ACCURATE RIGHT ASCENSIONS OF SELECTED SOUTHERN RADIO SOURCES

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Summary

Right ascensions of selected radio sources were measured using the east–west arm of the Molonglo radio telescope. A calibration curve was obtained by surveying the aerial structure and site, and by observing radio sources with accurately known positions. Right ascensions are given for 58 sources stronger than 5 f.u. at 408 MHz and in the declination range $+19°$ to $-90°$. The standard errors are typically $2''$.

I. Introduction

The Molonglo radio telescope (Mills *et al.* 1963) is a meridian transit instrument for which observations are restricted to declinations between $+19°$ and $-90°$. This paper describes some measurements with the first section of the instrument to be completed, the east–west arm operating at the principal frequency of 408 MHz. Used as a total-power device it has a fan-shaped beam with half-power widths of approximately $1'\cdot5$ east–west and $4°\cdot2$ north–south corresponding in beam area to a circular beam of diameter $19'\cdot5$. The array is extremely stable both mechanically and electrically due to (1) its construction from many relatively small elements independently mounted close to the ground, (2) the use of a constant phase local oscillator system (Little, Hunstead, and Calhoun 1966), and (3) the use of components with identical temperature properties in parallel situations. A long-term pointing accuracy of several seconds of arc was expected and measurements and reductions were intended to include all effects of $1''$ or greater.

At the time of the observations, the aperture distribution had been adjusted approximately for equal amplitude and equal phase; corresponding to a theoretical aerial pattern of the form $\{(\sin x)/x\}^2$ and a half-power beamwidth of $1'\cdot43$. The measured pattern had a symmetric main beam, a half-power beamwidth of $1'\cdot46$, and maximum side lobes of 8%. In order to overcome baseline drifts produced by instabilities in the total-power receiver, many sources were also observed by using the east arm and the west arm as the two elements of a phase-switched interferometer and using the receiver that had been built for the complete cross. A quarter wavelength cable was added to one arm, producing an aerial pattern of the form $\{(\sin\frac{1}{2}x)/\frac{1}{2}x\}^2\sin x$, that is, sinusoidal oscillations of period $3'\cdot24$ within an envelope of half-power beamwidth $2'\cdot88$.

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II. Observations

The primary objective of the observations was the pointing calibration of the instrument. Measurements were restricted to catalogued sources stronger than 5 f.u.* at 408 MHz, with diameters (if known) less than 1′ and galactic latitudes greater than 15°. North of −50° these included only a small number of sources, most of which had been observed by the method of lunar occultations (Hazard, Mackey, and Shimmins 1963) or had been reliably identified with quasi-stellar objects on the basis of positional coincidences and characteristically large redshifts (see Section V and Burbridge *et al.* 1966). South of declination −50° they included all sources for which identifications had been suggested (Bolton, Gardner, and Mackey 1964; Price and Milne 1965; Westerlund and Smith 1966) and which satisfied the conditions above. In a search for new identifications, many unidentified sources south of declination −50° (Bolton, Gardner, and Mackey 1964; Price and Milne 1965) were also observed.

Total-power transit measurements were made in May, June, and July 1965 and interferometer measurements were made in September 1965. Each observation extended at least 10 beamwidths on either side of transit. Transit observations were also made 2° north and 2° south of most sources in order to investigate confusion in the north–south direction.

Records were obtained on a chart recorder having a paper speed of 80 mm/min. Local sidereal time marks correct to $0^{s}\cdot03$ were superimposed on the records at intervals of 30^{s} and the paper speed was sufficiently uniform to enable times to be measured to the nearest $0^{s}\cdot1$. In order to calibrate the local sidereal clock relative to coordinated radio time signals with an accuracy of better than $0^{s}\cdot1$, it was necessary to include corrections for the travel times from the stations to the site, and for the differences between UT2 and UTC.

III. Analysis of Observations

(a) *Right Ascension*

On each chart record the transit time of the source through the beam was measured to the nearest $0^{s}\cdot1$ by averaging the midpoints of the observed distribution at approximately 30, 50, 70, and 90% of the peak amplitude. In the several cases where asymmetry was detected, the extrapolated position of the peak was used or, if confusion by a strong neighbouring source was evident, an attempt was made to remove its effects. For the observations with the phase-switched system, the transit time was measured by averaging the axes of symmetry of the two major lobes.

The apparent right ascension was obtained from the transit time by applying corrections for

(1) tilt of the aerial (see Section V),

(2) clock error,

(3) time constant of receiver and recorder, and

(4) pointing calibration, including change in collimation error.

* 1 flux unit = 10^{-26} W m^{-2} Hz^{-1}.

The effective *RC* time constant of the receiver–recorder system was measured as $0^{s}\cdot 80 \pm 0^{s}\cdot 05$ (standard error) by rapidly connecting the input from the aerial to the receiver and measuring the response on the chart recorder. It was assumed that transit times were delayed by this amount. By convolving time-constant responses with the aerial pattern, it can be shown that these corrections are slightly over-estimated, by as much as $0^{s}\cdot 06$ near the equator.

