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Optical astrometric positions of 59 northern ICRF radio sources

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ABSTRACT

Context. To investigate the link between the International Celestial Reference Frame (ICRF) and its optical Hipparcos-based representation on the northern hemisphere.

Aims. To present results of a pilot investigation on the astrometry of 59 northern ICRF sources.

Methods. We used the 0.6 m Zeiss telescope at Belogradchik Observatory, Bulgaria. The optical CCD source positions were referred to the UCAC2 catalog. Improved astrometric methods were applied including telescope shifting between exposures, (x, y) Gaussian measurements within 1 full width at half maximum, and the observation of a large number of frames per source. The huge amount of data generated was treated with a new astrometric package, PRAIA (Platform for Reduction of Astronomical Images Astrometrically).

Results. Average and standard deviation for the optical minus radio position offsets were +6 mas (51 mas) and +7 mas (57 mas) for RA and Dec, respectively. The errors of all (x, y) measurements from Gaussian fits displayed a typical distribution with respect to magnitude, dependent on the sky transparency. For the ICRF objects, the (x, y) errors per source ranged from 50 mas to 100 mas. The RA and Dec reduction mean errors were 46 mas.

Conclusions. No large scale systematic errors with respect to RA or Dec were found within the attained position precision. Comparison with three independent telescope/catalog datasets shows that the precision obtained here represents an important improvement on previous works. In comparison with the southern hemisphere, more astrometry on ICRF sources are needed in the north, and it is shown here that the continuation of this program can fill this need.

Key words. astrometry – reference systems – galaxies: quasars: general – telescopes

1. Introduction

To investigate the link between the ICRF and the Hipparcos Catalog Reference Frame (HCRF) (IAU 2002), the most straightforward approach is from the astrometry of ICRF sources in the optical domain. For this purpose, the best way to acquire astrometry of an adequate quality is to obtain high S/N images and good pixel sampling. For this, one needs good sky conditions and, ideally, large sized reflective telescopes. A high number of reference stars is also desirable. However, since large instruments are usually manufactured without having astrometry in mind, the larger the FOV (field of view), the stronger the optical distortions. Also, reference stars on the magnitude range from 13 to 15 may quickly become saturated. Thus, one should also consider the alternatives given by smaller telescopes. They are more available for long term programs, they can furnish FOVs with significantly less distortion and it is easier to observe the relatively brighter reference stars and the fainter targets within the linear range of CCD detectors. The problem is then to model the FOV with enough reference stars so as to keep the resulting positions aligned with the HCRF.

Currently, the UCAC2 (Zacharias et al. 2004) is the astrometric catalog that predominantly fulfills these requirements. It is the best representative of the HCRF available down to the 16th magnitude in terms of stellar density, position and proper motion accuracy. Thanks to the UCAC2, initial efforts toward precise optical astrometry of ICRF sources have been made possible, starting from the celestial equator (Assafin et al. 2003) and from the southern hemisphere (Assafin et al. 2005).

After the initial works in the Hipparcos era by Zacharias et al. (1999) and da Silva Neto et al. (2002) (hereafter papers ZA and SN), only a few efforts have been made to improve the situation in the northern hemisphere, as described in Fienga & Andrei (2002, paper FA), Fienga & Andrei (2004) and Zacharias & Zacharias (2005, paper ZZ). Most (if not all) of the available sets of optical positions on the north are not based on the UCAC2, thus they lack adequate HCRS representation in a homogeneous fashion with respect to the region south of the celestial equator.

In 2004 we started an observational program at the Belogradchik Observatory, Bulgaria, aiming to densify the northern hemisphere coverage with precise astrometric ICRF

