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CCD astrometry of faint compact extragalactic radio sources. II.*

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Abstract. Optical positions relative to the Hipparcos Catalogue (ESA 1997) have been obtained for the optical counterparts of 28 faint ($B \sim 20{-}23$) southern compact extragalactic radio sources (CERS). Most of these sources are not adequately observable (or simply not visible) by means of direct photography with a conventional wide-field telescope, so the positions were determined using a multi-step procedure involving CCD and photographic observations. This method responds both to the need of attaining small positional errors and the need to refer the positions to a standard astrometric system. Estimated precisions as good as 60 mas were achieved. For 13 of the above objects, namely 0214−522, 0614−349, 0700−465, 0823−500, 1120−274, 1143−331, 1347−218, 1349+027, 1817−254, 1829−718, 1920−211, 2139+028 and 2211−388, we are proposing a new optical identification. A comparison with VLBI radio positions available for these sources is presented. The residuals obtained are in most cases consistent with the precision of our optical data, and provide an evaluation of these faint objects as possible radio/optical frame link sources (or their identification as astrophysically interesting astrometric outliers). Fifteen of the CERS observed are either defining or candidate fiducial objects of the present realization of the International Celestial Reference System (ICRS, Ma et al. 1998), so the optical data we have obtained for them is potentially useful to help mantain and possibly improve the current link of the Hipparcos reference frame to the ICRS.

Key words. astrometry – reference systems

1. Introduction

In this paper we give new results of our program to identify the optical counterparts, and determine precise optical positions with respect to the Hipparcos frame, of faint ($B \sim 20{-}23$) CERS, being carried out at the Estación Astronómica de Cerro El Roble (EACR), Cerro Tololo Interamerican Observatory (CTIO) and Las Campanas Observatory (LCO).

In a first contribution (Costa & Loyola 1999, hereafter Paper I) we presented a detailed description of the program and the results of the observation of 24 CERS. There we gave positions for the optical counterparts of 15 CERS, and proposed 5 new optical identifications. Here we present the results of the exploration of the fields of 37 CERS. A variety of sources were observed, among them suspected empty fields, CERS with very faint provisional optical identifications, and CERS with optical counterparts showing evidence of structure. Thirteen new optical identifications are being proposed, and we give coordinates for 28 CERS. Targets were selected from the NRL/USNO proposed reference frame list (see e.g. Johnston et al. 1995) and the list of Jauncey et al. (1989).

2. Observations

A detailed description and justification of the observational procedure is given in Sect. 2 of Paper I.

Optical positions for the CERS were obtained by means of a hybrid method involving CCD and wide−field photographic observations. The CCD observations allow for very precise astrometry to faint limits in the local field of the targets, and the photographic observations permit, by means of a multi−step procedure in which ad−hoc secondary and tertiary reference frames are established, to link the former to a standard reference system. As the standard (primary) reference system we have adopted the Hipparcos Catalogue.

The photographic observations were carried out with the flat−field 70/100/210 cm Maksutov Astrograph (field: $5° \times 5°$, scale: $99.4''$/mm) at the EACR. Two forming gas hypersensitized Kodak IIIaJ plates, one long exposure (50 min) and one short exposure (2 min), were taken centered on each CERS. Two different exposure plates are necessary to minimize the magnitude error introduced

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* Figures 1–16 are only available in electronic form at http://www.edpsciences.org

by the fact that we are dealing with reference stars that vary greatly in brightness (as is the case of the primary, secondary and tertiary reference system stars). A Schott GG385 filter was used. Although not ideal, the use of the blue bandpass was dictated by emulsion availability.

The CCD observations were secured with the 1.5 m telescope at CTIO and the 2.5 m telescope at LCO. Both telescopes provide a very similar set−up in terms of scale and field: $0.24''$/pixel, $8.19' \times 8.19'$, CTIO and $0.26''$/pixel, $8.87' \times 8.87'$, LCO. In both cases the CCD detectors used were Tektronix 2048×2048 chips with 24 μ pixels. Five frames were typically obtained of each target, which were registered and then combined to produce a single work image. Extensive testing showed that 600 s exposures (CTIO; 300 s LCO) were necessary to obtain a good signal to noise ratio for the sources, without saturating the tertiary reference stars. A Johnson B filter was employed for consistency with the photographic observations. In optimum seeing conditions ($FWHM \leq 1.0''$) we estimate that the limit of detection of our survey is $B \sim 24$.