Owing to the omission of inoperative sections of the array, and the inaccuracy of the quarter wavelength cable used for the interferometer measurements, the collimation error changed between observing periods. The calibration curve was derived relative to the aerial system used for the June and July observations. Systematic corrections of $9''\cdot 0 \pm 1''\cdot 5$ (standard error) and $19''\cdot 5 \pm 0''\cdot 4$ were derived for the May and September observations respectively by repeating measurements of the same sources.

The apparent right ascension was reduced to the mean equator and equinox of 1950·0 using the Besselian Day Numbers and the precessional constants M and N as described in the Astronomical Ephemeris. The reductions include errors of as much as $1''$ due to the combined effects of

(1) the omission of diurnal aberration (maximum error $0''\cdot 3$),

(2) reducing observations for periods as long as 48 hr without changing the Day Numbers ($0''\cdot 4$), and

(3) the use of the precessional formulae involving M and N rather than the rigorous results given in the Explanatory Supplement to the Astronomical Ephemeris ($0''\cdot 12 \tan\delta$, where δ is the declination of the source).

At the time of analysis it was anticipated that an accuracy of $1''$ would be adequate. However, the measurements proved to be more accurate than expected, and the maximum errors in reduction are comparable with the random experimental errors.

(*b*) *Declination*

Declination could be derived from the deflections a source produced on drift scans at different elevations. The limiting accuracy, as determined by the uncertainty in setting the elevation and the day-to-day variations in the gains of the preamplifiers, was approximately 20 min of arc.

(*c*) *Equivalent Width*

Equivalent width θ, as defined by $\theta^2 = W_1^2 - W_2^2$, was calculated for each source; W_1 is the width of the observed record and W_2 is the effective width of the beam, both measured between half-power points. By combining measurements of narrow sources at different declinations, W_2 was found to be $1'\cdot 46 + 0'\cdot 07 \cos^2\delta$, where the term in $\cos^2\delta$ allows for the broadening caused by the *RC* time constant.

(*d*) *Flux Density*

Flux density was measured by the product of peak amplitude and equivalent width. Calibration was achieved by comparing flux densities recorded at Molonglo with those measured at Parkes at 408 MHz. Owing to differences in confusion errors for the two instruments, uncertainties in the Parkes flux densities, and possible temperature-dependent variations in the gain of the Molonglo system, the calibration is rather inaccurate.

IV. Errors in the Measurements of Right Ascension

The uncertainty in the right ascension derived for each source can be expressed as a standard error σ given by

$$\sigma^2 = \sigma_c^2 + n^{-1}(\sigma_n^2 + \sigma_t^2 + \sigma_r^2),$$

where n is the number of observations and the subscripted quantities are the component standard errors (for single measurements) due to confusion (σ_c), noise (σ_n), timing (σ_t), and refraction, reduction, and instrumental effects (σ_r). Systematic errors due to the uncertainties in the calibration curve and in the corrections for the time constant are not included. For convenience, all errors will be expressed as pointing errors in seconds of arc.

For the particular receiving and recording systems used, both total-power and phase-switched, the theoretical r.m.s. fluctuations due to random noise were $0 \cdot 13$ f.u. This level, which was attained only for the phase-switched measurements, corresponded to $\sigma_n = 3'' \cdot 1/S$, where S is the source intensity in flux units. For the total-power records, baseline instabilities increased σ_n to $16''/S$.

By superimposing source distributions on random sections of low noise total-power records, σ_c was found to be less than $10''/S$. This maximum value of $10''/S$ has been assumed for all error calculations. For phase-switched observations it is assumed that the decrease in random noise compensates approximately for the increased confusion errors.

Referring to Section III, the r.m.s. errors due to timing and reduction were expected to be about $0'' \cdot 75 \cos \delta$ and $0'' \cdot 5$ respectively. Since all measurements are of right ascension and are made on the meridian, errors caused by refraction in the spherically symmetric components of the atmosphere and ionosphere are zero. However, some refraction is to be expected from large-scale fluctuations and east–west gradients in the electron distribution of the ionosphere, particularly at sunrise and sunset. For meridian measurements at $19 \cdot 7$ MHz, Komesaroff (1960) observed maximum east–west refraction of 1°. Assuming that refraction is proportional to the square of the wavelength, this value corresponds to 8″ at 408 MHz.

Errors due to the combined effects of timing, reduction, refraction, and instrumental variations were found by comparing repeated measurements of the same sources. Confusion errors produced no variations and noise errors were reduced to a negligible level by confining attention to phase-switched measurements and to total-power measurements of strong sources. The errors were dependent on declination and were compatible with $\sigma_t = 1'' \cos \delta$ and $\sigma_r = 1''$. This low value for σ_r implies that the pointing of the instrument is remarkably stable over periods of weeks and that ionospheric refraction is considerably less than expected. A search for systematic refraction near sunset and sunrise showed that the effect was less than 1″.

