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ASTROMETRIC POSITIONS OF ICRF2 RADIO SOURCES WITH DIFFERENT REFERENCE CATALOGUES

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Abstract. We present the results of an investigation of astrometric positions of a few extragalactic radio sources (ERS) from the ICRF2 list. The reference systems are based on the resolutions of the international scientific unions. The celestial system is based on IAU (International Astronomical Union) Resolution A4 (1991). It was officially initiated and named International Celestial Reference System (ICRS) by IAU Resolution B2 (1997). Its definition was further refined by IAU Resolution B1 (2000) and Resolution B3 (2009). The fundamental celestial reference frame (International Celestial Reference Frame – ICRF) was adopted by the IAU (1997), with its original list of radio objects and two extensions (ICRF-ext1 and ICRF-ext2); hereafter referred to as ICRF1. Alltogether, there were 717 sources: 212 defining ones, 109 new ones, 294 candidate ones, and 102 additional sources. At the IAU XXVII GA (2009), the second realization of the ICRF (the ICRF2) was adopted with the list of precise positions for 3414 compact radio astronomical sources. It is more then five times the number as in the ICRF1. At that moment there were nearly 30 years of VLBI (Very Long Baseline Interferometry) observations of some radio sources. The ICRF2 has a noise threshold of about 0.04 mas (nearly 6 times better than ICRF1) and an axis stability of about 0.01 mas (nearly twice as stable as ICRF1). Also, a search for a relation between optical and radio reference frames is important. To do that, it is necessary to make the observations of some ICRF2 ERS which are visible in the optical domain, and to compare their optical and radio positions (VLBI ones). The optical positions (α and δ) could be calculated using reference stars from some of nowadays big star catalogues. The XPM, 2MASS (with XC1) and DR7 SDSS ones were used here, and the relative method was applied. We started to do that comparison using our CCD observations of a few ERS made with the 2 m RCC telescope[1] (with the focal length of 16 m) of Rozhen National Astronomical Observatory (Bulgarian Academy of Sciences). About 30 fields around ERS were observed with CCD camera VersArray 1300B (1340x1300 pixels, the pixel size is 20x20 micrometers, one pixel is 0.258 arcsec) in the end of March 2011. The main steps of our reduction and preliminary results are presented here.

[1]Based on observations with the 2 m RCC telescope of the Rozhen National Astronomical Observatory operated by the Institute of Astronomy, Bulgarian Academy of Sciences.

1. INTRODUCTION

The fundamental celestial reference frame, ICRF1 (Ma et al. 1998), was adopted by the IAU in 1997 and its extensions ICRF-ext1 (IERS 1999) and ICRF-ext2 (Fey et al. 2004) were later issued. The revised coordinates of candidate and other sources were given by Fey et al. (2004). The ICRF2 (IERS 2009) was presented at the GA of IAU (2009). The HCRF, Hipparcos Celestial Reference Frame, is the optical one. It was linked to the ICRF1 (radio one) with an accuracy of ±0.6 mas in position (for the epoch 1991.25) and ±0.25 mas per year in rotation (Kovalevsky et al. 1997), but that accuracy decreases over time. The reason is the error in the proper motions of stars. Because of it, it is necessary to verify and refine the relation between the HCRF and ICRF2 by using different telescopes and methods.

The ICRF1 consists of the precise coordinates of compact extragalactic objects, mostly quasars (QSO), BL Lacertae (BL Lac) sources and a few active galactic nuclei (AGNs). These sources are far away and their proper motions should be negligibly small. The current positions are known to be better than 1 mas. Also, there is the structure instability of the sources in radio wavelengths and because of it the ultimate accuracy is limited. The origin of ICRF1 is at the barycenter of the solar system. The directions of the axes should be fixed with respect to the quasars. Its principal plane and the origin of this plane are as close as possible to the mean equator at J2000.0 and to the dynamical equinox of J2000.0, respectively. The ICRF1 replaced the optical FK5 reference frame on January 1, 1998. The Hipparcos reference frame was realizing the ICRS in optical wavelengths; the accuracy is significantly better than that of FK5.