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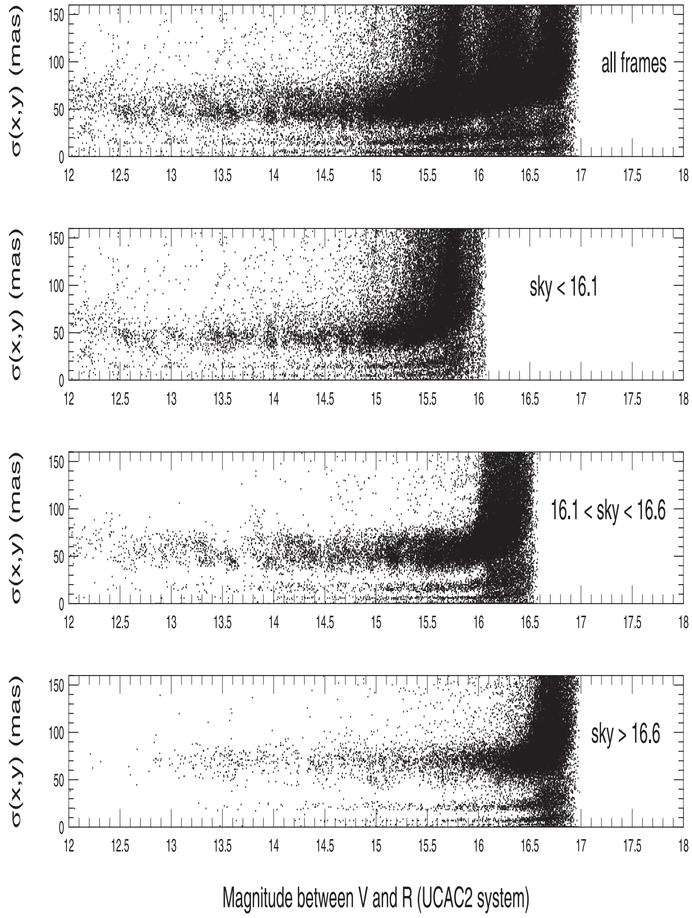

Fig. 1. (x, y) measurement errors with respect to to magnitude, for 3 distinct ranges of sky background magnitude. The errors were computed from Gaussian image profile model fits. In the top, all magnitude ranges are displayed. The error-magnitude relation displays a typical distribution, with the increase at the faint magnitude end depending on the sky transparency, as revealed by the 3 sky background magnitude regimes present in our observations.

source positions based on the UCAC2. Here, we present pilot results for 59 sources. In Sect. 2, we give the observation and reduction procedures and report the obtained positions and error estimates. Comparisons with other relevant datasets are presented in Sect. 3. Conclusions are discussed in Sect. 4.

2. Observations, reductions and results

Observations were carried out between 2004−2005 at the Belogradchik Observatory, Bulgaria ($\lambda = -22°40'30''$; $\phi = +43°37'22''$; h = 650 m) with a 0.6 m Zeiss telescope ($f/12.5$) equipped with an Apogee 47P CCD detector of 1024×1024 pixels of 13 μm size, operated in 2×2 binned mode, resulting in a FOV of $6.16' \times 6.16'$ with 1 pixel = 0.′72. Exposure time was 30 s. No filter was used. The frames for each source were taken at the same zenithal distance. Telescope shifts were applied between exposures to spread the object images over different pixels, thus minimizing bias on the (x, y) centers due to the occasional presence of hot/cold pixels.

Position reductions were made with the new astrometric package, PRAIA (Platform for Reduction of Astronomical Images Astrometrically; Assafin 2006). The first priority of the package is astrometric accuracy and precision. Although fast and automatic, it still allows for dealing with specifics on individual cases. PRAIA automatically identifies objects on the fields, measures them with bidimensional Gaussian fits, recognizes catalog stars and performs RA and Dec reductions with any chosen model. Positions and error estimates are generated, also including magnitude and seeing estimates for all objects. A new, more complete and detailed description of the package will be published in the future. In the following, we briefly describe the most relevant information from the final data reductions made using PRAIA.

PRAIA reduced the data at a rate of approximately 470 images per hour (or about 400 MB/h) with a 3.2 GHz CPU. Each complete run with PRAIA lasted less than 3 h. RA and Dec reductions were made using the UCAC2 catalog. On average 9 stars were used, with a minimum of 4 reference stars for relatively sparse fields. A standard 6 constant full linear model was used to relate the (x, y) measured and (X, Y) standard coordinates. Reference stars were eliminated in a one-by-one basis until none displayed (O−C) position residuals greater than 120 mas (approximately 2σ the typical catalog error). The RA and Dec reduction mean errors were 46 mas for both coordinates. The final ICRF source positions were obtained by the average of individual frame positions after eliminating outliers presenting discrepant positions larger than 150 mas (approximately 2.5σ typical UCAC2 errors) with respect to the other optical frame positions. On average we obtained 17 individual frame positions per source. For a few cases, only 1 to 5 frames were useful, due to very bad seeing and/or underexposure, which significantly affected the precision of the (x, y) measurements.