In all but two cases the CCD frames and the plate material were obtained at similar epochs, ensuring a negligible error contribition from the unknown proper motions of the intermediate reference stars. Table 1 gives the epochs of the observations, together with information related to the identification of the sources. The approximate B magnitudes given for the newly identified optical counterparts (and those given for sources that were detected to have varied considerably) were estimated from their signal to noise ratio on the combined CCD frames. CT indicates that the CCD observations were secured at CTIO; LC that they were secured at LCO. An asterisk in the Remarks column indicates that additional comments are made in Sect. 5 (Notes on individual objects).

Finding charts for the newly identified optical counterparts, namely 0214−522, 0614−349, 0700−465, 0823−500, 1120 − 274, 1143 − 331, 1347 − 218, 1349 + 027, 1817 − 254, 1829 − 718, 1920 − 211, 2139 + 028 and 2211 − 388, and for those objects which in our opinion requiered an improved finder (1110 − 217, 1142 − 225, and 1936 − 623), are presented in Figs. 1 to 16. They will appear only in the on-line edition of the journal.

3. Reductions

Details on the reduction procedure can be found in Sect. 3 of Paper I.

The X, Y coordinates of the reference stars on the photographic plates were measured with a digital Zeiss−Jena Ascorecord measuring machine. Plates were measured both in direct and reverse position, in an effort to cancel possible systematic errors in the X, Y values. Six term quadratic relations were used in the reductions. Third order terms were not included because the flat field of the Maksutov Astrograph is almost free of distortions; and, since all plates were taken near culmination, refraction third order terms were not important. The standard deviation of the differences between calculated and catalogue values of the Hipparcos stars was $0.24''$ in X and $0.21''$ in Y.

The five CCD frames taken of each CERS were first calibrated, and then registered and combined, using standard IRAF (version 2.11.3, NOAO, University of Arizona) tasks to produce the final image from which the X, Y coordinates of the PSF centroids of the CERS and the tertiary stars were extracted. This latter step was carried out by means of the PEAK task within the DAOPHOT package (Stetson 1987).

4. Results and errors

The resulting optical positions with respect to the Hipparcos catalogue are given in Table 2. The first column gives the IAU designation of the sources, the second and fourth columns their J2000.0 right ascensions and declinations, and the third and fifth columns their corresponding total internal errors. The positions based on CCD observations made at CTIO are identified as CT in the Remarks column; those based on CCD observations made at LCO as LC. The positions derived from direct photography are identified as Phot.

Since the Hipparcos catalogue was constructed to coincide with the ICRF (Kovalewsky et al. 1997), and therefore can be considered an extension to the optical domain of the extragalactic radio reference frame, our optical positions are in the system of the ICRF.

A detailed descripton of the relations used to estimate the total internal errors of the positions of the sources presented in Cols. 3 and 5 of Table 1 is given in Sect. 5 of Paper I.

The total error contribution of the Hipparcos Catalogue varied for the present fields between 2.3 and 13.4 mas in RA, and between 1.4 and 10.3 mas in DEC. The errors of the measurement of the tertiary stars image centroid positions varied this time between 3 and 19 mas in X, and between 3 and 14 mas in Y; those of the measurement of the source image centroid position varied between 5 and 120 mas in X, and and between 5 and 110 mas in Y. The fact that the upper limit for this latter error turned out to be higher that for the CERS presented in Paper I is not suprising considering the extreme faintness of some of the optical counterparts measured. For those cases in which the CERS was visible on the long exposure plate the measurement errors of the optical counterparts varied between 100 and 200 mas in X, and between 110 and 190 mas in Y. In any case, it must be kept in mind that all of the above Sigmas are based typically on only five independing settings.

5. Notes on individual objects

0214−522: No optical counterpart was known for this source. Figure 1 shows the identification we are proposing. Given the optical faintness of this object and the modest quality of the CCD images available, the optical position