V. Pointing Calibration

It was intended to determine the pointing calibration of the instrument by two independent methods:

(*a*) *Absolute calibration*, which consists of measuring the position and orientation of the aerial structure on the surface of the Earth, and also determining the relationship of the aerial beam to the physical structure (by measuring the phase distribution along the aperture), and

(*b*) *Relative calibration*, which consists of measuring the times of transit of radio sources whose positions are already accurately known.

An accuracy of 1″ was aimed for.

The absolute calibration was completed except for the measurement of the phase distribution. The relative calibration was completed but, owing to the small number of suitable calibration sources in the southern skies, was not sufficiently reliable. The final calibration curve was obtained by using observations of northern radio sources to provide the missing parameter in the absolute calibration. It was then found that the relative calibration curve was in fact substantially correct.

(*a*) *Absolute Calibration*

An ideal meridian transit instrument can be considered as one in which the aerial beam is restricted to the local astronomical meridian, i.e. the plane defined by two lines through the electrical centre of the instrument, the direction of gravity, and the direction to the south celestial pole. Such is the case if the instrument is an array of identical elements situated along a horizontal east–west line and the electrical paths from the elements to the receiver are equal. If local apparent sidereal time is calculated with respect to the astronomical longitude of the electrical centre of the instrument, the right ascension of a source is then given by the local apparent sidereal time at which the source transits the beam.

The east–west arm of the Molonglo radio-telescope was erected so as to approximate to these conditions, except that, in order to reduce the cost of foundations, it was inclined so as to better follow the surface of the Earth. The nominal slope was 11′ 51″·1 to the west, causing sources to transit late. (It is noted that in construction it was necessary to allow for the curvature of the Earth over the dimensions of the instrument.) The corresponding error in transit time was computed by rigorously solving the appropriate spherical triangle—the usual small-angle approximations were inadequate for such a large error in level. Although only preliminary electrical adjustments had been made to the array at the time of the observations, it was estimated that the mean phase gradient was less than 0·1 wavelengths in 2130 wavelengths, corresponding to a maximum collimation error of 10″.

The east–west pointing error of the telescope, in the sense that the beam points west of its assumed direction thus causing sources to transit late, can be written as

$$l\cos\delta + a\sin(\phi-\delta) + t\cos(\phi-\delta) + c\,,$$

where l is the angle by which the assumed longitude is east of the true longitude, a is the error in the mean astronomical azimuth (which is measured positively from north to east), t is the error in the mean level (a downward slope to the west is positive), c is the collimation error (a deflection of the beam to the west is positive), ϕ is the latitude of the instrument, δ is the declination, and l, a, t, and c are all measured in seconds of arc.

The astronomical coordinates of the electrical centre of the instrument were measured relative to FK4 stars as

$$\text{E. } 149^\circ 25' 25''\cdot 6 \pm 0''\cdot 3, \qquad \text{S. } 35^\circ 22' 19''\cdot 0 \pm 0''\cdot 2$$

and the telescope errors were found to be

$$l = 1''\cdot 8 \pm 0''\cdot 3, \qquad a = 3''\cdot 9 \pm 1''\cdot 5 \qquad \text{and} \qquad t = 0''\cdot 4 \pm 0''\cdot 3,$$

where all errors are standard errors. It is noted that an angle of 1″ corresponds to a displacement of 0·31 in. at a distance of 1 mile, the length of the east–west arm.

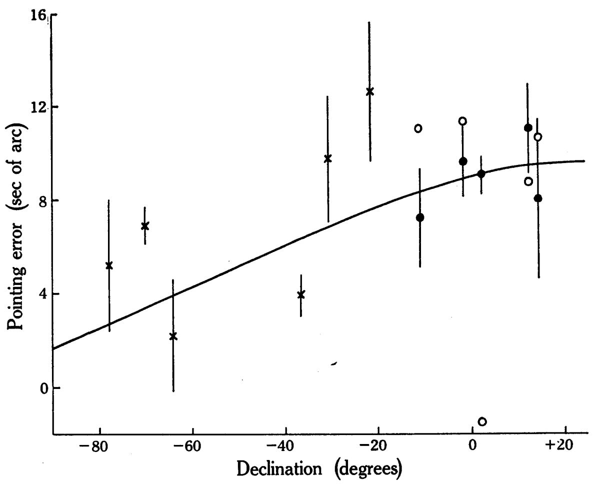

Fig. 1.—Adopted calibration curve and points of observed right ascension minus calibration right ascension expressed as pointing errors in seconds of arc and plotted as functions of declination. A positive error corresponds to the beam pointing west of its assumed position. The points are based on occultation positions (●) and optical positions (x). Also shown are the points obtained for the occultation sources by using the corresponding optical positions (o). Vertical bars indicate standard errors.

