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 behavior 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. Additional VLBA observations to extend the ICRF to K-band and Q-band have been temporarily discontinued due to lack of available resources. 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. In 2013 the ICRF-3 Working Group pursued new observations that will fill gaps and improve the most significant weaknesses of ICRF2 and pursued the establishment of reference frames derived from X/Ka band VLBI observations. It is anticipated that a progress report will be provided to the IAU General Assembly in 2015. The principal goal of the ICRF-3 WG is to complete 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, which launched 19 December 2013, are expected, in specific magnitude ranges, to achieve astrometric positional accuracies beyond that presently obtained by ground-based radio interferometric measurements. Whether future versions of the ICRF transition back from the radio to the optical depends at least partially upon the relative astrometric accuracy of future radio- and optical-based reference frames.

Assessment of VLBI realisations of the ICRF

In 2013, 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 aus2013a catalog was produced at Geoscience Australia (Canberra), using the OCCAM geodetic VLBI analysis software package. Both catalogs bkg2013a and opa2013a were produced with the NASA Goddard Space Flight Center's package SOLVE: at one side at the Federal Agency for Cartography and Geodesy (BKG Leipzig) together with the Institute of Geodesy and Geoinformation of the University of Bonn (IGGB), and at the other side at the OPAR IVS analysis center of the Paris Observatory. Exhaustive technical descriptions of the solutions are available at the IVS data center.

We evaluate the consistency of the three 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 slopes in right ascension and declination (usually noted $D\alpha$ and $D\delta$, respectively) have been omitted in the Table since they

Table 1: Characteristics and transformation parameters relevant to the three catalogs submitted to the IVS in 2013. Columns 4–5 correspond to the rms differences to ICRF2 after alignment.

	No. Sources		Rms		Transformation parameters			
	All	Defining	$\alpha \cos \delta$ µas	δ µas	A_1 µas	A_2 µas	A_3 µas	B_δ µas
aus2013a	2949	291	64	59	-22	3	3	-13
±					5	5	5	5
bkg2013a	3294	287	44	55	-3	12	-3	13
±					5	5	4	4
opa2013a	3580	295	45	54	-5	12	-9	5
±					5	5	4	4

do not exceed 0.6 mas per degree with formal error of 0.2 mas per degree. Table 1 represents the residual (i.e., after alignment onto the ICRS) differences between each catalog and the ICRF2.

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 2013. 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 2013, 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. 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. Imaging of additional radio sources has been temporarily suspended due to lack of available resources. 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 4033 Very Long Baseline Array (VLBA) images of 1170 sources mostly at radio frequencies of 2.3 GHz and 8.4 GHz, but includes images for some sources at 24 GHz and 43 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 (2013) ICRS Center personnel continued to make progress with several astrometric star catalogs the extragalactic link to ICRF sources, and in preparation for the Gaia astrometric space mission.

Study of the Quasars forming the ICRF with the Gaia mission

The current version of the ICRF (Fey, Gordon, and Jacobs, 2009) is formed by the unique, time independent positions of 3414 extragalactic objects. Such unique positions were extracted from the analysis of 30 years of VLBI observations – to about 6.5 million individual measurements – aiming at compact and stable sources. The above numbers expressively state the care that must be employed to select compact and stable objects among the intrinsically unstable and morphologically complex population of quasars and AGNs. The radio wavelength aspects, and the construction of the ICRF, are comprehensively presented in the IERS Technical Note 35. On the optical wavelengths the situation was comparatively simpler when faced through ground observations, back to the times in which the acronym quasi-stellar-object (QSO) was coined. In what concerned astrometry, and the optical representation of the ICRS, either the object aimed at was a QSO, or an unusable extended galaxy or just an empty field to the detection limit. The physics characteristics of the object would not matter to improve the optical astrometric precision.