Table 1. Identification of the sources

IAU Designation	Plate Epoch	CCD Epoch		Approx. Magnitude	Nature	Finding Chart	Remarks
0008−421	97.11.01	96.07.16	CT		EF		
0131−522	92.09.26	95.12.19	CT	19	QSO?	7	
0214−522	96.11.11	95.12.21	CT	23	QSO?	**1**	*
0334+014	97.11.20	95.12.19	CT		EF		
0400−319	96.11.13	95.12.21	CT	20.2	QSO	3	
0414−341	98.10.24	95.12.19	CT	20.6	QSO?	3	
0537−286	96.01.21	95.12.18	CT	19.3	QSO	2b	
0614−349	96.01.21	95.12.19	CT	22	QSO?	**1**	*
0700−465	95.02.26	95.12.18	CT	20	QSO?	**1**	
0823−500	97.11.24	95.04.22	CT	20	QSO?	**1**	
0834−196	97.04.06	95.12.21	CT	22.5	AGN	4	*
1015−314	97.04.07	95.04.21	CT	20	Gal?	6	
1057−797	94.05.04	95.05.08	LC	19.3	QSO?	5	
1110−217	97.04.04	95.05.04	LC	23.5	QSO?	**1**,3	*
1120−274	97.04.07	95.05.07	LC	?	?	**1**	*
1128−047	97.04.07	95.05.07	LC	21.4	AGN	3	
1134−739	97.05.07	95.04.22	CT	19.5	QSO?	5	*
1142−225	97.04.04	95.05.08	LC	20	QSO?	**1**,3	*
1143−331	97.04.07	95.04.23	CT	20.1	AGN?	**1**	*
1219+044	96.05.11	95.05.07	LC	18	QSO	2a	
1250−330	96.05.14	95.04.21	CT	21.4	BL Lac	3	
1347−218	96.05.11	95.05.04	LC	23.5	QSO?	**1**	*
1349+027	96.05.12	95.05.04	LC	23.5	QSO?	**1**	*
1406−267	95.06.21	95.04.21	CT	21.8	QSO?	5	
1648+015	91.06.08	96.07.17	CT	22.7	QSO?	3	
1714−336	95.08.25	96.07.17	CT		EF		
		95.05.05	LC				
1817−254	95.08.24	95.05.06	LC	?	?	**1**	*
1829−106	95.07.20	95.05.07	LC		EF		
1829−718	96.09.03	95.05.06	LC	?	QSO?	**1**	*
1920−211	95.09.23	95.05.07	LC	18	QSO?	**1**	*
1936−623	95.08.24	95.05.04	LC	22.5	QSO?	**1**,5	*
1950−613	96.09.05	95.05.07	LC		EF		
2008−068	98.09.23	95.05.08	LC		EF?		*
2036−577	95.07.20	95.05.08	LC	22	QSO?	5	
2139+028	96.09.04	96.07.16	CT	22.5	?	**1**	*
2211−388	95.08.25	96.07.17	CT	22	AGN?	**1**	*
2329−162	96.10.09	96.07.18	CT	20.9	QSO?	3	

1 indicates a newly identified optical counterpart.
LC stands for Las Campanas.
CT stands for Cerro Tololo.

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presented in Table 2 should be considered preliminary.

0614−349: Shimmins & Bolton (1974) claim the identification of this source as a galaxy. In their finder however, the two close objects that lie in the radio source position are not resolved, so their identification is uncertain. The high radio−optical residual obtained in RA for the object we indicate in Fig. 2 as the optical counterpart, suggests that the identification being proposed by us could also be incorrect. Our CCD material does not show any alternative object down to a magnitude limit of $B \sim 22.5$.

Table 2. Optical positions in the ICRS system of 28 compact extragalactic radio sources