The error c was not measured directly. A value of 4″·6 was chosen so as to make the absolute calibration curve pass through that part of the relative calibration curve defined by the five occultation sources (see Section V (b)). The final calibration curve based on these values of l, a, t, and c is shown in Figure 1. It is estimated that the standard error of this curve is 0″·7 near the equator, increasing gradually to 1″·5 near the south celestial pole.

For transit instruments, relationships between the telescope errors can be obtained by observing the same sources at both upper and lower culmination. Such results could not be obtained with the present instrument as it could not be pointed more than 1° below the south celestial pole.

(b) *Relative Calibration*

Sources suitable for relative calibration were carefully selected so as to obtain a small number of accurate calibration points rather than a large number of less accurate ones. Since the intensity distribution across a radio source can vary with frequency, as in the case of 3C 273 (Hazard, Mackey, and Shimmins 1963), the sources of highest quality for relative calibration are those whose diameters are small and whose positions have been measured at 408 MHz. Some use can also be made of positions measured optically or at other radio frequencies, providing the overall dimensions of the source are sufficiently small. Observations were restricted to sources having radio diameters less than 30″ (as detected by nonbroadening of the Molonglo beam), galactic latitudes greater than 15°, and flux densities greater than 5 f.u. at 408 MHz (so that confusion errors were generally less than 3″) and whose positions had been measured with an accuracy of 1″. The diameter restriction ensured that the aerial response was symmetric and the measured position was that of the centroid of radio emission at 408 MHz.

TABLE 1

ADOPTED POSITIONS OF CALIBRATION SOURCES

Catalogue No.	Position (1950·0) R.A. h	m	s	Dec. °	′	″	S. Error ″	Ref.*	S_{408} (f.u.)	Nature of Position
Occultation Positions										
3C 15	00	34	30·63	−01	25	39·6	0·5	(1)	10	Centroid at 408 MHz
3C 212	08	55	55·8	+14	21	23	2·0	(2)	7	Centroid at 237 MHz
3C 245	10	40	5·95	+12	19	16·0	0·5	(1)	8	Centroid at 408 MHz
3C 273	12	26	32·61	+02	19	33·1	0·5	(1)	59	Centroid at 408 MHz
MSH 14−*121*	14	53	12·48	−10	56	51	1·0	(1)	9	Centroid at 408 MHz
Optical Positions										
MSH 05−*36*	05	21	13·03	−36	30	15·8	0·5	(3)	32	15^{m} N galaxy
P 1327−21	13	27	23·2	−21	36	34	1·0	(4)	5	$16^{m}\cdot5$ QSO
P 1655−77	16	55	12·49	−77	37	33·0	0·5	(5)	5	$16^{m}\cdot5$ E0 galaxy
P 1934−63	19	34	47·57	−63	49	37·7	0·5	(3)	6	18^{m} N galaxy?
MSH 21−*34*	21	15	11·1	−30	31	50	1·0	(4)	6	$16^{m}\cdot7$ QSO
MSH 21−*64*A	21	52	57·80	−69	55	40·2	0·5	(5)	63	14^{m} E3 galaxy

* References to positions are from:

(1) Reanalysis of occultation records of Hazard, Mackey, and Shimmins (1963),

(2) Hazard (1962),

(3) Remeasurement of photographic plates,

(4) Ekers and Bolton (1965),

(5) Westerlund and Smith (1966).

The adopted calibration positions and their standard errors are given in Table 1. North of declination −20° they include only radio positions that have been measured by the method of lunar occultations. South of declination −20° optical positions are given for those objects that are considered most reliably identified with radio sources. Spectroscopic measurements by Burbridge and Kinman (1966) and Westerlund and Stokes (1966) confirm the identifications for P 1327−21 and MSH 05−*36*, while Ekers and Bolton (1965) find MSH 21−*34* to have UBV colours characteristic of a quasi-stellar object. The other three positions are for interesting objects located close to accurate Parkes radio positions (Shimmins, Clarke, and

