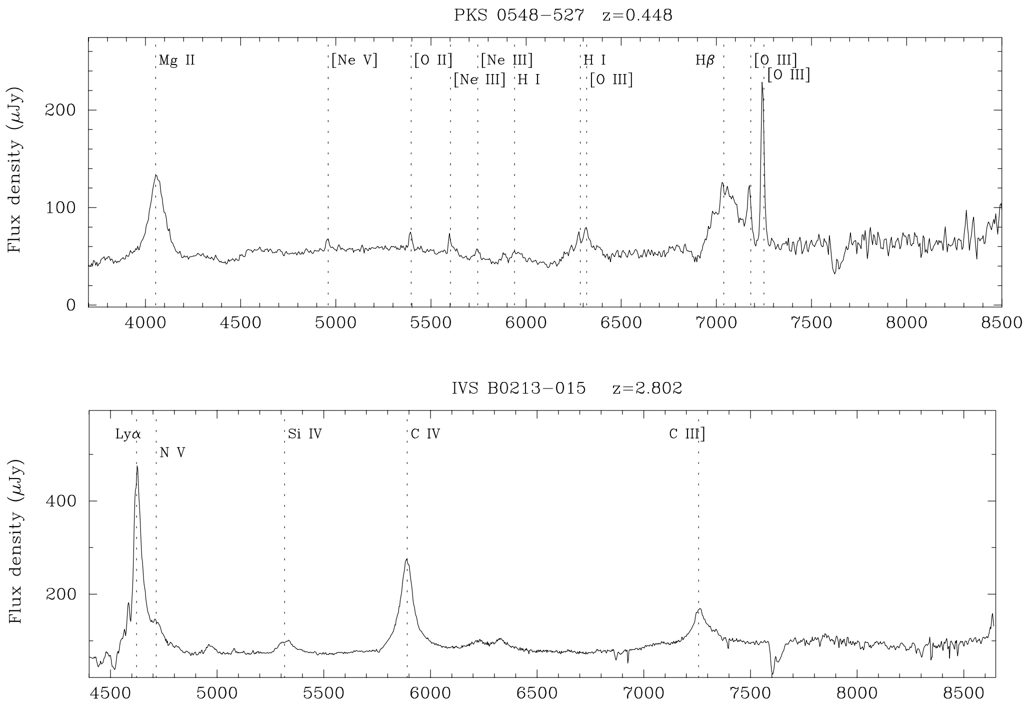

Fig. 7: A sample of spectra of quasars obtained with different telescopes. (GS – Gemini South, BTA – Big Telescope Azimuthal, NTT – New Technology Telescope).

A journal paper is in preparation. First results were presented at the IAU GA (Zacharias, Zacharias & Finch, 2012).

Recent epoch observations with a new generation CMOS detector of Hipparcos stars were performed and first results presented at an AAS meeting (Hennessy et al., 2012). Observed radio-optical position offsets of ICRF sources were discussed in connection with Gaia mission requirements (Makarov et al., 2012).

UCAC 4

The final USNO CCD Astrograph Catalog (UCAC4) was released at the IAU General Assembly in August 2012 (Zacharias et al., 2012). DVDs were sent to previous customers and the catalog is served by CDS. UCAC4 contains accurate positions of over 113 million objects (mostly stars). About 110 million of these have proper motions and 2MASS near-IR photometry. About 50% of stars in UCAC4 could be supplemented with accurate APASS 5-band optical photometry. Bright stars were added from FK6, Hipparcos and Tycho-2 to make UCAC4 a complete catalog down to about 16th magnitude. Meanwhile UCAC3 data were used to discover new high proper motion stars (Finch et al., 2012a).

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 USNO Robotic Astrometric Telescope (URAT) was installed at the Naval Observatory Flagstaff Station (NOFS) where it achieved first light on March 26, 2012. Regular survey observing began on April 24 (Finch et al., 2012b). Several technical issues had to be worked out, like dome shutter failure and lightning protection mitigation upgrades causing interruptions of regular survey observing. Nevertheless over 13,000 exposures were obtained with URAT by the end of 2012, each covering 28 sq.deg of sky. A long (240 sec) and short (60 sec) exposure are taken on each telescope pointing with a 15-fold overlap pattern of the sky to be completed within a year.

