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Optical identifications of reference frame benchmark radio sources

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Summary. Optical positions have been measured and finding charts verified for 84 of the sources that have been provisionally selected for establishing a positional reference frame based on extragalactic radio sources. The accuracy is ± 0.7 arcsec in each coordinate.

1 Introduction

Improvements in radio astrometry during the last 10 years have made it possible to determine positions of certain types of object to accuracies of the order of $\pm 0^s.001$ in RA and $\pm 0''.01$ in Dec. Compared with the systematic errors of fundamental optical positions, the errors in the radio positions are smaller by a factor of about 5. The radio positions are themselves fundamental, in the slightly restricted sense that the zero-point in RA is derived from optical calibrators. Apart from this, the independence of radio from optical, and the high accuracy of the former, provide a valuable method for correcting systematic errors in the latter, by intercomparing radio and optical counterparts.

Up to the present, although there has been good communication between radio and optical astrometrists, there has been no formally agreed list of what would be considered the best objects for radio and optical intercomparison. Optical astrometrists have learned to be cautious over the selection of objects because many of the objects on which they lavished careful work during the early 1970s have since had to be discarded, usually because of the discovery of radio structure under improved resolution. The need for liaison had become the more pressing with the promise of optical space astrometry during the 1980s, to give positions at the milliarcsec level of accuracy for large numbers of objects. The space measurements will need a reference frame, also of milliarcsec accuracy, to render the positions and proper motions absolute. It was against this background that IAU Commission 24 (Photographic Astrometry) set up, in 1978, a small working group under the chairmanship of Dr K. J. Johnston of the US Naval Research Laboratory, to select about 100 radio sources with optical counterparts suitable as a benchmark in establishing an inertial reference frame. The selection criteria for the sources were that there be no significant large-scale structure greater than 1 arcsec at frequencies above 1.4 GHz, the flux should exceed 1 Jy if possible, the optical image should be star-like with no companion closer than a few arcsec and no nebulosity that might affect the position measurement. The report of the working group to the Montreal Meeting of the IAU is being prepared for publication by Johnston (1979). The situation up to 1978 is reviewed in papers presented to *IAU Colloquium No. 48* 'Modern Astrometry' (Prochazka & Tucker 1978).

2 Scope of investigation

The benchmark sources fall into two distinct groups (i) extragalactic, and (ii) radio stars such as β Per that are bright enough for direct observation with optical instruments such as transit circles and astrolabes. In this paper we are concerned only with the first group. Our purpose has been to check the optical identifications in lists circulated to the working group by Johnston & Witzel (private communication).

Our results are set out in Table 1. This table must not be taken as representing any final and complete list. First, it omits sources with identifications that are already well established. Second, it includes some sources that have subsequently been rejected. These are denoted by a dash in column 2 of the table. They have been retained here to contribute to their observational history. In the same column, 'P' and 'S' denote primary and secondary status respectively. 'S' does not necessarily imply inferior quality as a benchmark; it may mean simply a lack of current knowledge. An asterisk denotes 'core list'. Such an object already posseses a substantial observational history, and will make a valuable contribution to the linking of the radio and optical reference frames. The definitions given above for the categories 'P', 'S' and 'core list' correspond to those given in the working group report.

3 The radio positions

These have been taken from Wade & Johnston (1977), Fanselow *et al.* (private communication), Elsmore & Ryle (1976) and Johnston & Witzel (private communication) as denoted in column 5. A zero-print correction has been applied to the Elsmore & Ryle RAs as advocated by Elsmore (see Prochazka & Tucker 1978, p. 93). Johnston & Witzel base their positions mainly on VLA measurements by Johnston and others.

4 Measurement and reduction

Our positions were measured from Palomar Observatory Sky Survey paper prints for fields having declinations north of $-20°$, and from ESO or SRC film prints for the remainder. This is indicated in column 6 of Table 1. The measurements were made using a Coradograph digitized x,y table. Each radio object was measured relative to six reference stars on average.