(1) IAU Designation	(2) RA(J2000.0) h m s	(3) $\epsilon_\alpha \cos\delta$ $\pm''$	(4) DEC(J2000.0) ° ′ ″	(5) ϵ_δ $\pm''$	(6) Remarks
0131−522	01 33 05.729	0.08	−52 00 03.84	0.07	CT
0214−522	02 16 03.383	0.12	−52 00 11.40	0.11	CT
0400−319	04 02 21.271	0.08	−31 47 25.76	0.07	CT
0414−341	04 16 10.055	0.09	−34 03 03.80	0.09	CT
0537−286	05 39 54.270	0.06	−28 39 55.77	0.06	CT
	54.285	0.20	56.06	0.16	Phot
0614−349	06 16 35.935	0.10	−34 56 16.66	0.10	CT
0700−465	07 01 34.471	0.09	−46 34 36.65	0.09	CT
0823−500	08 25 26.893	0.09	−50 10 38.54	0.08	CT
0834−196	08 37 11.111	0.11	−19 51 56.80	0.10	CT
1015−314	10 18 09.307	0.08	−31 44 13.73	0.07	CT
	09.373	0.21	13.91	0.20	Phot
1057−797	10 58 43.290	0.09	−80 03 53.98	0.09	LC
	43.351	0.21	53.41	0.17	Phot
1110−217	11 12 49.618	0.12	−21 58 34.70	0.10	LC
1128−047	11 31 30.516	0.08	−05 00 19.63	0.07	LC
	30.532	0.14	19.38	0.13	Phot
1134−739	11 36 09.567	0.06	−74 15 45.39	0.07	CT
1142−225	11 45 22.035	0.07	−22 50 31.41	0.07	LC
1143−331	11 46 28.445	0.07	−33 28 42.56	0.06	CT
	28.426	0.13	42.63	0.15	Phot
1219+044	12 22 22.546	0.06	+04 13 15.93	0.06	LC
	22.544	0.19	15.76	0.13	Phot
1250−330	12 52 58.390	0.08	−33 19 59.32	0.08	CT
	58.409	0.14	59.54	0.16	Phot
1347−218	13 50 14.326	0.10	−22 04 43.75	0.11	LC
1349+027	13 52 30.665	0.11	+02 32 46.87	0.09	LC
1406−267	14 09 50.127	0.09	−26 57 37.21	0.08	CT
1648+015	16 51 03.635	0.09	+01 29 23.54	0.11	CT
1920−211	19 23 32.197	0.06	−21 04 33.00	0.06	LC
1936−623	19 41 21.785	0.09	−62 11 21.06	0.09	LC
2036−577	20 40 01.120	0.09	−57 35 09.38	0.08	LC
2139+028	21 42 11.449	0.09	+03 02 29.16	0.10	CT
2211−388	22 14 38.531	0.10	−38 35 44.49	0.09	CT
2329−162	23 31 38.659	0.08	−15 56 57.27	0.09	CT

CT stands for Cerro Tololo.
LC stands for Las Campanas.
Phot. indicates a position derived from direct photography.

The fairly poor limit of detection achieved in this case was due to mediocre seeing conditions.

0700−465: The high radio−optical residual obtained in RA for the object we are proposing as the optical counterpart, suggests that our identification could be incorrect. Our CCD material does not show any alternative object down to a magnitude limit of $B \sim 22.5$. The fairly poor limit of detection achieved in this case was due to mediocre seeing conditions. See Fig. 3.

0823−500: No optical counterpart was known for this source. Figure 4 shows the identification we are proposing.

0834−196: Here we confirm the tentative identification proposed by Fugmann et al. (1988) and di Serego Alighieri (1994). In our material however the object appears to be fainter. Variable?

1110−217: Drinkwater et al. (1997) claim the optical identification of this source but their finding chart does not show the object. In Fig. 5 we present an improved fiding chart.

1120−274: Possible new identification (see Fig. 6). The tentative optical counterpart is at the limit of detection of the available CCD images, so its optical position could not be determined.

1134−739: Optically variable. This object was roughly two magnitudes fainter when observed by Jauncey et al. (1989).

1142−225: Optically variable? This object is classified as very faint by Drinkwater et al. (1997), and they point out that it has been confused with a close neighbour in the sky catalogues. Their optical position, based on a CCD image by means of which they resolved both objects, is consisitent with ours, but their finding chart does not clearly show the optical counterpart. Also, as shown by our improved finder (Fig. 7), the optical counterpart seems to have brightened.

1143−331: Not the object indicated in the finding chart published by Shimmins & Bolton (1974), although the B1950.0 optical position given by them seems to be correct. Jauncey et al. (1989) also give a seemingly correct B1950.0 optical position for this object, but do not publish a finding chart. Here we provide the correct identification (Fig. 8). It must be noted that a very faint – not measurable – object is seen to the NW, very close to that indicated in Fig. 8 as the optical counterpart. This latter object cannot be ruled out as the true counterpart.

1347−218: No optical counterpart was known for this source. Here we propose a tentative optical identification (Fig. 9).

1349+027: The identification proposed by Wills (1968) is incorrect. Here we propose a much fainter ($B \sim 23.5$) optical counterpart, shown in Fig. 10.

1817−254: Possible new identification, shown in Fig. 11. The extreme star density of this field prevented any type of coordinate determinations.

1829−718: Possible new identification. The proposed optical counterpart is not measurable. The object apparently indicated in Fig. 12 is a very close brighter object to the SE of the one we believe is the correct identification.

1920−211: No optical identification was available for this source. Here we propose a fairly bright object shown in Fig. 13. Very close to the object proposed other two very faint (not measurable) objects are seen. None of them can be ruled out as the true counterpart.

