Astron. Astrophys. 348, 653–658 (1999)

ASTRONOMY
AND
ASTROPHYSICS

A direct link of the CAMC catalogue to the extragalactic frame

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Received 8 April 1999 / Accepted 4 June 1999

Abstract. We determine the positions of twelve radio sources in the frame of the Carlsberg Automatic Meridian Circle catalogue using observations based solely on CCD images. The precision per frame is 50 mas and most sources have 5 or more frames thus the accuracy of these positions is solely limited by the error in the reference stars.

Key words: astrometry – reference systems

1. Introduction

With the advent of high precision VLBI radio observations the reference frame defined by radio sources has become progressively more precise than the best optically defined one. Being based on extragalactic sources with assumed zero proper motions this is the best observational realization one can have of an inertial system. The tying of the optical stellar frame to this system is required for the study of galactic and stellar kinematics and consequential effort has gone into doing this. This is especially true with the release of the Hipparcos mission data which defines a rigid frame at the 0.1–0.2 milliarcsecond (mas) level but is instrumental and linking it to an inertial system requires both zero point and rotation parameters (Lindegren and Kovalevsky 1995).

Here we present our determination of extragalactic radio source positions, for brevity we shall call these QSOs, in the system of the Carlsberg Automatic Meridian Circle catalogue (CAMC9 1997). The CAMC is based on meridian circle observations and for the last 5 years there has been a joint CAMC-Torino QSO program to observe stars close to selected QSOs (Chiumiento et al. 1991). Originally it was intended to use a combination of photographic plates to find the QSO position, and for the majority of the program this is still the case; however, for the subset discussed here we found that the required observations could be carried out more precisely and easily using CCD images.

We discuss the choice of targets, observations, reduction methods and the comparison of our results with the radio determinations.

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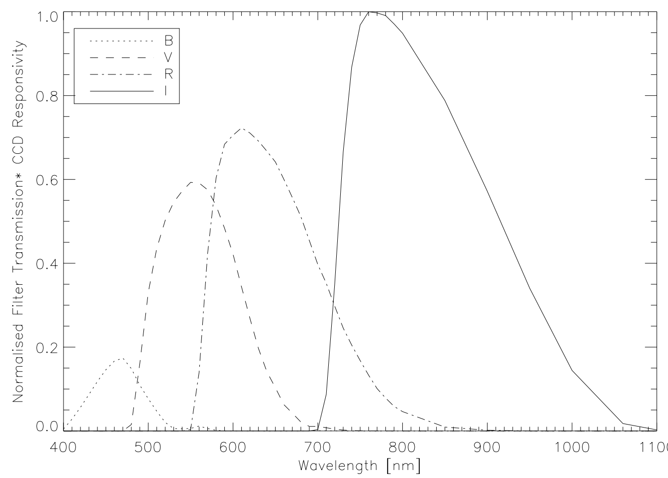

Fig. 1. Convolution of nominal CCD sensitivity and filter transmission for the OATo system.

2. Instrument and observations

The 1.05m REOSC telescope of the Torino Observatory is a long focus (9.942 m) large plate scale (20.7″/mm) reflecting telescope with a parabolic primary and a flat secondary. The main aberration on this telescope is coma and this aberration to a radius of ∼6.5′ is smaller than the seeing disc (Pannunzio 1979); therefore the astrometrically usable field of view is about 13′. Observations are made using a 1296×1152 pixel EEV CCD05−30 with a per pixel scale of 0.47″and a field of view of $10' \times 9'$. All observations are carried out through a Bessel (1979) realisation of a Cousins I filter. We observe in this band to reduce the effects of refraction and because the nominal quantum efficiency of the system is greatest. Fig. 1 shows the convolution of the nominal CCD sensitivity and transmission of the 4 standard filters, the solid line is our default combination.

All the observations were carried out over the 2 year period beginning December 1994. For 5 of the targets we have extensive data as these were included as calibration targets in the OATo parallax program. From an examination of these 5 targets our precision per frame is 50 mas in each coordinate at the magnitude of the QSO, i.e. 16–18 in I, and better at the magnitude of the CAMC stars. As the average catalogue error of a CAMC star is 90 mas we can see that the use of 3 frames

Table 1. Sources with at least 4 CAMC stars in a $10' \times 9'$ field. Positions are for J2000; O =classification A=other, L=BL Lac, Q=Quasar and *=used to tie Hipparcos frame to ICRF; X= Structure in X band; S = Structure in S band; I=Categorization of sources in IERS 24 for defining the ICRF where D=defining source, C=candidate source and O=other source.