Table 1. Optical positions, radio–optical offsets and references to finding charts for 84 candidate benchmark sources

Source	Category	Optical RA (1950.0)	Optical Dec (1950.0)	Residual (Radio-Opt.) RA	Residual (Radio-Opt.) Dec	Radio Ref	Chart	Ref. for Chart
(1)	(2)	(3)	(3)	(4)	(4)	(5)	(6)	(7)
0016+731	P	$00^h16^m54^s.021$	$+73°10'50''.40$	+0''.52	+1''.20	JW	E	Here
0106+013	P	01 06 04.510	+01 19 00.85	+0''.19	+0''.21	JW	O	5
0116−219	S	01 16 32.383	−21 57 15.33	+1''.06	−2''.17	JW	B	24
0133+476	P	01 33 55.105	+47 36 13.03	+0''.05	−0''.03	JW	E	10
0150−334	S	01 50 56.994	−33 25 12.30	−0''.55	+2''.70	JW	B	19 (elongated image)
0153+744	P	01 53 04.398	+74 28 05.92	−0''.59	−0''.42	JW	E	Here
0212+735	P	02 12 49.974	+73 35 40.57	−0''.44	−0''.37	JW	E	Here
0224+671	S	02 24 41.312	+67 07 38.73	−0''.96	−0''.15	JW	E	12
0237−027	P	02 37 13.685	−02 47 32.57	+0''.37	+0''.07	JW	O	Here
0237−233	P*	02 37 52.715	−23 22 06.44	+1''.17	+0''.04	JW	E	2