TABLE 2

RADIO SOURCE DATA

(1)	(2)	(3)	(4)	(5)		(6)	(7)	(8)	(9)
Catalogue Number MSH	3C	Parkes	R.A. (1950·0) h m s	R.M.S. Error in R.A. s	″	No. Obs.	S_{408} (f.u.)	EW Equiv. Width	Remarks*
			(a) Declinations North of −20°						
	9	0017+15	00 17 49·9	0·14	2·1	2	8	< 40″	
	15	0034−01	00 34 30·65	0·09	1·4	6	10	< 30″	
	47	0133+20	01 33 40·05	0·17	2·4	2	—	35″	1°·5 beyond N. dec. limit
03+0*8*	93	0340+04	03 40 51·6	0·14	2·1	2	8	< 1′	
	208	0850+14	08 50 23·2	0·17	2·5	2	8	< 40″	
	212	0855+14	08 55 55·7	0·19	2·8	2	7	< 40″	
	228	0947+14	09 47 28·0	0·13	1·9	2	9	< 40″	
	245	1040+12	10 40 06·1	0·12	1·8	6	8	< 30″	
12+0*8*	273	1226+02	12 26 32·60	0·04	0·6	10	59	< 20″	
12−0*20*	279	1253−05	12 53 35·75	0·08	1·2	6	12	< 30″	Scint. 18° from Sun
13−0*11*		1335−06	13 35 31·2	0·11	1·7	6	8	< 30″	Conf.
14−1*21*		1453−10	14 53 12·3	0·13	1·9	5	9	< 40″	
19+0*10*	403	1949+02	19 49 44·1	0·13	2·0	1	14	1′·9	
Cygnus A	405		19 57 44·8	0·24	2·7	4	—	2′·2	Obs. in side lobes, posn. of centroid given[(a)]
22−0*10*	446	2223−05	22 23 10·85	0·10	1·4	4	11	< 30″	
CTA 102		2230+11	22 30 08·0	0·12	1·8	4	8	< 40″	Conf.
			(b) Declinations South of −20°						
00−5*1*		0003−56	00 03 25·8	0·6	4·9	1	4	< 1′	Conf. by 1·5 f.u. source 2′ to W.
		0349−88	03 52 08	10·2	4·5	2	4	1′	1·5 f.u. source 4′ to E.[(b)]
04−6*2*		0408−65	04 07 57·7	0·17	1·0	2	45	< 30″	MSH 15″ EW
04−7*1*		0410−75	04 09 58·5	0·19	0·7	6	31	< 20″	MSH 20″ EW
04−6*3*		0420−62	04 20 18·3	0·21	1·5	4	9	< 30″	MSH 20″ EW
04−6*4*		0429−61	04 29 34·7	0·5	3·9	1	5	1′·4	
05−3*6*		0521−36	05 21 12·8	0·06	0·7	9	32	25″	MSH 20″ EW
06−5*5*		0625−53	06 25 19·0	0·12	1·1	2	20	50″	MSH 20″ EW[(c)]
			06 25 46·4	0·4	3·1	2	10	1′·2	Not catalogued
		0744−67	07 43 21·3	0·4	2·6	1	8	40″	
08−7*1*		0842−75	08 42 10·4	0·4	1·5	2	12	< 50″	MSH 20″ EW
		0905−68	09 06 14·7	0·6	3·3	1	6	< 1′	
		0943−76	09 43 22·3	1·1	3·9	1	5	< 1′	2 f.u. source 5′ to E.
11−6*4*		1136−67	11 36 06·9	0·6	3·3	1	6	< 1′	
11−6*6*		1151−69	11 52 03·5	0·8	4·4	1	—	~1′	Source ⩾1 f.u. 4′ to W.
		1327−21	13 27 23·55	0·20	2·8	3	5	< 30″	
		1547−79	15 47 38·7	0·5	1·4	5	11	< 40″	Spectral index 0·7, sep. 27′
		1549−79	15 49 26·7	0·6	1·7	5	9	< 40″	Spectral index 0·3
		1602−63	16 01 40	0·6	4·3	1	9	2′·3	EW sep. 5′·9, each comp. ext. towards centre
			16 02 33	0·5	3·5	2	8	1′·5	
		1610−77	16 10 51·3	0·9	2·9	4	5	< 40″	
		1637−77	16 37 03·1	0·4	1·3	4	15	1′·5	
		1655−77	16 55 13·3	0·9	2·8	5	5	< 1′	
		1716−80	17 16 36·0	0·9	2·4	5	6	< 1′	
		1733−56	17 33 09·5	0·3	2·5	3	7	40″	EW sep. 2′·4
			17 33 27·8	0·19	1·6	3	13	< 30″	
		1737−60	17 37 27·6	0·3	2·1	4	8	50″	
17−5*1*		1754−59	17 54 37·95	0·17	1·3	6	12	< 20″	
18−6*1*		1814−63	18 14 46·0	0·11	0·7	6	32	< 25″	Possibly 20″ EW; MSH 20″ EW[(d)]
		—	18 17 26	—	—	1	~10	< 40″	Not catalogued
19−6*1*		1922−62	19 22 52·2	0·5	3·1	2	6	1′·2	
		1934−63	19 34 47·3	0·4	2·3	4	6	< 30″	
19−5*7*		1954−55	19 54 18·5	0·16	1·4	3	16	0′·9	
20−5*2*		2006−56	—	—	—	4	—	> 3′	Possibly 2 comps. sep. 10′ EW
20−5*4*		2014−55	—	—	—	3	—	> 3′	Not detected
20−5*5*		2020−57	20 20 21·7	0·21	1·7	4	9	< 40″	Conf., MSH 15″ EW