During periods of full moon a very short exposure survey (30 and 10 sec) is performed with a grating mounted in front of the lens to provide 1st order diffraction images of bright stars attenuated by about 4.5 mag. The combination of regular and grating survey allows URAT to cover the magnitude range of about 3.5 to 17.5 in a bandpass between R and I. While operations software reached a stable production level by end of 2012, development of reduction code had just begun. For latest information see

<www.usno.navy.mil/usno/astrometry/optical-IR-prod/urat>.

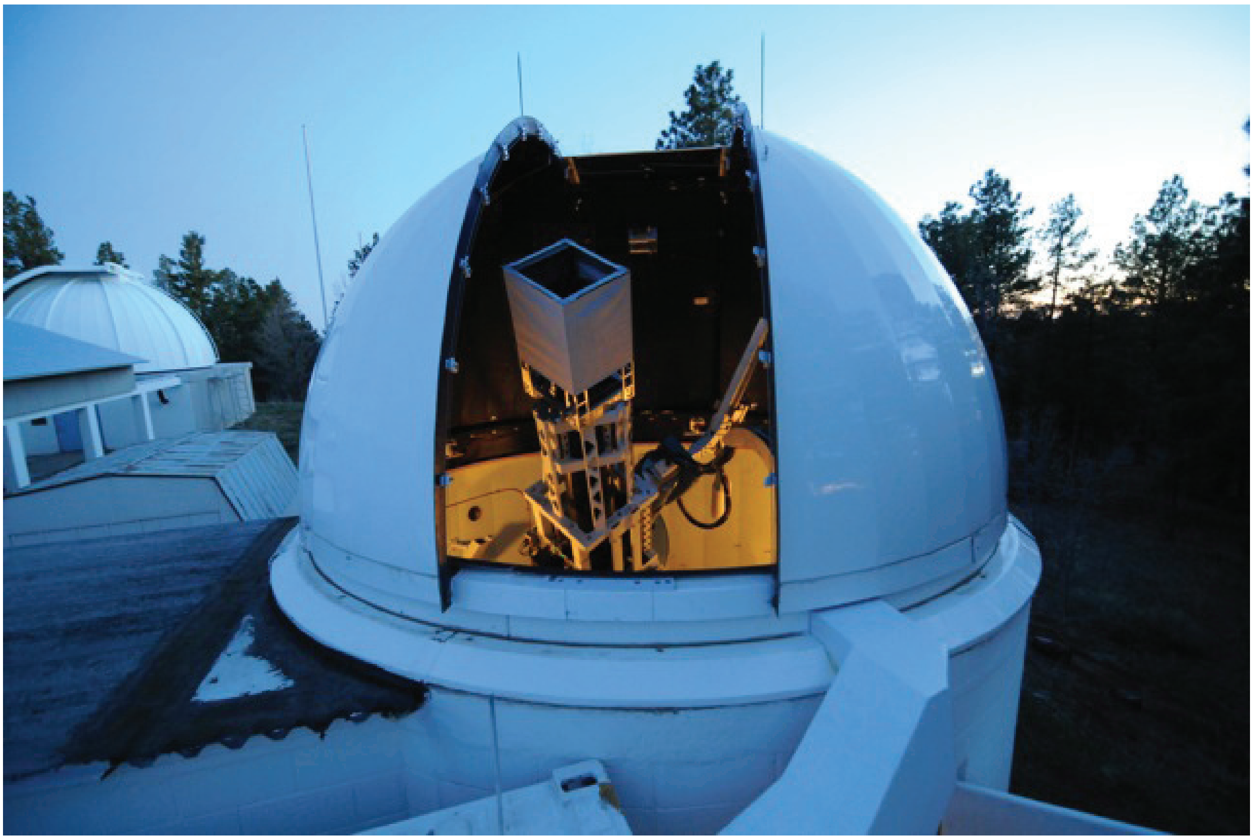

Fig. 8: The URAT dome at NOFS at the beginning of a night of observations in April 2012, as seen from the roof of the control room container.

Fig. 9: The URAT telescope at NOFS with heads of instrument shops Mike DiVittorio (NOFS, left) and Gary Wieder (Washington DC, right). The movable counterweight is seen on the top right to keep the telescope mount in balance depending on liquid nitrogen fill level inside the dewar.

Fig. 10: The URAT "red lens" enabling accurate astrometry in a bandpass between R and I. In this picture the lens is seen without the shutter box.

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