This situation changes when the optical positions reach sub-milliarcsecond to micro-arcsecond precision, like for instance on the ongoing Gaia mission, or with very small scale measurements. Isophotes or unmodeled light from the host galaxy disturb the centroid determination. Variability introduces quasi-periodic terms on the astrometric error budget and centroid wandering. Instabilities of a large scale dust wrap, if not in the boundaries of the accretion disk, would change the photocenter balance. So would episodes of luminous enhancement along the jets. In practice all these phenomena are bound to appear in changeable combinations. A number of investigations begun in 2013 address these issues, mostly in connection with the Gaia mission.

Optical counterparts of the ICRF

The “Rio survey” published the positions of 300 optical counterparts of ICRF2 sources, between declinations -90° and +30°, referred to the second version of the United States Naval Observatory CCD Astrograph Catalog (UCAC2). The positions were compared with 10 other selected optical astrometric surveys and studied the link between the Hipparcos Catalogue Reference Frame (HCRF) and the International Celestial Reference Frame, Second Realization (ICRF2). The main goal was to investigate the possible causes for the observed non-coincidence between the optical and VLBI positions. The correlation between position disagreement and the source morphology was investigated on basis of the structure indexes defined in the radio (Fey and Charlot, 1997) and in the optical (Souchay et al., 2012) domain. It was also investigated how the position offset could originate from the perturbation of the optical point spread function (PSF) of the source’s core, for instance by a second source of flux. An analytical relation describes the resulting centroid shift, as a function of the atmospheric seeing, the brightness ratio and the relative distance between the two contributing flux sources. Two scenarios, modeled by this relation, can be discussed: an extinction window in the dust torus nearby the core, and a Galactic star near the line of sight.

Optical monitoring of extragalactic radio sources for the link between ICRF and the future Gaia celestial reference frame

First observation of AGN's has been obtained in 2010 with the 1.2m telescope of the "Observatoire de Haute Provence" (OHP). Since then a lot of telescopes have been involved in the monitoring of AGN's both for morphology and for photometry purposes. Fig. 1 gives an overview of the telescopes spread all over the world that contribute to this effort of observation in the goal to bring information to astrophysicists and astrometrists. The observations currently go on for both aspects of the program, morphology and photometry. The first results about photometry have been published in A&A (Taris et al., 2013). The "Telescopi Joan Oró" (TJO) has been used from July 2013 to observe a new list of 47 targets (Petrov, 2011; Bourda et al., 2011). Fifty hours have been allocated by the Time Allocation Committee of this telescope to begin our program that will be pursued in 2014. Together with this telescope, the twin TAROT telescopes continue their observations and have obtained some long term series with very good time sampling (Fig. 2). Statistical analysis of these series will be performed to determine periodic signatures due to astrophysical processes, and will be compared to time series obtained at other wavelength (radio…). Two other 60cm telescopes have provided photometric data in 2013, one at Rozhen Observatory (Bulgaria)