Source	Category	Optical RA (1950.0)	Optical Dec (1950.0)	Residual (Radio-Opt.) RA	Residual (Radio-Opt.) Dec	Radio Ref	Chart	Ref. for Chart
(1)	(2)	(3)		(4)		(5)	(6)	(7)
0300+471	P	03 00 10.089	+47 04 33.72	+0″.32	−0″.02	JW	O	21
0332−403	P	03 32 25.068	−40 18 24.68	+1″.85	+1″.28	JW	J	25
0338−214	P	03 38 23.273	−21 29 07.77	−0″.04	+0″.27	JW	B	6
0355+508	−	03 55 44.428	+50 49 24.76	+7″.91	−4″.47	WJ	E	Empty
0402−362	P	04 02 02.502	−36 13 11.90	+1″.06	+0″.10	JW	B	11
0420+417	−	04 20 27.863	+41 43 08.59	+1″.39	−1″.62	F	E	Here
0422−380	P	04 22 56.165	−38 03 08.10	−0″.06	−0″.90	JW	B	18
0429+415	−	04 29 07.959	+41 32 10.28	−0″.62	−1″.78	ER	E	23
0438−436	P	04 38 43.217	−43 38 52.17	−0″.40	−1″.33	JW	B	17
0454+844	P*	04 54 57.398	+84 27 52.51	−0″.55	+0″.59	JW	O	Here
0454−234	−	$04^h54^m57^s.297$	$-23^\circ29'28''.95$	+0″.32	+0″.05	JW	B	24
0531+194	−	05 31 47.415	+19 25 24.62	−0″.88	+0″.14	ER	E	9
0537−441	P	05 37 21.041	−44 06 44.67	+0″.31	−0″.33	JW	B	18
0552+398	P	05 52 01.470	+39 48 21.45	−0″.70	+0″.49	JW	O	33
0605−085	−	06 05 35.984	−08 34 20.02	+0″.62	+0″.75	WJ	O	32 (NF of double)
0607−157	S	06 07 26.039	−15 42 03.78	−0″.85	+0″.38	JW	O	31 (centre of elongated image)
0615+820	P	06 15 33.163	+82 03 56.52	−0″.75	−0″.02	JW	E	Here
0636+680	P	06 36 47.436	+68 01 28.08	+1″.15	−0″.88	JW	E	16
0653+694	−	06 53 21.822	+69 24 59.67	−5″.92	−7″.67	JW	E	Empty
0707+476	−	07 07 02.713	+47 37 10.44	−1″.75	−2″.04	JW	O	16
0814+425	P	08 14 51.717	+42 32 07.42	−0″.50	+0″.26	JW	O,E	12 (OJ 425)
0828+494	P	08 28 47.874	+49 23 33.02	+0″.64	+0″.38	JW	O,E	4 (object 77b)
0836+711	−	08 36 21.431	+71 04 22.41	+0″.57	+0″.07	F	O	Here
0859+681	−	08 59 23.029	+68 09 16.67	−0″.05	−0″.97	JW	E	16
0859+470	P	08 59 40.040	+47 02 56.26	−0″.51	+0″.64	JW	O	16
0945+408	S	09 45 50.079	+40 53 43.23	+0″.01	+0″.27	JW	O	27 (4C 20.24)
0954+556	P	09 54 14.367	+55 37 16.25	−0″.23	+0″.35	JW	O	27 (4C 55.17)
0954+658	P	09 54 57.819	+65 48 15.83	+0″.25	−0″.33	JW	O	16
0959−443	S	09 59 58.760	−44 23 29.90	0″.00	−0″.10	JW	B	18 image blended
1030+415	P	10 30 07.774	+41 31 33.91	+0″.18	+0″.99	JW	O	16
1034−293	P	$10^h34^m55^s.836$	$-29^\circ18'26''.52$	−0″.21	−0″.38	JW	B	6
1104−445	P	11 04 50.399	−44 32 53.11	−0″.44	+0″.41	JW	J	25
1143−245	P	11 43 36.307	−24 30 52.55	+0″.86	−0″.15	JW	B	22 (OM-272, their S object)
1144−379	−	11 44 30.897	−37 55 31.24	−0″.51	+0″.58	F	B	30
1253−055	P*	12 53 35.851	−05 31 07.99	−0″.19	−0″.05	JW	O	34 (3C 279)
1311+678	S	13 11 43.821	+67 51 50.72	+7″.00	−8″.52	JW	O,E	Empty
1313−334	−	13 13 20.014	−33 23 09.02	+0″.29	−0″.69	F	B	30
1349−439	−	13 49 50.804	−43 57 56.12	−5″.52	+7″.99	F	B	Here (object a)
		50.194	49.21	+1″.07	+1″.08	F	B	Here (object b)
1418+546	−	14 18 06.231	+54 36 57.42	+6″.07	+0″.68	JW	O	16 (? empty)
1430−178	S	14 30 10.644	−17 48 23.56	+0″.09	−0″.54	JW	E	20
1451−375	S	14 51 18.207	−37 35 23.40	+0″.87	+0″.80	JW	Jp	18
1514+197	S	15 14 40.960	+19 43 11.03	+0″.30	−0″.23	JW	E	8
1517+204	S	15 17 50.627	+20 26 52.60	−0″.18	+0″.43	JW	O	26 (3C 318)
1519−273	P	15 19 37.287	−27 19 30.81	+0″.76	+1″.21	JW	J	20
1629+680	S	16 29 50.890	+68 03 37.88	−0″.39	+0″.82	JW	O	10
1634+628	P	16 34 00.942	+62 51 42.25	+0″.79	−0″.42	JW	E	15 (3C 343)
1637+575	−	16 37 35.477	+57 26 23.46	−0″.38	−7″.66	JW	E	Empty
1638+398	P*	16 38 48.202	+39 52 30.17	−0″.35	−0″.09	JW	O	14 (NRAO 512)
1642+690	P	16 42 17.967	+69 02 13.17	+0″.34	+0″.03	JW	E	10
1656+571	P	16 56 26.427	+57 10 25.76	+0″.43	+0″.24	JW	O	10