Source	α	δ	O	X	S	I
0111+021	01 13 43.1450	+02 22 17.316	A*			C
0138−097	01 41 25.8321	−09 28 43.673	L	2	1	D
0607−157	06 09 40.9495	−15 42 40.672	Q			C
0736+017	07 39 18.0339	+01 37 04.618	Q			C
0859−140	09 02 16.8309	−14 15 30.875	Q			C
1040+123	10 42 44.6052	+12 03 31.264	Q			D
1127−145	11 30 07.0526	−14 49 27.388	Q	4	2	C
1302−102	13 05 33.0150	−10 33 19.428	Q*			C
1510−089	15 12 50.5329	−09 05 59.829	Q	3	1	O
1821+107	18 24 02.8553	+10 44 23.774	Q	3	1	C
2128−123	21 31 35.2617	−12 07 04.796	Q*	3	2	O
2155−152	21 58 06.2819	−15 01 09.327	L			O

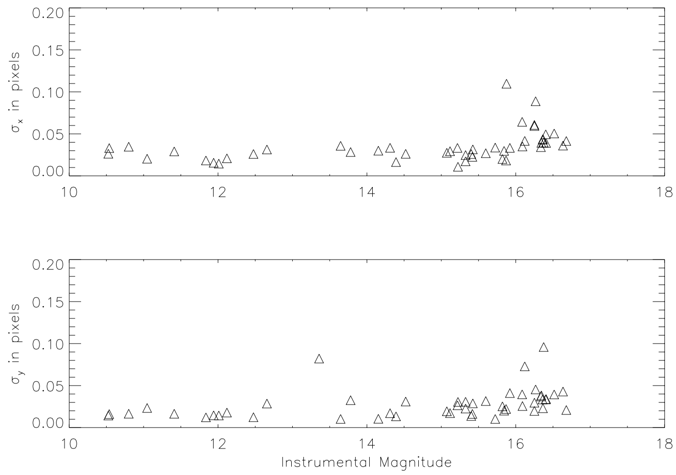

Fig. 2. Centroiding test for LHS 254. The sigmas are from the residuals of 20 consecutive 300 second frames taken of this target over the period of a night. One pixel equals 0.47 arcseconds.

per target will make the contribution of the random error in the CCD position negligible ($< 10\%$). Photometry was found for all fields and will be published in a future paper.

3. Choice of targets

This telescope and CCD combination is mainly dedicated to the Torino Observatory Parallax Program but the determination of QSO positions has been incorporated into this program as both targets in the parallax program, calibration fields and optional targets during the midnight hours when parallax observations are of less value.

We choose those QSOs which have at least 4 CAMC stars within the limits of the CCD from our original CAMC-Torino program. The original program has 74 QSOs mainly from the list proposed by the Working Group of IAU Commission 24 (Argue et al. 1984). In Table 1 we list the QSOs chosen along with their position (J2000) and classification taken from the Commission 24 list. We have also included the structure values as given in IERS Technical note 23 (Ma and Feissel 1997), with a range of 1–4 with the higher numbers indicating the most structure and that the radio position maybe unsure.

4. Centroiding routines and weights

The fundamental quantity in this project is the position of the objects in the frame of the CCD. Hence, we carried out a number of experiments to find the centroiding method and software package most suitable for our CCD/telescope/site combination to determine this quantity. Two packages were tested: ROBIN (Lanteri 1990), an in-house suite of routines that fits a two-dimensional Gaussian to the stellar profile providing centroids and magnitudes, and the IRAF implementation of DAOPHOT II (Stetson 1987).

For testing we took sequences consisting of between 5 and 45 frames for 5 different fields on 10 different nights. Fig. 2 shows an example of such a sequence for the field around LHS254. Here we took 20 frames of 300 s exposure with the same center and have plotted the sigma of the stellar position about the mean position after suitable linear transformations. Using this technique with different fields on different nights we can test the effect of crowding, varying sky conditions and different exposure times. The sequences which covered the longest hour angle were used to calibrate differential color refraction. As we are only comparing centroiding procedures any refraction, focal plane distortions and changing conditions within a given night divide out. The calculated sigma is a worse case scenario of the true centroiding error.

From Fig. 2, which used the ROBIN package, for the majority of stars the sigma is 0.02 pixels (=10 mas), this is typical for the sequences examined from reasonable nights. Note that the magnitude range covered in this test, 6, is approximately equal to the largest difference between the target QSOs and brightest CAMC in their field, the worse case is in the field 1821+107 where the difference is 6.3 magnitudes. As the exposure times were calculated to maximize the QSO counts without saturating the CAMC stars, the results of this test are particularly applicable.