TABLE 2 (*Continued*)

(1) Catalogue Number MSH	(2) 3C	(3) Parkes	(4) R.A. (1950·0) h m s	(5) R.M.S. Error in R.A. s	(5) ″	(6) No. Obs.	(7) S_{408} (f.u.)	(8) EW Equiv. Width	(9) Remarks*
20−*71*		2028−73	20 28 21·8	0·7	3·0	3	5	1′·5	Ext. late
20−*61*		2041−60	20 41 17·7	0·21	1·6	4	12	<40″	Conf., MSH 15″ EW
20−*57*		2048−57	20 48 12·1	0·5	3·7	3	6	1′·1	Conf.(e)
21−*34*		2115−30	21 15 11·3	0·23	2·5	4	6	<30″	
		2141−81	21 40 34·0	0·7	1·6	4	9	<50″	
21−*64*		2152−69	21 52 58·5	0·11	0·6	6	63	35″	EW sep. 3′·42,
			21 53 38·1	0·3	1·5	4	12	<1′	MSH 24″ EW
		2227−66	22 27 39	0·7	4·4	1	—	1′·5	
23−*63*		2332−66	23 32 19·6	0·3	2·0	2	8	40″	
23−*64*		2356−61	23 56 12·3	0·4	3	2	32	1′·0	EW sep. 2′·7,
			23 56 34·4	0·4	3	2	34	2′·0	MSH 40″ EW

* Further remarks are:

(a) Cygnus A. This source is 21°·5 beyond the northern declination limit of the aerial but can be observed in side lobes of approximately 0·5%. The observed east–west distribution at 408 MHz is 0′·4 narrower than the corresponding distribution that would be seen with a 1′·5 beam at 1420 MHz (derived from the results obtained by Ryle, Elsmore, and Neville (1965) with a 20″ beam). The difference can be attributed to a larger proportion of radiation coming from the region between the two main components at low frequencies than at high frequencies.

(b) P 0349−88. Owing to the large variation in the level correction near the south celestial pole, a 1′ change in declination will change the east–west position by 4″. The assumed declination was −88° 25′ 57″ (1950·0).

(c) MSH 06−*55*. The weaker component, approximately 1° south of P 0625−53, was missed in the Parkes survey even though MSH 06−*55* was listed by Mills, Slee, and Hill (1961) as "extended; perhaps two sources, (20″)". The declination of the weaker component was measured as −54° 30′ at Parkes (F. Gardner, personal communication). It has a flux density of 3·4 f.u. at 21 cm, giving a spectral index of 0·9.

(d) MSH 18−*61*. The weaker component was missed in the Parkes survey. It is 18′ east of P 1814−63 and, although its declination has not yet been measured, its omission from the Parkes catalogue suggests that it is 0°·5 to 1° away, i.e. sufficiently close to be unresolved by the Parkes finding survey at 408 MHz, but sufficiently distant to be outside the search area about the peak deflection.

(e) MSH 20−*57*. There is a 2 f.u. source 4′ earlier and within 2° in declination. The difference of 50″ between the Molonglo and accurate Parkes right ascensions (Shimmins, Clarke, and Ekers 1966) suggests that the two sources are separated in declination by less than 5′.

Ekers 1966). As suggested by the remainder of the calibration data, it is assumed that only the stronger component of the double radio source MSH 21−*64* is associated with the listed galaxy.

Right ascensions of the calibration sources were measured as described in Section III (except of course for the application of pointing corrections) and the deviations from the calibration right ascensions were expressed as east–west pointing errors in seconds of arc. The individual differences were assigned standard errors according to the expressions given in Section IV, together with additional terms covering the uncertainties in the optical positions. The results are plotted in Figure 1.

Also shown are the calibration points that would result if the optical positions of the objects associated with occultation sources were used rather than the radio centroids (Jeffreys 1964; Sandage, Véron, and Wyndham 1965; Véron 1965*b*, 1966; Wills and Parker 1966).

VI. Radio Source Data

The basic programme of positional calibration has also led to accurate determinations of right ascension and east–west structure for a number of sources. These results are presented in Table 2, which gives, in detail:

Column 1. Number in the MSH catalogue (Mills, Slee, and Hill 1958, 1960, 1961).

Column 2. Number in the revised 3C catalogue (Bennett 1962).

Column 3. Number in the Parkes catalogue (Bolton, Gardner, and Mackey 1964; Price and Milne 1965; Day *et al.* 1966; Shimmins *et al.* 1966). In the text, Parkes sources are denoted by the prefix P.

Column 4. Measured right ascension (1950·0). Level corrections were computed using declinations given in the Parkes catalogue. In combining observations, weight 1/2 is given to scans 2° north or south of the source, and to all records obtained in May 1965 when the change in collimation error was not well determined. The positions of sources marked confused are unlikely to be affected by more than 5″.