The (x, y) centers were obtained by 2−dimensional circular symmetric Gaussian fits within 1 *FWHM* (seeing was usually within $2''$ to $3''$). This means that the fit with the 2D symetric Gaussian profile was performed within one Full Width Half Maximum (1 *FWHM* = seeing) of the (x, y) center in an iterative process. This part of the image distribution is believed to be very well described by a Gaussian profile, free from wing distortions which otherwise would bias the center determination. There are some theoretical considerations about that as well as empirical results supporting this (see the classical works of Moffat 1969, and Stone 1989). For the ICRF sources, the (x, y) Gaussian errors ranged from 50 mas to 100 mas. Figure 1 displays the (x, y) position errors from Gaussian image profile fittings, for 3 distinct ranges of sky background magnitude. In the top of Fig. 1, all objects measured in the frames are displayed. The error-magnitude distribution displays a typical behavior, with the increase at the faint magnitude end depending on the sky transparency, as revealed by the 3 sky background magnitude regimes verified in our observations. The 3 regimes seem to be related to the annual seasons; we performed runs on February, July and October. The extra tails below the main distribution between magnitudes 14 and 16 refer to somewhat extended, non-stellar objects that display well sampled images with relatively small central brightness. They are neither reference stars nor ICRF QSOs and represent just a small fraction of the objects measured, so no significant statistical contribution can be assigned from this part of the distribution. Typically reference stars with (x, y) errors beyond 100 mas were naturally eliminated during the reduction process. Individual ICRF source positions with large Gaussian errors were also eliminated in the concatenation of individual positions from all frames. The cutoff in Fig. 1 at magnitude 17 seems somewhat shifted since at least some of the measured sources are known to have magnitudes up to 18. This might have been caused by the use of non-photometric UCAC2 magnitudes as standards.

Table 1. Optical astrometric positions for 59 northern ICRF sources.

Source	Optical − ICRF				Frames[b]	Mag	Epoch	(RA, Dec) Reductions		
	$\Delta\alpha\cos\delta$ (mas)	$\Delta\delta$ (mas)	σ^a_α (mas)	σ^a_δ (mas)	per source		yrs	M.e. σ_α (mas)	M.e.σ_δ (mas)	UCAC2 ref. stars
B0003+380	+46	−5	52	73	30	16.2	2004.7702	35	34	5
B0019+058	+15	+35	67	60	23	16.0	2004.7677	29	22	4
B0109+224	−6	+17	27	21	23	14.7	2004.7731	48	61	5
B0119+115	+18	+16	...	...	1	16.1	2004.7678	38	50	4
B0201+113	+40	−1	84	66	2	16.0	2004.7679	12	2	4
B0202+319	+34	−43	37	41	24	16.3	2004.7652	70	61	8
B0237+040	−32	+66	44	51	18	16.3	2004.7706	39	64	5
B0309+411	−48	−35	50	62	26	15.9	2005.1094	38	44	17
B0317+188	−28	−3	90	58	8	16.2	2004.7654	24	30	8
B0319+121	+41	−2	72	70	8	16.4	2004.7680	64	46	4
B0333+321	+102	−64	45	49	17	15.5	2005.1040	22	32	7
B0400+258	+20	−13	93	121	7	16.7	2004.7707	36	50	9
B0422+004	−22	−52	19	18	30	15.2	2005.1013	56	38	5
B0425+048	−29	+59	...	...	1	16.0	2005.1041	66	29	5
B0430+052	−103	−55	23	23	35	14.9	2005.1068	117	27	4
B0457+024	+86	−86	...	...	1	15.7	2005.1014	60	67	8
B0502+049	+4	+21	87	100	12	15.6	2005.0986	58	84	6
B0507+179	+142	+114	...	...	1	15.7	2005.1095	25	51	13
B0528+134	+22	−56	50	55	36	15.7	2005.1096	30	64	8
B0552+398	+0	+79	53	39	29	16.0	2005.7867	49	46	18
B0657+172	−59	−52	...	...	1	15.8	2005.0986	43	52	29
B0735+178	−61	+6	17	25	40	14.8	2005.0988	30	38	9
B0736+017	−22	−42	24	35	18	15.3	2005.1016	51	46	11
B0738+313	+40	+32	27	24	39	15.6	2005.1072	59	64	5
B0743+259	−102	+55	...	...	1	15.9	2005.1017	17	29	7
B0745+241	−13	−46	57	84	15	15.4	2005.1045	33	48	11
B0748+126	+57	+41	50	69	36	15.7	2005.1071	42	41	13
B0754+100	−82	+68	22	26	24	15.4	2005.1018	40	46	14
B0808+019	+99	+135	33	2	2	15.3	2005.0989	47	44	13
B0823+033	−29	−127	...	...	1	14.8	2005.1046	42	42	4
B0827+243	+17	+27	64	63	34	15.4	2005.1072	35	39	5
B0851+202	+33	−16	27	14	30	15.0	2005.0989	53	42	7
B0906+015	−53	+6	114	52	4	14.8	2005.1047	30	56	10
B0953+254	+21	+72	39	34	4	15.7	2005.1101	128	51	4
B0955+326	−58	+91	17	25	20	15.3	2005.1048	27	57	5
B1004+141	−18	−58	...	...	1	14.7	2005.0991	72	20	4
B1012+232	+87	−122	...	...	1	15.3	2005.1074	48	48	6
B1038+064	+2	−14	64	48	23	15.6	2005.1021	21	41	4
B1055+018	−29	−32	56	61	38	16.0	2005.1075	102	58	4
B1633+382	+16	+12	44	36	10	16.4	2005.5066	72	46	6
B1717+178	−24	+21	66	60	19	15.7	2005.4991	49	64	10
B1725+044	+59	+21	63	85	16	15.4	2005.4989	46	43	14
B1732+389	−21	+22	87	70	4	15.4	2005.4990	13	10	4
B1749+096	+6	−24	16	26	25	15.9	2005.5067	48	45	14
B1751+288	+46	+81	40	53	17	16.4	2005.5068	63	54	8
B1758+388	+78	+41	25	51	25	16.2	2005.5068	55	57	7
B1821+107	+41	+91	61	28	5	15.4	2004.7754	43	55	27
B1830+285	−7	+15	44	61	27	15.7	2005.4992	54	48	17
B2029+121	+73	−37	54	64	35	15.7	2004.7701	40	57	18
B2059+034	−92	+36	22	68	24	16.2	2005.5070	59	44	7
B2121+053	−3	+19	59	77	12	16.2	2004.7649	54	64	6
B2134+004	+2	+94	56	31	6	15.5	2005.7804	56	60	6
B2136+141	−1	−21	62	68	23	16.1	2004.7674	42	67	12
B2150+173	+79	+111	97	38	2	16.2	2004.7728	47	47	13
B2200+420	+10	+32	14	22	32	14.3	2004.7728	48	48	18
B2209+236	−25	−68	45	46	2	16.2	2004.7648	63	38	10
B2253+417	+5	−26	67	82	13	16.1	2004.7700	37	34	18
B2318+049	−13	−34	48	102	3	16.0	2004.7623	9	21	4
B2319+272	−15	+12	34	35	33	16.1	2004.7675	65	32	6
average	+6	+7	50	51	17	15.7	2004.7687	47	46	9
standard deviation	51	57	24	25	13	0.5	0.0033	22	15	6