The reference directions of ICRS should be fixed and there is the continuing improvement in the ERS coordinates via VLBI observations; a regular maintenance of the system and improvement of the frame are necessary. Because of it, there are many observations which define ERS over a long data span, and they are useful to maintain the axes of the ICRS via good position stability. The frame stability is based upon the assumption that the proper motions of ERS are negligible. The ICRF1 is based on positions of 212 'defining' ERS, but to densify the frame, we added 294 less observed 'candidate' and 102 less suitable 'other' sources. The total number of objects is 667 in ICRF-Ext.1, 717 in ICRF-Ext.2 and 3414 in ICRF2 (295 'defining' and 3119 additional ones). The alignment of ICRF2 with the ICRS was made by using common ICRF2/ICRF-Ext.2 138 stable ERS. The two largest weaknesses of ICRF1 were eliminated: more uniform sky distribution of ERS and the position stability of the 295 ICRF2 defining sources. From 1 January 2010, the realization of the ICRS is the ICRF2.

The Hipparcos Catalogue provides the equatorial coordinates for 117955 star on the ICRS for epoch 1991.25; also, their proper motions, parallaxes and magnitudes. The stars are brighter than $V = 12$, mostly from $V = 7$ to $V = 9$. The median uncertainties are (for bright stars with magnitude $V < 9$): 0.8 mas in α, 0.6 mas in δ, 0.9 mas/yr in μ_α and 0.7 mas/yr in μ_δ. The proper motions of many double or multiple stars are unreliable due to the short epoch span of Hipparcos observations (less than 4 years). Van Leeuwen (2007) did a new reduction of the Hipparcos data. It resulted in significant improvements (mainly for the parallaxes) which had effect on the ICRS. The densification catalogues were derived from the HCRF because the

HCRF was primary realization of the ICRS at optical wavelengths. Some of these catalogues are: Tycho-2 (as the first step of the densification, the AC was included in Tycho-2 proper motions data), UCAC3, 2MASS (near-IR), PPMXL, XPM, etc.

It is possible to investigate the relation between optical and radio frames using the differences between optical and radio (VLBI) coordinates ($(O-R)_\alpha$, $(O-R)_\delta$) of ERS. It means, we can use the secondary reference frame to derive the optical positions of ERS. Partly, the optical/radio frames relation is dependent of star catalogues. Here, the positions (α, δ) of the optical counterparts to ERS were determined, and the relative method was applied with respect to the XPM (Fedorov et al. 2010), 2MASS (Cutri at al. 2003) and DR7 SDSS (Abazajian et al. 2009) catalogues. We used the 2MASS positions with XC1 proper motions of stars, and DR7 SDSS (The Seventh Data Release of the Sloan Digital Sky Survey) positions without proper motions (because the epoch difference between DR7 SDSS observations and our ones is small). The HCRF was used to calculate astrometric positions of ERS via small fields of view of our CCD observations. We assume that the centers of emission (of radio/optical sources) coincide between each other in line with the accuracy level of the optical observations.

2. DATA AND CALCULATION

To align radio frame (ICRF2) and optical one (HCRF) with high accuracy, we need to observe the common objects and to calculate their accurate optical positions. Because of it, the ground based astrometric observations of ERS are very important. In the end of March 2011, we spent a few nights at the Rozhen National Astronomical Observatory (Bulgarian Academy of Sciences). After the summer of 2010, the Rozhen telescope ($D/F = 2m/16m$) was fully automated. Its geographic coordinates are: $\lambda = 1^h38^m58^s(24^o44'38'')$, $\varphi = 41^o41'35''$. The altitude is 1759 m. Our observations were carried out with that RCC telescope equipped with CCD camera VersArray 1300B. The main characteristics of CCD camera are: the size of CCD chip is 1340x1300 pixels, the pixel size is 20x20 mkm, the scale is 0.258 arcsec/pix, and the field of view (FOV) is about 5.5x5.5 arcmin.