Column 5. R.M.S. error in right ascension calculated according to Section IV and expressed in both seconds of time and seconds of arc. In assessing n, results of weight 1/2 count as quarter observations. No estimate of the error in the calibration curve is included.

Column 6. Number of observations.

Column 7. Measured flux density at 408 MHz expressed in flux units. Standard errors due to noise and confusion are approximately $2\cdot5/S$ f.u. and systematic errors due to calibration are not expected to exceed 20%.

Column 8. East–west equivalent width as defined in Section III.

Column 9. Remarks and references to further remarks given as footnotes to the table. Where available, east–west diameters (EW) measured by interferometry at 85 MHz (Mills, Slee, and Hill 1960, 1961) are included. Also recorded are any sources stronger than 1 f.u. and within 5′ in right ascension and 2° in declination. Abbreviations used in the column are: comp., component; conf., confused; ext., extended; scint., scintillating; sep., separation.

VII. Comparison of Radio and Optical Positions

In Tables 3(*a*) and 3(*b*), Molonglo right ascensions are compared with those of similar accuracy measured optically and at other radio frequencies (omitting occultation results). Standard errors are given for radio positions; for the optical positions they are 0″·5 to 1″·0.

TABLE 3(*a*)

COMPARISONS OF RIGHT ASCENSIONS FOR SOURCES NORTH OF DECLINATION −20°

Positions are for epoch 1950·0 and only the seconds of right ascension are tabulated. The radio positions are the centroids of radio emission

Source	Right Ascension: Molonglo (408 MHz) s s	Malvern* (610 MHz) s s	N.R.A.O.† (2695 MHz) s s	Optical‡ s		Optical Object
3C 9	49·9 ±0·14	49·95±0·18		49·83	(1)	QSO
3C 15	30·65±0·09			30·52	(2)	Galaxy
3C 47	40·05±0·17			40·3	(1)	QSO
3C 93	51·6 ±0·14	51·38±0·19		51·47	(3)	QSO
3C 208	23·2 ±0·17			22·79	(1)	QSO
3C 212	55·7 ±0·19	55·91±0·17		55·62	(4)	N galaxy
3C 228	28·0 ±0·13	27·73±0·14				QSO?
3C 245	06·1 ±0·12	06·07±0·13	06·00±0·10	06·11	(1)	QSO
3C 273	32·60±0·04		33·27±0·11	33·31	(5)	QSO
3C 279	35·75±0·08	35·85±0·11	35·87±0·14	35·94	(1)	QSO
13−0*11*	31·2 ±0·11			31·34	(1)	QSO
14−1*21*	12·3 ±0·13			12·22	(6)	QSO
3C 403	44·1 ±0·13		44·0	44·45	(7)	Galaxy§
Cyg. A	44·8 ±0·24			44·35 44·52	(8)	Galaxy
3C 446	10·85±0·10	10·94±0·12		11·05	(3)	QSO
CTA 102	08·0 ±0·12	07·71±0·14	07·76±0·09	07·71	(3)	QSO

* Adgie and Gent (1966).

† Clark and Hogg (1966).

‡ References to optical positions are: (1) Sandage, Véron, and Wyndham (1965); (2) Véron (1966); (3) Véron (1965*a*); (4) Wills and Parker (1966); (5) Jeffreys (1964); (6) Véron (1965*b*); (7) Sandage and Wyndham (1965); (8) Griffin (1963).

§ The Molonglo position for 3C 403 is consistent with that of the galaxy suggested by Sandage and Wyndham (1965) and 18″ east of the blue starlike object they first suggested as the identification. In addition, the Molonglo east–west width of 1′·9 is consistent with the double structure obtained by Maltby and Moffett (1962), and exceptionally large for a quasi-stellar radio source.

Table 3(*a*) includes all sources observed north of declination −20°. The right ascensions are in excellent agreement, and only in the cases of 3C 208, 3C 273, and 3C 403 do the differences between the Molonglo and optical values exceed twice their standard errors. The result for 3C 273 is due to the radio contribution from the jet, and the difference of 5″ for 3C 403 is quite reasonable considering its equivalent width of 1′·9. The difference of 6″ for 3C 208 may well be real and suggests two radio components separated by at least 10″ either having unequal intensities or being asymmetrically placed about the optical object. This would be consistent with the east–west diameter of about 20″ obtained by Allen *et al.* (1962). The relatively large difference for CTA 102 is attributed to confusion.

The new right ascension data presented in Table 3(*b*) can be used to support or reject the suggested southern identifications.