All the profile fitting methods in DAOPHOT II were tried: penny, lorentz, moffat1 moffat2 and gaussian. For centroiding, the gaussian consistently produced the best results except on frames with bad guiding which are of poor quality anyway. The theory behind the gaussian fit of DAOPHOT and that of ROBIN is not much different. DAOPHOT allows an extra level of parameterization in that the fit includes a correction between the calculated PSF and the observed PSF in the form of a lookup table. However, DAOPHOT applies weights which are inversely proportional to the radial distance of the pixel from the centroid of the star. This makes perfect sense when the aim is to get photometry, i.e. photon counting, but is opposite to that for centroiding where one wishes to weight the parts of the image with the largest gradient, i.e. the wings. Stetson (private communica-

Table 2. Expected refraction effects: V,V-I of the QSO, mean V-I of the CAMC reference stars and the differential effect of refraction based on the results of Monet et al. (1992) with the difference of the QSO V-I and mean V-I.

Source	V	(V−I)	$<$V−I$>_{\rm CAMC}$	Diff Ref mas
0111+021	15.84	1.128	1.032	-0.33
0736+017	16.96	1.064	0.941	-0.43
0859−140	16.64	0.372	1.073	2.22
1040+123	17.72	0.406	0.899	1.59
1302−102	14.80	0.385	0.905	1.67

tion) also indicated that the weights are used to make the fit as deterministic and robust as possible. We found that increasing the fitting radius parameter, thus weighting quite a large portion of the star, improved the centroid found but only to the point that it was equal to that found by the default ROBIN parameters. The magnitudes found by DAOPHOT are more precise by a small amount (0.004).

Using ROBIN we have the ability to apply different weights to the individual pixels. We tried weighting by possion noise (the correct theoretical weight if we assume possion statistics), by counts per pixel, by the distance from the nominal stellar center as done in DAOPHOT, and by the inverse of the distance from the stellar center to give more weight to the wings. These tests were not conclusive, there is no clearly best weighting system for this data and on average a weight of 1 (i.e. equal weights) gave as good a precision as any other. There is one caveat, we give zero weight to any pixels where the counts are more than 95% the nominal non-linearity limit of the CCD.

5. Refraction effects

The positions measured on the CCD are subject to refraction. The majority of the refraction effect is removed by the linear adjustment to the unrefracted CAMC star positions. There remains a small correction caused by the different colors of the reference stars and the QSO. In Fig. 1 we show that our filter + CCD combination is centered at 780nm where the effects of refraction are very small. Additionally, the refraction due to different colors will change sign depending on which side of the meridian the observations were taken; hence, if observations are spaced around the meridian, the systematic effects of refraction will cancel out in the averaging of the different frames.

In Table 2 we estimate the maximum expected refraction from a comparison of the color of the QSO and the mean color of the CAMC stars. This was calculated using the method described in Monet et al. (1992), Eq. 5. We use a redder filter and therefore the estimates below will be maximum values for the differential refraction caused by the difference between the QSO and the mean reference star colors. Even given that QSO's have non-stellar spectral energy distributions, the expected refraction should not differ much from these estimates. From this we can say that the effect of differential refraction is negligible.

6. Reductions

For each sequence of frames we used a linear model to combine the frames in the x,y coordinates weighting each star by the inverse of its flux. For each object we then derived a mean position and standard deviation about that position. Note that in the calculation of mean x,y positions we ignore the effects of proper motion over the 2 year period. Apart from being negligible compared to the catalogue errors, this will only affect the candidates covered for the whole period and most were covered for just a few close nights. When the CAMC catalogue contains proper motion we propagate the coordinates of the star to the epoch corresponding to the mean position.

We have between 4–7 CAMC stars per field, hence we are limited to a linear model to relate the measured positions to standard coordinates. A comparison of several frames around the QSO 2201+315 with the same region taken with the US Naval CCD Astrograph (UCA) telescope indicated that the systematic differences between the two systems were less than 20 mas. These differences are probably due to filter and environment effects and even at this level they are negligible compared to the expected random errors of 50–70 mas in our final positions. A vector plot of the differences showed no systematic pattern and as the positions of the QSOs on the CCD vary depending on the CAMC star positions, distortions will manifest themselves as random errors in the final comparison to the IAU positions.