A total of 5 optical counterparts of the ICRF2 radio sources were observed (see Table 1):Q 1252+119(ICRF J125438.2+114105), L 1215+303 (ICRF J121752.0+300700), Q 1240+381 (ICRF J124251.3+375100), Q 1219+044 (ICRF J122222.5+041315) and L1221+809 (ICRF J122340.4+804004). We made 6 frames per source (3 at R filter and 3 at V one). These ERS are visible in optical part of wavelengths and the magnitudes ranged from 15.7 to 19.0 (ICRF, V domain) or from 15.2 to 18.8 (GSC, R domain). All exposures were guided, and the exposure time ranged from 5^s to 90^s (see Table 1). The contents of some columns in Table 1 is self-evident; for this reason each of them is not mentioned. The source designation and ERS type are in the second column, Q means quasar, L BL Lac, the next two columns give α and δ (ICRF2 coordinates) of ERS, the fourth one the magnitude for V and R domains, whereas the last two columns give our exposure time also for V and R domains.

The bias and flat-field frames were not applied to our raw frames. The dark correction is not significant because the CCD chip was cooled to -110^o C (good for ERS fainter objects). The APEXII image processing package (Kouprianov 2008) was applied for CCD observations, and the DR7 SDSS and 2MASS (+XC1) catalogues

Table 1: Observed ERS.

No	Type of ERS, source name	RA(ICRF2) (h,m,s)	DEC(ICRF2) (^{o},$'$,$''$)	Mag V, R	Exp(s) for V	Exp(s) for R
1	Q 1252+119	12 54 38.256	11 41 05.90	16.2 15.2	3,5	5
2	L 1215+303	12 17 52.082	30 07 00.64	15.7 15.2	5	5
3	Q 1240+381	12 42 51.369	37 51 00.03	19.0 18.3	30,60,90	10,15
4	Q 1219+044	12 22 22.550	04 13 15.78	18.0 16.8	20	20
5	L 1221+809	12 23 40.494	80 40 04.34	18.0 18.8	20	20

were used for reduction of data. Also, the software AIP4WIN (Berry and Burnell 2002) was used together with XPM catalogue. All frames were reduced individually.

The main steps for processing the CCD images are: the identification of star-like objects (ERS) and reference stars, measuring the positions (x, y) of their centers, and the reduction (to get tangential and equatorial coordinates). We used the linear model, a standard astrometric "plate" reduction with the available reference stars,

$$\xi = ax + by + c$$

$$\eta = dx + ey + f$$

to transform the measured CCD coordinates (x, y) into tangential ones (ξ, η). The Least-Squares Method (LSM), the unweighted one, was applied to calculate the unknown values of the parameters a, b and c (to determine α), and d, e, and f (to determine δ). The FOV of CCD frames was small (5.5x5.5 arcmin) and we did not apply the corrections for apparent displacements, such as differential refraction (Aslan at al. 2010, Kiselev 1989). Because of small FOV, the big problem during astrometric reduction is that there are not enough reference stars (at least 3) with accurate coordinates and proper motions to calculate the values of α and δ of ERS; it was the case for the ERS L 1221+809. Also, if we have the low accuracy of astrometric data for reference stars from a catalogue, we cannot determine a good link between the radio and optical frames.

We used the positions from 2MASS together with XC1 proper motions, because the 2MASS catalogue has no proper motions. The Two Micron All Sky Survey (2MASS) covers all sky and contains positions and photometry (J, H, K_s) for about 470 million point sources; the observations were made very close to 2000. Another possibility was the DR7 SDSS positions without proper motions (because of small epoch difference between our observations and catalogue ones). Also, we used the XPM catalogue which contains the positions and proper motions for 314 million stars distributed all over the sky for the epoch 2000.0. The 2MASS and XPM are in ICRS. The magnitudes of our reference stars are from 13.5 to 19.5.