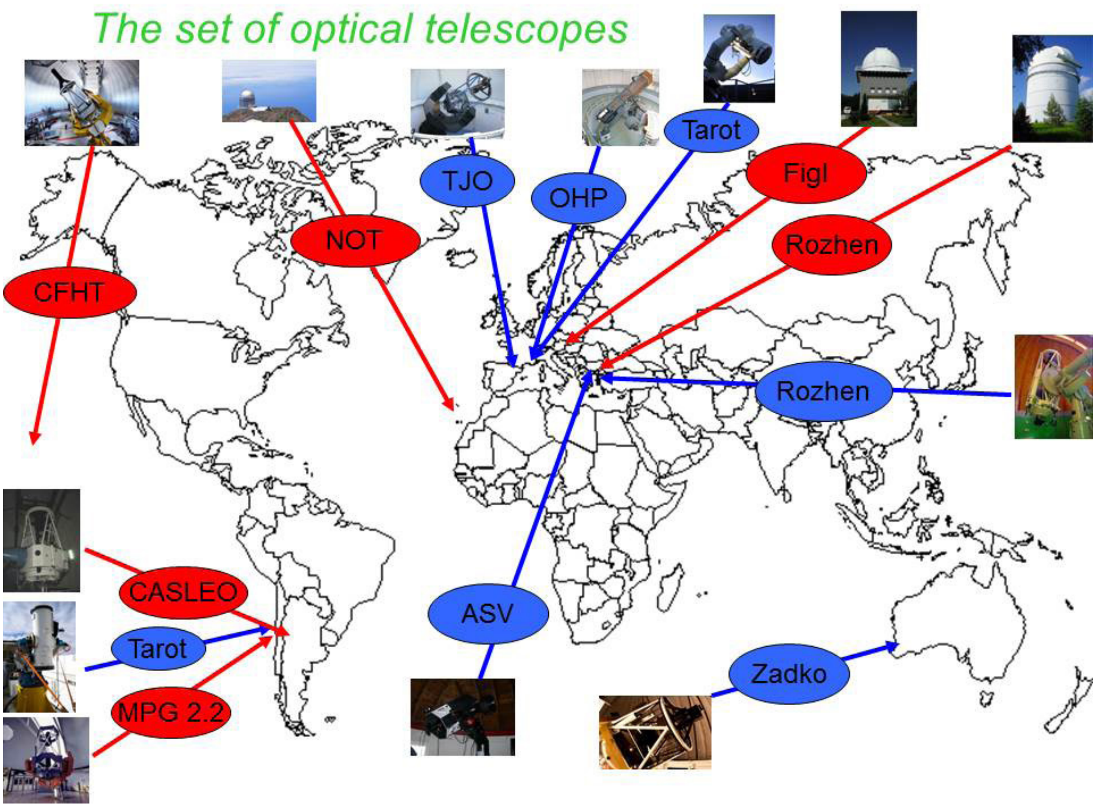

Fig. 1: The set of optical telescopes providing images for the astro-photometry program. In red the telescopes that have provided images for morphology and in blue for photometry.

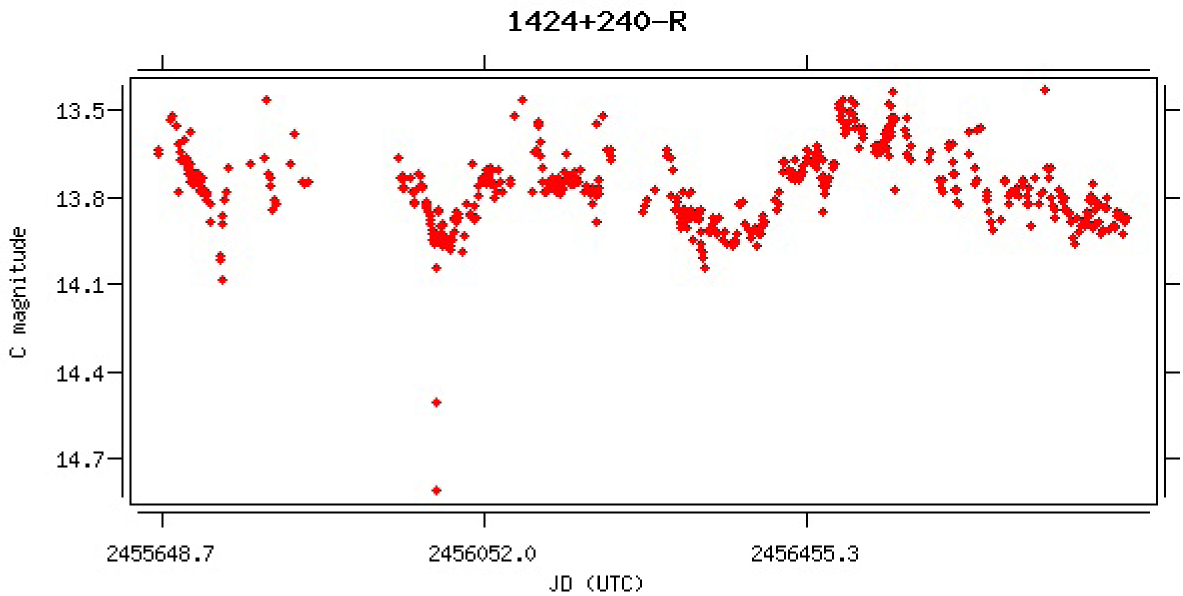

Fig. 2: QSO1424+240 in R filter. 465 measurements obtained with the TAROT telescope in Observatoire de la Côte d'Azur.

and the other at the Astronomical Station Vidojevica (Serbia). These two telescopes are used in the frame of an international collaboration with the Astronomical Observatory of Belgrade (AOB) that formerly begins in 2013.