TABLE 3(*b*)

COMPARISONS OF RIGHT ASCENSIONS FOR SUGGESTED IDENTIFICATIONS SOUTH OF DECLINATION $-20°$

Positions are for the mean equinox of epoch 1950·0 and only the seconds of right ascension are tabulated. $M-O$ is the difference between the Molonglo and optical right ascensions expressed as an angular separation in seconds of arc

Source*	Right Ascension Molonglo (408 MHz) s s	Optical† s	Suggested Identification	$M-O$
MSH 00−*51*(a)	25·8 ±0·6	26·64 (1)	17^m E galaxy	−7″
MSH 04−*71*(b)	58·5 ±0·19	58·1 (1)	15^m S0 galaxy	1″
MSH 05−*36*	12·8 ±0·06	13·0 (5)	15^m N galaxy	−2″·5
P 1327−21	23·55±0·20	23·2 (2)	17^m QSO	5″
P 1655−77	13·3 ±0·9	12·4 (1)	$16^m·5$ E0 galaxy	3″
P 1716−80(c)	36·0 ±0·9	−23 (3)	IC 4640	153″
P 1934−63(d)	47·3 ±0·4	47·6 (5)	18^m N galaxy?	−2″
MSH 19−*57*(e)	18·5 ±0·16	18·74 (1)	13^m G0 star	−2″
MSH 20−*71*	21·8 ±0·7	132 (3)	IC 5016	−480″
MSH 20−*61*	17·7 ±0·21	12·7 (1)	17^m E galaxy	37″
MSH 20−*57*	12·1 ±0·5	$0^m·2$ (4)	IC 5063 13^m S0 galaxy	<60″
MSH 21−*34*	11·3 ±0·23	$11^s·1$ (2)	$17^m·5$ QSO	2″·5
MSH 21−*64*A(f)	58·5 ±0·11	57·8 (1)	14^m E3 galaxy	3″·5
MSH 23−*64*(g)	12·3 ±0·4 34·5 ±0·4	29·3 (1)	17^m E3 galaxy	−123″ 37″

* Remarks on individual sources are:

(a) MSH 00−*51*. The optical position of the listed galaxy is consistent with the Molonglo right ascension, but is 79″±14″ (standard error) north of the accurate Parkes declination (Shimmins, Clarke, and Ekers 1966). The discrepancy in declination could possibly be due to the nearby source mentioned in Table 2(*b*), column 9.

(b) MSH 04−*71*. The alternative galaxy suggested by Westerlund and Smith (1966) is 80″ further east and clearly not involved. However, the galaxy listed here is 74″±13″ (standard error) north of the accurate Parkes declination. Considering the strength of the source and the lack of beam broadening, it is unlikely that the declination discrepancy can be attributed to confusion or to a north–south elongation of the source. It is concluded that either the identification is incorrect, or else one of the declination measurements is in error.

(c) P 1716−80. The accurate location of the radio position on a photographic plate shows that the suggested identification is incorrect.

(d) P 1934−63. The peculiar radio spectrum of this source has been discussed in some detail by Kellermann (1966). It is similar to that of the quasi-stellar radio source CTA 102, being markedly curved and having a maximum flux density near 1000 MHz. The suggested identification, which has an apparent extension of 3″ at position angle 300°, is the only peculiarly shaped optical object in the vicinity of the radio position. Its position is consistent with the Molonglo right ascension. It has a diameter less than 2″ and could be either a compact N galaxy or a quasi-stellar radio source. UBV colours, which would help decide its optical classification, are not yet available.

[*Footnotes to Table 3*(*b*) *continued opposite*]

Three identifications (P 1716−80, MSH 20−*71*, and MSH 20−*61*) can be rejected on the basis of poor positional agreement. For MSH 20−*57* a more accurate optical position is required, and the declination of the nearby radio source needs to be measured.

For the remaining 10 sources, the agreement in right ascension is good. However, as indicated in the footnotes, there are some doubts concerning the identifications for MSH 00−*51*, MSH 04−*71*, P 1934−63, MSH 19−*57*, and MSH 23−*64*. The five remaining identifications (MSH 05−*36*, P 1327−21, P 1655−77, MSH 21−*34*, and MSH 21−*64*A) are considered reliable.

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[*Continuation of footnotes to Table 3(b)*]

(e) MSH 19−*57*. Westerlund and Smith (1966) have located a stellar object with a typical G0 spectrum close to the radio position, but do not consider it as the identification. The east–west radio diameter is 0′·9. The radio source may be related to two very faint nebulosities situated on opposite sides of the star at distances of 10″ and 20″.

(f) MSH 21−*64*. Scans north and south show that the two components of the radio source are separated in declination by less than 15′. The stronger and earlier component, of diameter 30″, is identified with a 14th magnitude D galaxy having a prominent nucleus and an extended envelope of diameter 30″ to 50″. The later component is most likely an unrelated object.

(g) MSH 23−*64*. This is probably a double radio source unsymmetrically placed about the galaxy listed here. There may also be some radiation from the adjacent galaxies 1 and 3 of Westerlund and Smith (1966).

† References to optical positions are: (1) Westerlund and Smith (1966), (2) Ekers and Bolton (1965), (3) Index catalogue, (4) Becvar catalogue, (5) Remeasurement of a photographic plate.

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