Source	Category	Optical RA (1950.0)	Optical Dec	Residual (Radio-Opt.) RA	Dec	Radio Ref	Chart	Ref. for Chart
(1)	(2)	(3)		(4)		(5)	(6)	(7)
1705+456	P	17h05m50s.344	+45°40'01".95	+0".80	-0".05	JW	O	10
1716+686	S	17 16 27.822	+68 39 48.00	-0".01	+0".30	JW	E	16
1726+455	P	17 26 01.194	+45 33 04.87	-1".72	+0".53	JW	O	16
1730-130	P	17 30 13.476	-13 02 45.17	+0".91	-0".76	JW	O	15 (NRAO 530)
1738+477	-	17 38 36.284	+47 39 29.26	+0".26	-0".61	F	E	16
1739+522	S	17 39 29.002	+52 13 10.35	-0".02	+0".05	JW	O	16
1741-038	P	17 41 20.623	-03 48 49.23	-0".03	+0".22	JW	E	29
1749+701	P	17 49 03.423	+70 06 39.51	-0".22	-0".01	JW	O	3
1821+107	S	18 21 41.673	+10 42 43.80	-0".34	+0".20	JW	E	12
1823+568	S	18 23 14.789	+56 49 18.21	+1".65	-0".21	JW	E	16
1849+670	S	18 49 16.494	+67 02 09.01	-0".08	-1".21	JW	O	16
1901+319	S	19 01 02.256	+31 55 15.02	+0".73	-1".21	JW	E	28 (3C 395 SP component)
1921-293	P	19 21 42.261	-29 20 26.66	-1".06	+1".76	JW	J	22 (OV-236)
1928+738	P*	19 28 49.379	+73 51 44.29	-0".16	+0".41	JW	O	Here
1933-400	S	19 33 51.122	-40 04 48.18	-0".14	+1".08	JW	B	25
1954+513	P	19 54 22.524	+51 23 46.67	-0".79	-0".07	JW	E	8 (OV 591)
2005+403	P	20 05 59.561	+40 21 02.74	-0".01	+0".06	JW	O	1
2008-159	P	20 08 25.864	-15 55 38.81	+0".52	+1".21	JW	E	20
2021+614	-	20 21 13.301	+61 27 17.35	-0".14	+0".79	JW	E	22 (OW 637)
2223-052	P	22 23 11.139	-05 12 18.00	-0".88	+0".20	JW	O	34 (3C 446)
2227-399	S	22h27m44s.999	-39°58'17".64	-0".10	+0".74	JW	B	19
2318+049	-	23 18 12.151	+04 57 23.36	-0".31	-0".06	JW	O	7
2331-240	S	23 31 17.943	-24 00 15.69	-1".27	+2".39	JW	B	22 (OZ-252, optical structure)
2352+495	P	23 52 37.724	+49 33 26.69	+0".64	+0".07	JW	E	13

Column 2 P: primary source; S: secondary; *: core list; -: discarded. See Section 2.

Column 5 Source of radio position. See Section 3.

Column 6 Chart measured. O,E: Palomar Sky Survey O or E chart; B: ESO B film; J: SRC IIIa-J film; Jp: provisional J.

Column 7 References:

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Positions for these were obtained from AGK 3 for declinations north of $-2°$ and from SAO for the remainder. The reference star positions were corrected for proper motion to the epoch of the photograph using the data in the catalogues. In general we measured only one print for each field, and that only once, although better results would have been obtained, at the cost of time, by a repeated measurement with the print rotated through 180°. This is discussed below in Section 8. Our objective being to filter out the obviously unsuitable candidates, we decided the faster procedure to be the more appropriate.

In our discussion we will assume that the radio positions are considerably more accurate than the optical, so that in forming the differences between radio and optical positions the errors are almost entirely of optical origin (Table 2).

5 Finding charts

In searching the literature we found many charts that were either difficult to use or completely wrong. In Table 1, last column, we give a reference to what we consider to be an adequate chart. For the fields for which our search was unsuccessful, we give our own in Plate 1. Dr A. Witzel has kindly sent us his own unpublished charts, enabling us to verify those given in Plate 1.

6 Discussion

Five of the fields in Table 1 are marked 'empty'. This denotes that the residual (i.e. the difference between the radio and optical positions) exceeds 3 arcsec in either coordinate.

Histograms illustrating the distribution of residuals in RA and Dec for the remaining 79 sources are shown in Fig. 1(a) and (b).

In our analysis we have divided the sources into two groups: (1) those having Dec > 0°. These were measured from POSS charts using reference positions from AGK3. The standard deviation σ of a single residual was found to be 0.7 arcsec in both RA and Dec; (2) those having Dec < 0°. Three-quarters were measured from ESO and SRC film prints, the rest from POSS, and all had reference positions taken from SAO. In RA, σ was found to be 0.7 arcsec as for group 1, but in Dec it was 1.0 arcsec.

In RA therefore the two groups are not distinguishable as regards σ, allowing the use of a single Gaussian curve for $\sigma = 0.7$ arcsec for Fig. 1(a). The number of residuals in RA that lie outside the range $\pm 2\sigma$ is 4, in agreement with the number to be expected for the 79 sources for a normal distribution, namely 3.6.