In the Figure 1, as an example, one CCD frame (at R filter) of ERS Q 1252+119 is presented. The ERS is near the central part of the image. It is marked with direction arrow and circle. The reference star is marked with a circle; there are six ones.

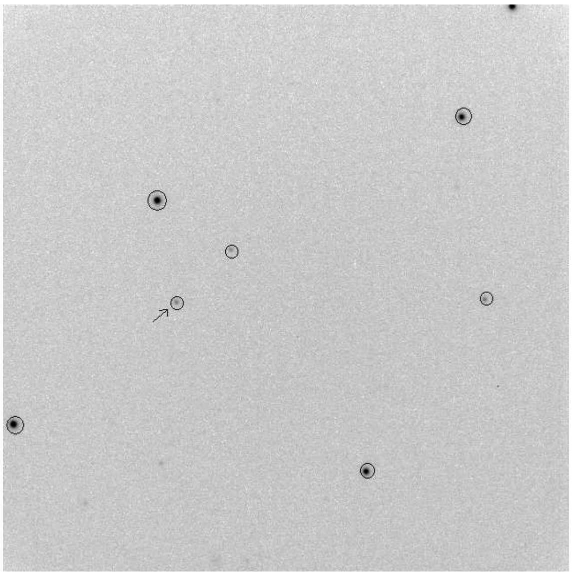

Figure 1: The observation of ERS Q 1252+119 (ICRF J125438.2+114105) in R filter.

3. RESULTS AND CONCLUSIONS

The positions of ERS were calibrated with respect to the XPM, 2MASS+XC1, and DR7 SDSS catalogues by using CCD observations. To calculate the stellar apparent positions we used some programmes from SOFA package. The ERS coordinates are from ICRF2 list. Some of XPM stars (or 2MASS, DR7 SDSS ones) were not taken into account because of their very low signal-to-noise ratio. By using 2MASS (or DR7 SDSS), the reduction was made with different reference stars (than in the case of XPM), and a different software (APEXII) was applied to get x and y coordinates (AIP4WIN in the case of XPM). After calculation of the optical positions of ERS we compared their optical positions and radio ones (to determine the values $(O-R)_\alpha$ and $(O-R)_\delta$); see Tables 2 and 3. From the results of Tables 2 and 3 we get the unweighted mean offsets of $(O-R)_\alpha$ and $(O-R)_\delta$ values. Relative to the XPM catalogue they are $-0''.06$ in α and $-0''.05$ in δ. In the case of 2MASS+XC1 it is $0''.15$ and $0''.13$, and of DR7 SDSS it is $-0''.01$ and $0''.05$, respectively. These offsets in α are close one to another; also, in δ.

We can conclude that the optical observations of ERS are possible by using 2m Rozhen telescope and a good CCD camera. The offsets (in α and in δ) are small and very similar for catalogues (XPM, 2MASS and DR7 SDSS). So, it is possible to use XPM, 2MASS and DR7 SDSS as the reference catalogues for astrometric reduction in small FOV of CCD observations. The XPM, 2MASS and DR7 SDSS are with high star density and a good densification of HCRF, but a higher accuracy catalogue of higher star density is required. The link between HCRF and ICRF2 is good enough at the mean epoch of our observations; XPM, 2MASS and DR7 SDSS are similar frames. Also, some problems during calculation of ERS optical positions can be caused by: faintness of the optical counterparts to ERS, atmospheric influences and technical problems.

Table 2: The values $(O-R)_\alpha$ and $(O-R)_\delta$ from 2MASS+XC1 and DR7 SDSS.