The parameters to find the QSO position were then found by adjusting the mean x,y positions of the CAMC stars to the standard coordinates derived from their equatorial positions and the nominal CCD center. The formal errors were derived from the Eichhorn and Williams (1963) formulation which includes both measuring errors, being the standard deviations of the observations, and catalogue errors. The error in the standard coordinate ξ is given by:

$$\sigma_\xi^2 = (\frac{\delta\xi}{\delta\mathbf{x}}^T \frac{\delta\xi}{\delta\mathbf{a}}^T) \left(\begin{array}{cc} Q_{\mathbf{xx}} & 0 \\ 0^T & Q_{\mathbf{aa}} \end{array} \right) \left(\begin{array}{c} \frac{\delta\xi}{\delta\mathbf{x}} \\ \frac{\delta\xi}{\delta\mathbf{a}} \end{array} \right)$$

where $Q_{\mathbf{xx}}, Q_{\mathbf{aa}}$ are the covariance matrices in the coordinates and the parameters. We expect these formal errors to be good representations of the true errors because of the methods used to calculate the constituent parts. The final accuracy of the QSO position depends on the deviations of the CAMC catalogue with respect to an absolute frame and, of lesser importance, internal systematic errors.

The errors of CAMC star positions measured on our CCD frames average to 16 mas in each coordinate while the QSO measuring errors average to 56 mas. Note that the average CAMC measuring error is slightly higher than expected from a consideration of Fig. 2 because of the effect of proper motion and the fact that the frames were taken on different nights in different conditions. The errors of the catalogue positions of the CAMC range from 65 to 169 mas and average 92 and 104 mas in right ascension and declination respectively.

The variance of the QSO can be approximated by:

$$\sigma^2 \simeq \frac{\sigma_{cen}^2}{\sqrt{nf}} + \frac{\sigma_{atm}^2}{\sqrt{nf}} + \frac{\sigma_{cat}^2\sqrt{3}}{\sqrt{Nc}}$$

Table 3. Mean measured positions for the reference stars and the QSOs along with their standard deviations for the multiple frames.

Source	X''	Y''	σ_x mas	σ_y mas
0111+021	258.5981	401.6677	23.1	50.1
801213	63.1819	430.2085	16.6	17.3
801212	104.3597	226.2650	17.7	17.1
801211	143.8002	360.9065	20.9	30.1
801210	152.2190	389.3769	10.2	11.2
400530	453.1046	103.8800	6.8	13.6
700663	522.0657	514.7444	4.1	4.0
0138−097	392.8946	251.8044	85.0	9.4
600864	22.7319	16.8393	5.9	2.6
600863	82.5587	426.1119	6.6	6.9
600862	143.1493	89.9936	7.5	5.3
600860	224.4903	537.2835	6.7	6.1
400714	427.0030	264.5661	3.6	5.0
0607−157	433.4368	295.1488	72.2	48.1
805857	49.1010	460.6548	42.6	32.8
503787	219.3504	205.2747	9.2	6.5
703645	232.0429	401.5408	38.8	23.3
304410	354.6476	530.3917	14.4	8.3
805852	366.5371	210.3733	30.1	20.9
304409	521.6892	51.6798	4.7	2.2
0736+017	400.3833	392.9005	42.8	41.0
806915	14.7598	232.0905	5.8	9.5
704841	107.7273	467.3431	8.3	10.8
806909	244.3670	528.1818	10.4	10.5
704838	383.8981	143.7336	3.0	2.7
0859−140	209.1980	231.0961	30.6	22.5
604110	37.4356	20.2759	9.2	10.8
604106	433.6721	176.8248	2.8	4.0
405570	482.9585	543.4010	3.6	9.3
505119	500.0718	417.1207	4.9	8.1
1040+123	203.7373	364.5137	139.7	39.7
808743	93.3704	265.2539	21.0	10.9
604769	95.7326	392.9413	10.9	3.5
707580	258.9660	68.2080	14.4	4.1
604767	267.8001	362.0370	3.4	1.6

where the first term is the error due to centroiding, the second is due to the fact that our frames were taken in different atmospheric conditions and the final term is an approximation of the propagation of the catalogue error into the position via the 3 plate parameters. We have assumed that the non-random errors due to atmospheric effects from different frames are uncorrelated. Since the catalogue errors do not improve with the number of frames and the other errors do, after 4 frames the measuring error becomes negligible and the precision of the QSO position is dominated by the catalogue errors of the CAMC stars.