[a] Standard deviation about the mean from individual frame positions.
[b] Frames taken for mean position.

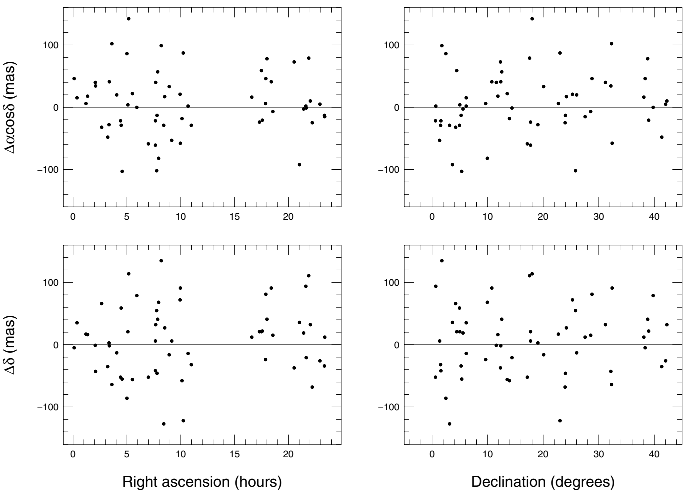

Fig. 2. Optical minus radio position offsets with respect to RA and Dec for the 59 northern ICRF sources listed in Table 1.

Table 2. Comparison with other northern optical astrometric surveys.

Survey	Optical astrometric survey Optical − ICRF $\sigma(\Delta\alpha\cos\delta)$ (mas)	$\sigma(\Delta\delta)$ (mas)	This paper Optical − ICRF $\sigma(\Delta\alpha\cos\delta)$ (mas)	$\sigma(\Delta\delta)$ (mas)	No. of common sources
ZZ	25	20	50	42	6
ZA nc	68	81	50	56	46
ZA co	69	81	50	56	46
SN HIP	194	236	54	57	41
SN TYC	177	152	54	57	41
SN ACT	154	158	54	57	41
FA A2	135	123	59	47	13
FA GSC	118	137	59	47	13

ZZ stands for Zacharias & Zacharias (2005); ZA co and nc refers to Zacharias et al. (1999) with and without galactic rotation correction, respectively; SN HIP, TYC and ACT stand for positions referred to the Hipparcos, Tycho and ACT catalogs from da Silva Neto et al. (2000); FA A2 and GSC refer to positions from Fienga & Andrei (2002) based on the USNO A2 and GSC 2.2 catalogs.