In Dec on the other hand the two groups are statistically distinct as shown by their significantly different values of σ, 0.7 and 1.0 arcsec ($P = 0.01$). In the first group the number of residuals outside the range $\pm 2\sigma$ is 3 where 2.1 would be expected, but in the second the number is 3 where only 1.4 would be expected. On examining these last three objects we found physical reasons for rejecting two of them, 0150 − 334 and 2331 − 240. These reasons are given in Section 7. It might seem at first sight that the third, 0116 − 219, ought to be retained since we can advance no physical reasons for rejecting it, and a single residual outside the range $\pm 2\sigma$ is consistent with a normal distribution. But if this source also is rejected and the new value of σ calculated, we find its residual is now outside the range $\pm 3\sigma$, justifying its rejection. The new σ has the same value in each coordinate, 0.7 arcsec: its being now the same as for the sources in group 1 (Dec > 0°) justifies our using it as discriminant in rejecting 0116–219 at the 3σ level.

Now that the apparent difference between the two groups as regards σ has disappeared, a single Gaussian curve is appropriate for both distributions in Fig. 1. The mean residual and its standard error in each coordinate for each group are shown in Table 2.

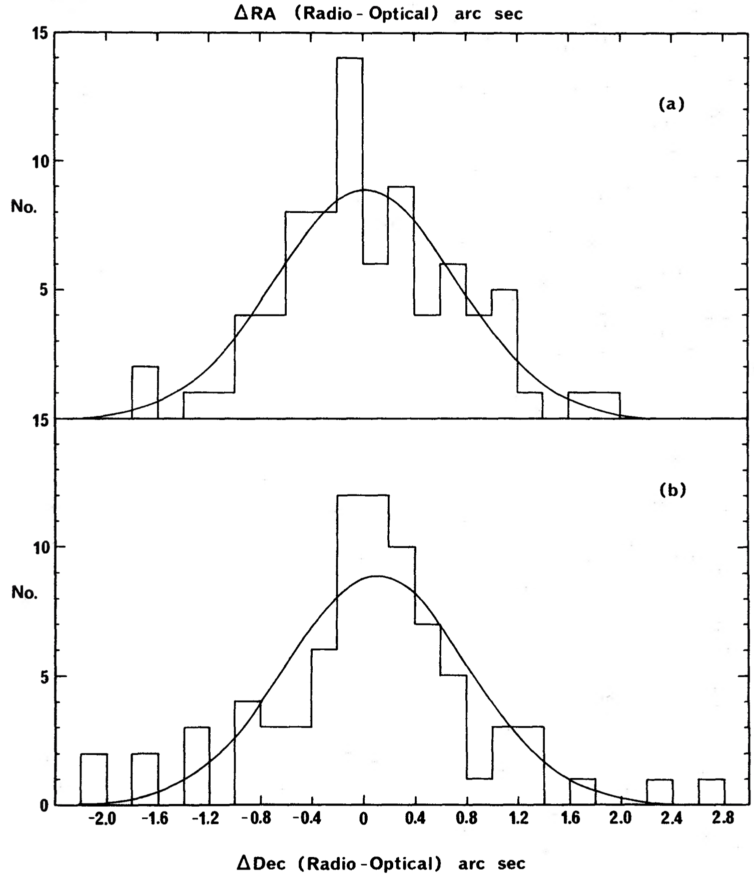

Figure 1. Distribution of residuals (differences between radio and optical positions) in Table 1: (a) in RA; (b) in Dec. Ordinates: number of residuals in 0.2 arcsec intervals; abscissae: residuals in arcsec. Gaussian curves for $\sigma = 0.7$ arcsec are superimposed.

Table 2. Mean residuals and standard errors of means for various comparisons. The numbers of sources are in the last column. Groups 1 and 2 compare the radio with our measured positions based on AGK3 and SAO respectively. Group 3 compares radio with optical positions measured by Walter & West (1979) who used the Perth 70 Catalogue. Group 4 gives a direct comparison between Walter & West and ourselves, and group 3–2 the same but computed from groups 2 and 3.