7. Results

In Tables 3 and 4 we list the mean x,y positions in arcseconds and the corresponding standard deviations in milliarcseconds. This information is sufficient for a complete re-reduction should the catalogue positions of the CAMC stars improve.

Table 4. Mean measured positions for the reference stars and the QSOs along with their standard deviations for the multiple frames.

Source	X''	Y''	σ_x mas	σ_y mas
1127−145	279.1428	383.2995	60.1	44.6
308311	134.3400	374.5925	6.9	12.4
809110	244.8721	199.9105	13.7	15.7
708332	259.2697	248.0410	17.4	18.9
809108	411.9979	125.9845	13.1	15.4
809107	412.1507	306.0790	11.3	14.6
1302−102	208.4288	368.7628	52.0	85.0
309435	75.0593	557.7482	1.0	2.0
911435	128.5918	326.3926	27.1	42.6
606039	198.4728	465.9208	21.4	40.0
809902	288.8087	456.4915	14.8	25.9
710173	402.0290	35.0840	21.3	35.5
710172	411.8065	502.9817	28.6	18.5
1510−089	258.0566	120.7119	85.7	32.8
712686	97.5025	76.0452	21.6	14.9
508734	109.3036	475.2932	14.0	18.0
508730	215.0939	256.8449	26.6	24.0
712685	240.3539	156.6092	28.3	16.1
811023	321.7208	159.0998	16.5	9.4
811022	351.4978	82.9947	29.2	20.1
1821+107	354.7077	202.5236	25.2	46.7
716749	45.6764	343.0018	22.1	20.7
412666	92.0456	86.1835	36.2	32.9
716745	184.7299	401.9434	14.5	22.7
716744	226.3988	500.2328	8.1	14.0
716743	288.6464	186.3147	19.7	27.1
609099	416.5470	252.9131	12.4	43.0
2128−123	356.7286	295.5004	34.0	53.0
719928	88.0379	479.9251	7.7	14.6
719927	135.0248	529.3423	9.5	14.3
719926	291.8740	118.3552	11.8	24.7
815584	434.8614	-1.3544	74.4	83.2
719922	510.1703	84.1082	21.9	33.5
2155−152	263.4384	196.5594	24.6	150.6
515083	41.7020	323.9822	4.1	12.0
815997	193.1693	16.7645	1.8	7.3
414981	231.0394	512.2858	18.9	21.2
515078	404.0926	559.2691	7.1	9.0
720315	424.7956	164.8724	21.8	34.2

Table 5 lists the number of I frames used, the number of CAMC stars in that field, the right ascension and declination found from the reduction along with the internal dispersion from the frames used, the difference of our value from that of the IAU 24 list and finally the V magnitude.

8. Discussion

In general the errors and differences in declination are worse than those in right ascension, this reflects the lower accuracy of the CAMC in that coordinate. The formal errors have contributions from the position of the QSO with respect to the reference stars, the errors of the CAMC positions, the centroiding errors

Table 5. Positional results: Nc = number of CAMC stars in field, Nf = number of frames used, α, δ right ascension and declination, $\sigma_\alpha \cos\delta$,σ_δ = formal errors from Eichhorn and Williams (1963) formulation, $\Delta_\alpha \cos\delta$,Δ_δ = the IAU 24 list position minus this position.

Source	N_c	N_f	RA, α	$\sigma_\alpha \cos\delta$"	$\Delta_\alpha \cos\delta$"	Dec, δ	σ_δ"	Δ_δ"	m(v)
0111+021	6	25	01 13 43.1528	0.049	-0.119	02 22 17.418	0.054	-0.101	16.3
0138−097	5	5	01 41 25.8274	0.063	0.069	-09 28 43.095	0.079	-0.578	16.6
0607−157	6	5	06 09 40.9607	0.048	-0.160	-15 42 40.830	0.059	0.159	18.5
0736+017	4	15	07 39 18.0372	0.067	-0.051	01 37 04.765	0.077	-0.146	16.5
0859−140	4	4	09 02 16.8287	0.058	0.032	-14 15 30.956	0.071	0.082	16.6
1040+123	4	9	10 42 44.6023	0.049	0.042	12 03 31.414	0.053	-0.150	17.3
1127−145	5	18	11 30 07.0559	0.082	-0.047	-14 49 27.314	0.100	-0.073	16.9
1302−102	6	20	13 05 33.0225	0.038	-0.111	-10 33 19.483	0.046	0.056	15.2
1510−089	6	30	15 12 50.5301	0.053	0.041	-09 05 59.913	0.059	0.085	16.5
1821+107	6	30	18 24 02.8617	0.049	-0.096	10 44 23.833	0.061	-0.059	17.3
2128−123	5	9	21 31 35.2655	0.072	-0.055	-12 07 04.624	0.089	-0.172	16.1
2155−152	5	7	21 58 06.2768	0.049	0.075	-15 01 09.365	0.061	0.038	19.4