In the frame of this collaboration, the 2m Rozhen telescope is also in use for the morphology aspect of our program. It has begun to provide images that are currently analysed with the Galfit and Iraf software. Together with this telescope two other ones have provided images for the morphology studies. The 1.52m telescope from Leopold-Figl-Observatorium für Astrophysik (LFOA, Universität Wien) in the frame of the AOB collaboration, and the 2.5m Nordic Optical Telescope (Observatorio del Roque de los Muchachos, La Palma, Canarias, Spain) in the frame of another collaboration with Observatorio Nacional – MCT (Brazil).

In 2013, the space probe Gaia has been launched from Kourou. The CU9 (Catalogue access) of the Data Processing and Analysis Consortium (DPAC) is in charge, among others, to check the consistency of correlations between several parameters and more particularly between astrometry and photometry (Work Package 945). Our group plan to be part of this WP and some discussions and meetings are in progress in the frame of the DPAC. Another WP is in charge of variability (WP946) where we will be invested.

Optical Images of the QSOs linking the VLBI and the Gaia Celestial Reference frames

The connection between the International Celestial Reference Frame, currently defined by Very Long Baseline Interferometry (VLBI) observations of quasars, and the future Gaia Celestial Reference Frame (GCRF) is demanded for continuity reasons, since it is foreseen that the GCRF will be the future materialization of the International Celestial Reference System. Each quasar candidate to be used for this alignment should be scrutinized so that the ones that are retained for the link represent the top precision astrometry that can be reached by VLBI and Gaia observations. On the VLBI side specific observations are already being made. On the optical window long term campaigns follow the sources variability (see more on this topic elsewhere in this report). The program here described obtain optical images to high SNR, using the B and R Johnston filters, for the candidate sources appropriate for the link. The main goal is to establish whether there is an apparent underlying host galaxy, and to which level are the corresponding isophotes. If prominent, the source must be flagged in the Gaia observations, because its centroid ought to be determined with special care for the sake of precision and to be properly compared against the VLBI centroid. During 2013, northern observations were conducted at the 2.5m Nordic Optical Telescope at Roque de los Muchachos, and southern observations were conducted at the 2.15m CASLEO telescope in the Argentinian Andes. The observations will continue through the following year, also through a successful time bid at the 1.60m LNA telescope, in Brazil.

The Gaia Initial QSO Catalog

The latest, updated, and fully corrected version of the Gaia Initial QSO Catalog (GIQC) was produced by the CU3 GWP-S-335-13000. It contains 1,248,372 objects, of which 191,372 are considered and marked as “defining” ones, because of their observational history and the existence of spectroscopic redshift. Also objects with strong, calibrator-like radio emission are included in this category. The “defining” objects represent a clean sample of quasars. The remaining objects aim to bring completeness to the GIQC at the time of its compilation. For the whole GIQC the average density is 30.3 sources per sq.deg. Practically all sources have an indication of magnitude and of morphological indexes, and 90% of the sources have an indication of redshift and of variability indexes. Besides presenting morphological variability, and classification indexes (plus a one-letter comment on the source main feature), the MDB version currently contains nearly 1 million more quasars than in the IGSL and should preferably be used to match Gaia own observations.

Spectroscopic observations of ICRF sources

We continued in 2013 the program of optical spectroscopic observations of reference ICRF radio sources. The targets were selected from the International VLBI Service (IVS) candidate ICRF catalogue. New redshifts were obtained with four optical telescopes: the 3.58m ESO New Telescope Technology (NTT) Visitor program (092.A-0139(A)), the two 8.2m Gemini telescopes (Chile, program

GN-2012B-Q-127 and Hawaii, program GS-2013A-Q-99), and 2.5m Nordic Optical Telescope (NOT) at La Palma (Spain).