Group		RA	Dec	*n*
1	Radio-here ($\delta > 0°$)	$-0^s.016 \pm 0^s.016$ $-0''.04 \pm 0''.10$	$-0''.07 \pm 0''.10$	47
2	Radio-here ($\delta < 0°$)	$+0^s.017 \pm 0^s.010$ $+0''.21 \pm 0''.13$	$+0''.24 \pm 0''.14$	29
3	Radio-WW ($\delta < 0°$)	$-0^s.024 \pm 0^s.008$ $-0''.32 \pm 0''.11$	$+0''.09 \pm 0''.09$	19
4	Here-WW ($\delta < 0°$)	$-0^s.043 \pm 0^s.023$ $-0''.54 \pm 0''.28$	$+0''.20 \pm 0''.25$	11
3–2	Here-WW	$-0^s.041 \pm 0^s.013$ $-0''.53 \pm 0''.17$	$-0''.15 \pm 0''.17$	29, 19

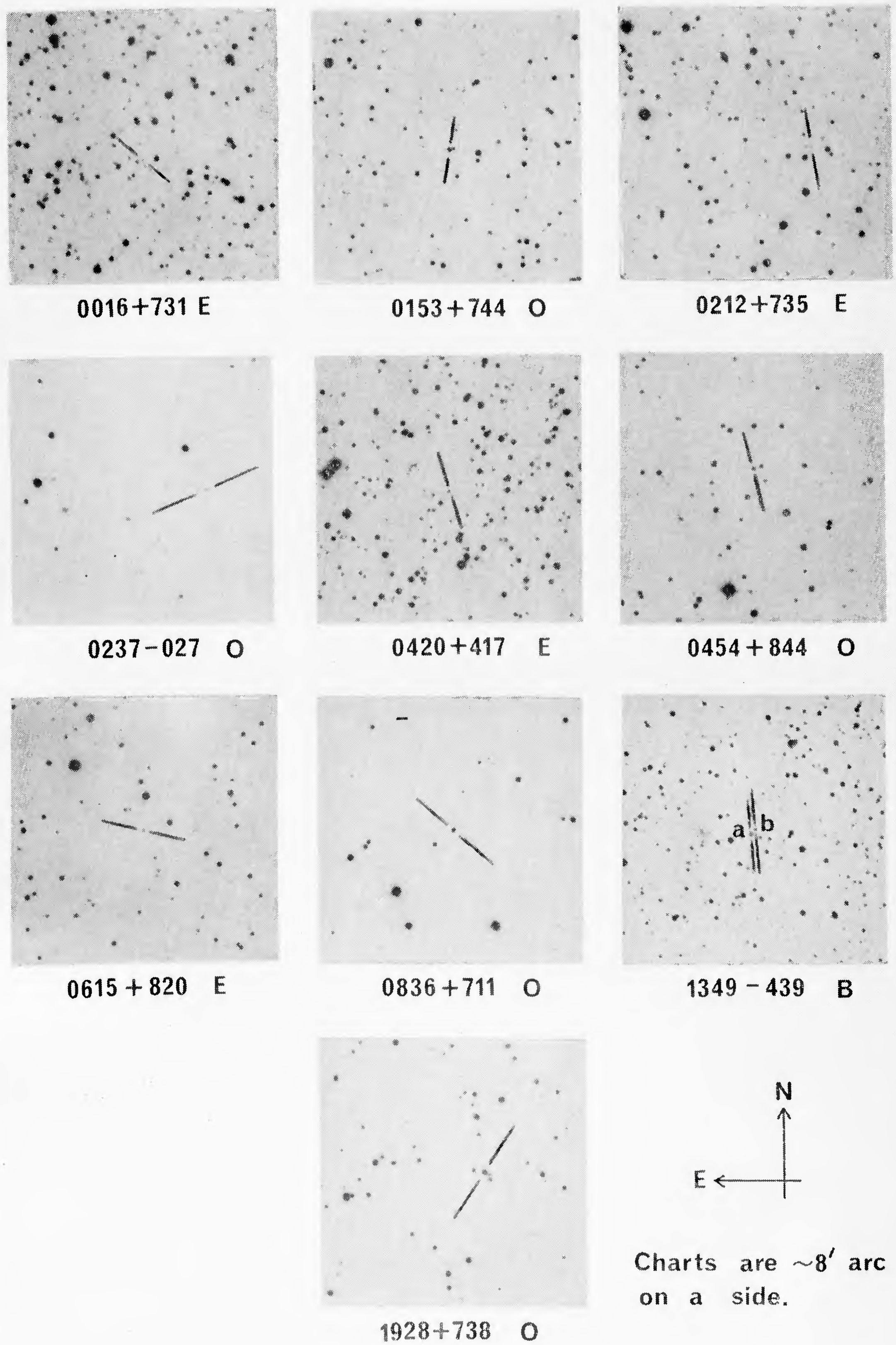

Plate 1. Finding charts for the unpublished fields in Table 1. That for 1349–439 is reproduced from the ESO B Survey by permission of ESO. The remainder are copyright by the National Geographic Society – Palomar Observatory Sky Survey and reproduced by permission from the Hale Observatories.