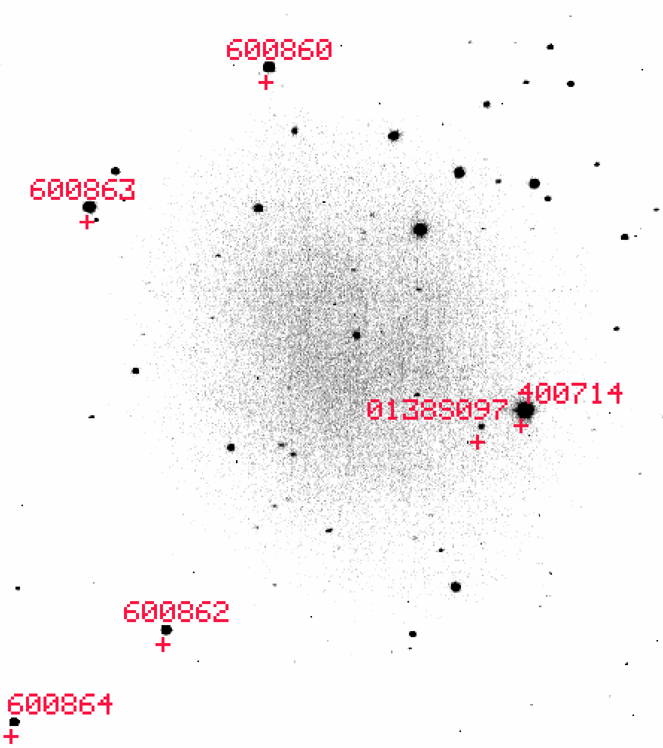

Fig. 3. Field of 0138−097 showing the relative positions and magnitudes of the CAMC stars and the QSO.

(especially in cases where the QSO to the brightest CAMC star magnitude difference is large), the contribution of refraction which is dependent on declination and the contamination of the measured positions by nearby stars. The differences between the radio and our position are only dependent on the refraction and orientation effects; but these should be small and therefore any differences that are greater than ∼3 times the formal error of the optical position we consider significant inconsistencies.

0138−097 has a difference in declination of 7 times the formal error. An examination of the reference stars indicates that this field has both below average measurement and catalogue errors. While the x measurement error is quite high, it is not especially so and the geometry of the QSO with respect to the CAMC stars is reasonable, see Fig. 3. A search of the literature indicates that this source is not noted for variability or structure. We are forced to conclude that this difference is either due to a large systematic error in the CAMC in that region or a difference of the optical and radio position.

0607−157 is close to a star of approximately the same magnitude at position 6:9:41.1,-15:42:42.8. In fact many of the images of this field could not be used because the seeing was such that the image of the star and the QSO blended. This contaminates the centroiding and the difference is consistent with a "pull" of the QSO image center towards the star.

1040+123 is faint, being 5.5 magnitudes fainter than the brightest CAMC star which is also faint, hence we had to manually locate this QSO as it was outside the range of the object finding defaults. Considering this, it appears that the formal error is underestimated.

1302−102 has higher than average errors in the CAMC stars, and the range of the brightest CAMC star to the QSO is very large (5.6 magnitudes) which means the signal to noise of the QSO is low. Again, perhaps the formal error here is an underestimate and the difference found is not significant.

In conclusion, we have found the positions in the frame defined by the CAMC catalogue of 12 QSOs limited only by the precision of the CAMC stars. This is the first part of the full Torino project which will cover 74 QSOs with equivalent precision. We expect therefore to eventually be able to determine the parameters of the tie from the CAMC system to the extragalactic frame using solely Torino observations. The CAMC system has been brought onto the Hipparcos system using the overlap with these results (CAMC9 1997). Therefore, apart from highlighting discrepant sources, these positions can be used to tie the optical frame to the ICRF. The current tie is dominated by a small number of radio stars (Kovalevsky et al. 1997), and the optical determination of extragalactic sources can be used to confirm and densify this link.

Acknowledgements. The authors are grateful to Drs Eichhorn and Zacharias for their comments and to Dr Mignard for a critical refereeing of the manuscript. RLS acknowledges the support of the British Royal Society and Torino University during this work.

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