1936−623: Originally identified by Jauncey et al. (1989). Here we provide an improved finding chart (Fig 14).

2008−068: EF? At the limit of detection an object seems to be present in the radio source position.

2139+028: No optical counterpart was known for this source. Althought not noticeable in Fig. 15, the object being proposed shows some evidence of optical structure.

2211−388: No optical identification was available for this source. The counterpart being proposed (Fig. 16) is diffuse; it is probably a galaxy.

6. Discussion

The present results confirm that combining CCD observations with conventional photographic astrometry, it is possible to obtain "absolute" (i.e. refered to a standard astrometric system) optical positions of very faint ($B \sim 20-23$) CERS with an estimated precision level as good as 60 mas.

Although the ultimate precision attainable with our method is hampered by the accuracy with which the positions of the reference stars can be determined measuring the plates with a conventional manual measuring device, an important reduction of the total internal error results from the significant decrease of the error in the determination of the centroid of the optical counterpart. This error completely dominates the total internal error in a purely photographic approach, even in the case of moderately faint ($B \sim 19.5$) objects (see Costa & Loyola 1992). Furthermore, the method proposed is capable of precise astrometry of objects that are not measurable – or simply not visible – on a wide-field telescope plate, and very effective at exploring suspected empty fields in search for faint optical counterparts (for roughly 45% of the empty fields explored we are proposing a new optical identification).

In Table 3 we present a comparison in the ICRS with the VLBI radio positions given by Ma et al. (1998), in the sense radio minus this work (C). To calculate the mean differences presented at the bottom of the table we only considered positions derived from CCD observations.

Since our optical positions are displayed in essentially the same reference system as the radio positions, the radio−C differences given in Table 3 provide an evaluation of these objects as possible radio/optical frame link sources; in six cases (namely 0131–522, 0614–349, 0700–465, 0823–500, 1920–211 and 2211–388) the first one available. It is interesting to note that those sources which show the highest residuals are CERS for which we are proposing a new optical counterpart. One direct interpretation is that they are not appropriate benchmark objects (we believe that this could be the case of source 2211–388); another is that the proposed optical

Table 3. Comparison in the ICRS with the VLBI radio positions given by Ma et al. (1998). See Sect. 6 for details

IAU Designation	(Radio − C) $\Delta\alpha\cos\delta$ ″	$\Delta\delta$ ″	Remarks
0131−522	0.31	−0.11	CT
0400−319	−0.06	−0.19	CT
0537−286	0.15	−0.18	CT
	−0.20	0.16	Phot
0614−349	0.56	0.10	CT
0700−465	0.69	0.03	CT
0823−500	−0.23	0.05	CT
1057−797	0.05	−0.18	LC
	−0.21	−0.17	Phot
1128−047	0.01	−0.03	LC
	−0.14	−0.13	Phot
1219+044	0.05	−0.15	LC
	0.19	0.13	Phot
1920−211	−0.10	−0.33	LC
1936−623	−0.12	0.00	LC
2211−388	0.45	−0.52	CT
2329−162	−0.09	0.26	CT

Mean residual	+0.13	−0.10
Sigma	0.28	0.20
Standard error	0.08	0.06
No. of common objects	13	

CT and LC stand for Cerro Tololo and Las Campanas respectively.

Phot. indicates a comparison with a position derived from direct photography.

identifications are not correct (this could be the case of sources 0614–349, 0700–465 and 1920–211). See Sect. 5 for details. In the event that they are real astrometric outliers (i.e. the residuals are showing real offsets between the radio and optical emission centroids), these sources are potentially interesting from an astrophysical point of view.

Apart from the above sources, the residuals obtained are consistent with the overall estimated precision of our data. In any case, it must be kept in mind that the errors in the measurement of the primary, secondary and tertiary reference stars used to calculate the total internal errors of our positions were average values based on previous experience (see Sect. 5.1 of Paper I), which opens the possibility that for some objects these errors may have been underestimated. Also, we cannot rule out the existence of an undetected magnitude equation.

Considering that 15 of the CERS observed are either defining or candidate fiducial radio sources of the present realization of the ICRS, the data presented is potentially useful to help mantain, and possibly improve, the current link of the Hipparcos reference frame to the ICRS. Although at this moment a link based on CERS that display optical emission is less precise than other methods that contributed to the realization of the present link (see e.g. Kovalewsky et al. 1997), on account of the large number of well distributed link sources involved it has a great potential (see e.g. Zacharias et al. 1995).

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