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7 Conclusion

The three negative Dec sources rejected in Section 6 are:

0116–219 a 19.0 mag QSO. Possibly a misidentification on account of the residual in Dec exceeding 3σ.

0150 – 334 a 16.5 mag QSO with $z = 0.610$. The identification therefore seems secure, but the image on ESO B is slightly elongated.

2331 – 240 a 17 mag galaxy having a fuzzy image on ESO B. According to Dr R. S. Harrington (private communication) the optical image shows structure.

These three, and the five empty fields in Table 1, are unsuitable as benchmark objects. Statistically the remainder may be accepted as radio/optical counterparts with normally distributed residuals ($\sigma = 0.7$ arcsec). Harrington (private communication) has, however, also provided the following information:

0537 – 441 optical variable (4 mag);
0959 – 443 image blend with bright star;
1143 – 245 optical structure, blending;
1629 + 680 optical structure;
1726 + 455 close companion.

8 Comparison with Walter & West

Walter & West (1979) gave measured positions for 24 southern sources, 14 of which are included here. Their measurements were made from glass copies of the ESO Survey using as reference the Perth 70 Catalogue; therefore they are independent of ours in respect of measurement and reduction, although probably most of the original ESO plates are common. A comparison of the two sets should therefore be useful.

We have excluded 0605 – 085, 0607 – 157 and 1349 – 439 for which Walter & West obtained large differences from the radio positions. For the remaining 11 objects we differ from them by the amounts shown in Table 2, group 4. In RA we are seen to differ significantly in zero-point, by $-0^s.043 \pm 0^s.023$. In Dec, on the other hand, there is no significant difference.

Walter & West point out in their paper their difference in zero-point in RA from radio positions measured by Fanselow *et al.* We give their figures here in Table 2, group 3, and the similarity with group 4 is suggestive, but not conclusive since only 11 sources are included in the latter group. We can, however, improve our estimate for group 4 by forming the difference between groups 3 and 2, both of which contain more sources. The result is given at the end of the table, group 3–2, and confirms the zero-point difference in group 4. Hence a significant difference has been established between us and Walter & West in zero-point in RA.

Walter & West discuss their difference from Fanselow *et al.* without reaching any final conclusion. One suggestion they advance tentatively is that the RAs of Fanselow *et al.* are in error with respect to FK4 by $-0^s.024$. But were this to be the case the effect on our own zero-point would be considerable: it would mean our error would have to be as much as $-0^s.042$ (in angular measure, -0.53 arcsec) to satisfy groups 2, 4 and 3–2 simultaneously. We are reluctant to accept this: it would be surprising if our measuring errors, combined with the errors in the reference positions from SAO, came to such a large amount and yet when compared with the radio gave the much smaller residual in group 2.

In fact we can get very good agreement for all the groups in Table 2 (apart from the first, which is not relevant here since we are concerned only with fields having Dec $< 0^\circ$) by postulating zero-point errors of $0^s.000$, $-0^s.017$ and $+0^s.024$ for radio, us and Walter & West respectively. Unfortunately this good agreement must be fortuitous in view of the standard errors of the data, and to pursue this line of thought, attractive though it might seem, would leave us open to the charge of overdiscussing the results. Undoubtedly zero-point errors exist, in the radio data as discussed by Walter & West (1979), and in both sets of optical data because of measuring errors and errors in Perth 70 and SAO, but we lack the information to disentangle them properly. The most we can say is that systematic errors certainly exist between the surveys.

A remark about the optical measurements. Both we and Walter & West omitted to reverse the fields during measurement, so opening the way to systematic differences between the source and the much brighter reference stars. This is due not only to personal effects but also to the use of different parts of the measuring graticule or cross-wire depending on the size of the photographic image. This error can be eliminated by reversing the field.

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