In Table 1 we display the results and related reduction information for each of the 59 ICRF sources. The optical positions are given relative to the VLBI ICRF coordinates. Average and standard deviation for all entries are listed at the bottom.

The optical minus radio position offsets are independent of the magnitude. Figure 2 displays these position offsets against RA and Dec. No correlations are seen.

3. Comparisons with other datasets

In the ICRS era, the paper ZA is the first global optical astrometric survey of ICRF sources to give positions in the HCRS. A total of 369 source positions covering all the sky were derived from long-focus, CCD observations. The small CCD FOVs were referred to secondary catalogs of stars obtained by the use of astrographic plates directly reduced with the Hipparcos catalog. A reasonable coverage of the northern sky was achieved. One problem was the epoch difference between CCD and plate observations, which sometimes reached up to 15 years. The authors tried a galactic rotation correction to take into account the unknown proper motion of the secondary catalogs. Two lists, with and without galactic rotation correction, were published.

Later on, a second global effort was made by SN, with 315 positions reduced by the use of the Digital Sky Survey (DSS). Three sets of positions were obtained based on the Hipparcos, Tycho and ACT catalog frames. The reductions were made relative to the Guide Star Catalog (GSC) star positions, previously corrected towards those same catalogs using common bright stars. Here, also a good number of northern source positions was derived.

Recently, paper FA published optical positions for 38 northern ICRF sources by the use of the USNOA2 and GSC 2.2 catalogs. Sources were observed with a CCD detector at the 1.2 m telescope at Observatoire de Haute-Provence, France. The reduction of the small FOVs was possible due to the stellar density of the catalogs. More recently, the observations were re-reduced by the use of the USNOB1 catalog and published in Fienga & Andrei (2004). The known zonal errors in the USNOA2 catalog were corrected in the FA paper using values obtained by Assafin et al. (2001). Thus, since both sets of positions are of similar value and since no individual positions were published in the later paper, we have only compared our positions with the set published in FA.

In paper ZZ, the presented northern source positions are almost directly tied to the Tycho2 frame. They are based on CCD observations taken simultaneously at larger telescopes and at the UCAC astrograph, around J2000. Their source position precisions were about 25 mas, which is consistent with the Tycho2 at J2000.

In Table 2 we list the standard deviation of the optical minus radio position offsets for each of the above surveys, using only ICRF sources common to this work. For each survey, we also present the standard deviation for our own position offsets, computed by taking only the common sources into account. The averages of the offsets of the compared sources ranged from 2 mas to 188 mas (modulus) for the other surveys and varied between 2 mas and 37 mas for our common positions. Due to the small number of sources involved, these averages are of no significance. On the other hand, the standard deviations give valuable information about the attained precision of the position sets. From Table 2, all surveys (with the exception of ZZ) show standard deviations from the ICRF much larger than ours, indicating the gain represented by the presented observation strategy and reduction method.

Finally, we note that from the position offsets listed on Table 1, our obtained standard deviation (precision) of about 55 mas for the northern part of the ICRF is in very good agreement with those obtained for the south by Assafin et al. (2005), where similar telescopes, observation and reduction procedures were used.

4. Conclusions

It seems that the best way to get optical astrometric positions for ICRF sources is by taking CCD observations. Although possible, the use of digitized images of Schmidt plates lack the much larger linear dynamical range of intensity counts that one can get from CCDs. Another important factor is the use of a good HCRF reference catalog with reliable proper motions for at least an intermediate range of magnitudes, such as the UCAC2 catalog – the best HCRF representative available to date for magnitudes as faint as 16.

We conclude that good quality astrometry of ICRF sources can be accomplished by the use of small to average sized telescopes. They furnish CCD FOVs sufficiently large to find enough reference stars from the UCAC2, without introducing too much optical distortions, yet allowing for good source imaging once adequate time exposures are used and a large number of frames are taken.

In comparison with the southern hemisphere, more astrometry on ICRF sources are needed in the north. We continue our observational program on northern ICRF sources at the Belogradchik Observatory, Bulgaria. Many sources above +52 degrees declination have already been observed. In the near future, with the conclusion of the UCAC project, we will be able to reduce all northern observations up to the pole. Only then can we do a deeper analysis of the status of the link between the HCRF and ICRF over the northern hemisphere and, by extension, over the entire celestial sphere.

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