We obtained spectra of about 140 compact radio-sources, and measured redshifts of 113 emission-line objects, together with a set of BL Lac objects and faint several targets with low signal-to-noise ratio. These identifications contribute to the precise radio-optical frame tie to be undertaken by Gaia mission, launched in December 2013. A few cases of close alignment (1”–2”) of the reference radio sources and foreground galactic stars were reported. In particular, the radio source IVSB 0758-737 (alias PKS 0757-737) obscured by a galactic star is relatively strong and could be monitored for indication of possible lensing effects.

Link between HCRS and extragalactic frame

Regarding the radio-optical reference frame link the final catalog of over 600 optical counterpart positions of over 400 ICRF sources on the Hipparcos system was published (Zacharias & Zacharias, 2013). With a mean optical position error of 25 mas per coordinate this is the most precise investigation of its kind to date. The associated journal paper (Zacharias & Zacharias, 2014) postulates a detrimental, astrophysical, random noise (DARN) effect on the order of 10 mas per coordinate and source, likely caused by optical structure of the host galaxies which is unresolved on the arc second scale. Part of the larger than expected radio-optical position differences can be explained by optical reference star catalog issues. However, too many sources are found to be “outliers” in the observed radio-optical position offsets of ICRF sources, correlated with redshift, leading to the DARN hypothesis supported by other, similar investigations. If confirmed, this effect will have a large impact on the Gaia to VLBI position link accuracy of a future celestial reference frame. Gaia’s absolute proper motions and parallaxes should not be affected.

UCAC 4

The final USNO CCD Astrograph Catalog (UCAC4) journal paper was published (Zacharias et al., 2013). Over 60,000 astrometric and photometric observations of known double stars were extracted from UCAC4 data and 4755 new common proper motion pairs identified (Hartkopf et al., 2013).

URAT

The USNO Robotic Astrometric Telescope (URAT) continued its all-sky survey from the Naval Observatory Flagstaff Station (NOFS). By end of 2013 a total of 41,261 exposures were taken with the 4-shooter camera, each covering 28 square deg of sky. The quality control pipeline was completed and analysis of calibration data revealed astrometric performance as expected over the entire 3rd to 18th magnitude range covered by URAT. For latest information see <http://www.usno.navy.mil/USNO/astrometry/optical-IR-prod/urat>.

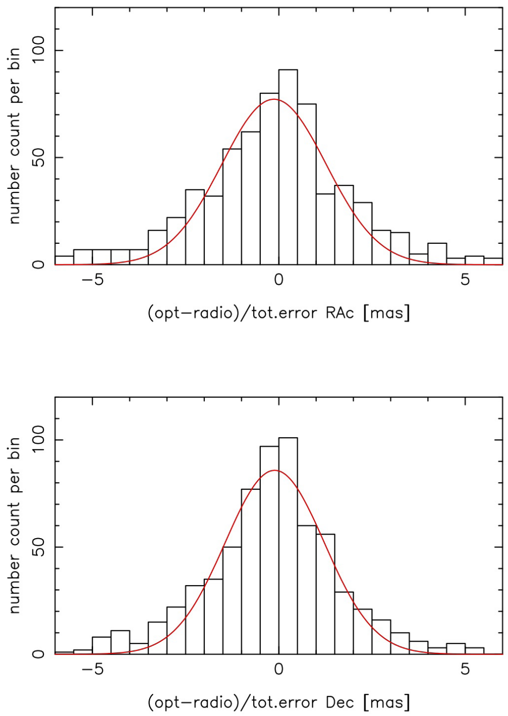

Fig 3: Histogram of the scaled (optical-radio)/ error position differences per coordinate of ICRF sources from the USNO RORF program based on CTIO 0.9m data and contemporary astrograph reference stars tied to Hipparcos via Tycho-2.The plot line represents the best fit normal distribution. A large number of "outliers" is seen. Taken from Zacharias & Zacharias, 2014, AJ 147, 95, Figure 7.