Source name	2MASS+XC1 $(O-R)_\alpha['']$	$(O-R)_\delta['']$	DR7 SDSS $(O-R)_\alpha['']$	$(O-R)_\delta['']$
1252+119	0.441±0.027	0.051±0.020	0.096±0.040	0.007±0.038
1215+303	-0.025±0.008	0.088±0.027	-0.114±0.015	0.010±0.036
1240+381	0.056±0.038	0.132±0.052	-0.036±0.021	0.084±0.018
1219+044	0.117±0.014	0.231±0.020	0.031±0.051	0.095±0.036

Table 3: The values $(O-R)_\alpha$ and $(O-R)_\delta$ from XPM.

Source name	XPM $(O-R)_\alpha['']$	$(O-R)_\delta['']$
1252+119	0.181±0.047	-0.014±0.014
1215+303	-0.479±0.394	-0.223±0.581
1240+381	0.041±0.011	-0.082±0.011
1219+044	0.015±0.009	0.137±0.003

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References

Abazajian, K. N. et al.: 2009, "The Seventh Data Release of the Sloan Digital Sky Survey", *ApJS*, **182**, 543-558.

Aslan, Z., Gumerov, R., Jin, W., Khamitov, I., Maigurova, N., Pinigin, G., Tang, Z., Wang, S.: 2010, "Optical counterpart positions of extragalactic radio sources and connecting optical and radio reference frame", *A&A*, **510**, A10.

Berry, R., Burnell, J.: 2002, "The Handbook of Astronomical Image Processing, Includes AIP4WIN Software", Willmann-Bell, Inc., Richmond, USA.

Cutri, R. M., et al.: 2003, "The IRSA 2MASS All-Sky Point Source Catalog", NASA/IPAC.

Fedorov, P. N., Akhmetov, V. S., Bobylev, V. V., Bajkova, A. T.: 2010, "An investigation of the absolute proper motions of the XPM catalogue", *MNRAS*, **406**, 1734-1744.

Fey, A. L., Ma, C., Arias, E. F., Charlot, P., Feissel-Vernier, M., Gontier, A.-M., Jacobs, C. S., Li, J., MacMillan, D. S.: 2004, "The Second Extension of the International Celestial Reference Frame: ICRF-EXT.1", *Astron. J.*, **127(6)**, 3587-3608.

IERS: 1999, "1998 International Earth Rotation Service Annual Report", Observatoire de Paris, Paris.
IERS: 2009, "The Second Realization of the International Celestial Reference Frame by Very Long Baseline Interferometry", *IERS Technical Note 35*, Presented on behalf of the IERS/IVS Working Group, Fey A.L., Gordon D. and Jacobs C.S. (eds.), Frankfurt am Main, Verlag des Bundesamts für Kartographie und Geodäsie, 204 p.
Kiselev, A. A.: 1989, "Theoretical foundations of photographic astrometry", Nauka, Moskva.
Kovalevsky, J., Lindegren, L., Perryman, M. A. C., Hemenway, P. D., Johnston, K. J., Kislyuk, V. S., Lestrade, J.-F., Morrison, L. V., Platais, I., Röser, S., Schilbach, E., Tucholke, H.-J., de Vegt, C., Vondrák, J., Arias, F., Gontier, A.-M., Arenou, F., Brosche, P., Florkowski, D. R., Garrington, S. T., Preston, R. A., Ron, C., Rybka, S. P., Scholz,R.-D., Zacharias, N.: 1997, "The Hipparcos Catalogue as a realization of the extragalactic reference system", *A&A*, **323(2)**, 620-633.
Kouprianov, V.: 2008, *Adv. Space Res.*, **41**, 1029.
Ma, C., Arias, E. F., Eubanks, T. M., Fey, A. L., Gontier, A.-M., Jacobs, C. S., Sovers, O. J., Archinal, B. A., Charlot, P.: 1998, "The International Celestial Reference Frame as realized by Very Long Baseline Interferometry", *Astron. J.*, **116(1)**, 516-546.
van Leeuwen, F.: 2007, "Hipparcos, the new reduction of the raw data", *ASPL series*, Springer.