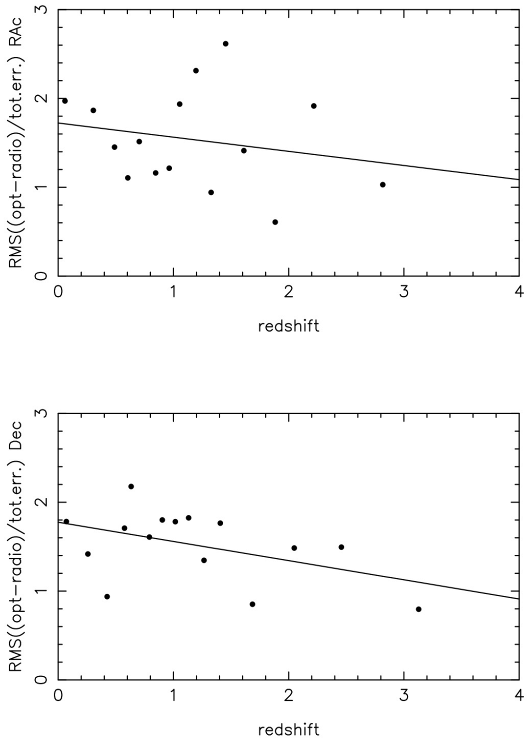

Fig 4: Optical-radio position differences divided by total formal error of individual sources (RMS over 16 offsets per dot) as a function of redshift, RA component on top, Dec at bottom, using USNO RORF program data. A correlation is seen which can not be explained by reference star catalog errors. Taken from Zacharias & Zacharias, 2014, AJ 147, 95, Figure 13.

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References

Bourda, G., Collioud, A., Charlot, P., Porcas, R., Garrington, S. 2011, Astronomy and Astrophysics, 526, 102

Charlot, P.; Boboltz, D. A.; Fey, A. L.; Fomalont, E. B.; Geldzahler, B. J.; Gordon, D.; Jacobs, C. S.; Lanyi, G. E.; Ma, C.; Naudet, C. J.; Romney, J. D.; Sovers, O. J.; Zhang, L. D. 2010, AJ, 139, 1713

Fey, A.L., & Charlot, P. 1997, ApJ Supp., 111, 95

Fey, A.L., Gordon, D., and Jacobs, C.S. (eds.) 2009, The Second Realization of the International Celestial Reference Frame by Very Long Baseline Interferometry, IERS Technical Note 35.

Fomalont, E. , Johnston, K., Fey, A., Boboltz, D., Oyama, T. & Honma, M. 2011, AJ, 141, 91

Hartkopf, W.I., Mason, B.D., Finch, C.T., Zacharias, N., Wycoff, G.L., Hsu, D. 2013, 146, 76

Lanyi, G. E.; Boboltz, D. A.; Charlot, P.; Fey, A. L.; Fomalont, E. B.; Geldzahler, B. J.; Gordon, D.; Jacobs, C. S.; Ma, C.; Naudet, C. J.; Romney, J. D.; Sovers, O. J.; Zhang, L. D. 2010, AJ, 139, 1695

Petrov, L. 2011, AJ, 142, 105

Souchay, J.; Andrei, A. H.; Barache, C.; Bouquillon, S.; Suchet, D.; Taris, F.; Peralta, R. 2012, Astronomy & Astrophysics 537, id.A99, 13 pp.

Taris, F., Andrei, A., Klotz, A., Vachier, F., Côte, R., Bouquillon, S., Souchay, J., Lambert, S., Anton, S., Bourda, G., Coward, D. 2013, Astronomy and Astrophysics 552, 98

Zacharias, M.I., & Zacharias, N. 2013, VizieR Online Data Catalog: Radio-optical reference frame link (Zacharias+ 2013), 2013yCat. 1325, <http://vizier.cfa.harvard.edu/viz-bin/VizieR?-source=I/325>

Zacharias, N., Finch, C.T., Girard, T.M., Henden, A., Bartlett, J.L., Monet, D.G., Zacharias, M.I. 2013, AJ, 145, 44

Zacharias, N., & Zacharias, M.I. 2014, AJ 147, 95

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