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Position and Flux Density Calibration at Molonglo*

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Abstract

When the Molonglo Cross was brought into full operation its higher angular resolution and greater pointing accuracy posed special problems for position calibration. The development of a southern radio calibration grid is described, together with its extension for the MOST. The techniques developed in this program have found wide applicability in radio-source identification searches at other observatories. Calibration in flux density was based on absolute measurements at 408 MHz and transferred via secondary standards; at 843 MHz, the flux density calibration was based partly on absolute measurements and partly on the earlier 408 MHz data. The collection of data spanning several years led to the discovery of significant time variability at 408 MHz.

1. Introduction

One of the fundamental concerns in astronomy is the accurate determination of the positions of celestial objects. The rapid development of extragalactic astronomy through the 1960s and 1970s can be attributed directly to the vast improvements in the precision with which the positions of discrete radio sources could be measured. The improved positional accuracy provided in turn the essential basis for the optical identification of radio sources. Radio–optical associations form the crucial starting point for studies of the astrophysics of radio sources; they also serve a more mundane but equally important role in defining position calibrators for radio telescopes.

As a meridian transit telescope, the Molonglo Cross lacked the versatility of a fully-steerable paraboloid such as Parkes but made up for this in having more stable and predictable pointing and gain. Indeed, in the first issue of *Proceedings of the Astronomical Society of Australia*, Large and Murdoch (1967) stated that ‘the accurate determination of radio source positions is one of the principal uses of high-resolution instruments such as the Molonglo Radio Telescope’. The Molonglo Reference Catalogue (Large *et al.* 1981) of 12,141 sources was the culmination of a decade of Cross observing, and its demonstrated uniformity, completeness and positional accuracy were (and still are) unparalleled among major radio surveys.

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In the following sections I will describe the calibration techniques adopted for both the Molonglo Cross and its successor, the Molonglo Observatory Synthesis Telescope (MOST). This account does not pretend to be a general review of the subject, but reflects instead my own direct involvement in devising and implementing the calibration programs at Molonglo over the full 25 years of its operation. Some of the material in this review is based on unpublished material from my Ph.D. thesis (Hunstead 1972*a*), while the calibration of MOST was the subject of a paper (previously unpublished) which was first presented at the August 1988 Annual General Meeting of the ASA in Narrabri. Details of telescope operation, data recording and source fitting have been described previously in many papers (e.g. Davies *et al.* 1973, and references therein; Mills 1981).

2. Position Calibration at 408 MHz

(a) Radio Calibration Procedures

For an ideal meridian transit instrument the apparent right ascension and declination of a source are related simply to the sidereal time of transit and the beam elevation respectively, assuming the astronomical coordinates of the site are known. For Molonglo, departures from the ideal structure were caused by tilting of the EW and NS arms from the horizontal and a small deviation in the azimuth of the EW arm from the ideal east–west orientation. The structure geometry and the site coordinates were determined by accurate survey techniques (Sutton 1966, 1968).

After correction for aerial geometry, the residual collimation errors were assumed to be modelled by a phase gradient along each arm plus a zenith-angle-dependent declination error due to the spherical component of ionospheric refraction. Final corrections were then determined empirically from comparisons with accurately known positions, either 408 MHz centroid positions measured by lunar occultation techniques (Sutton 1968) or optical positions for well-established identifications (e.g. Westerlund and Smith 1966). Although there were very few suitable (i.e. compact) identified sources south of −30°, there was sufficient redundancy to define the appropriate form for the pointing corrections (Hunstead 1969).

Examples of early calibration curves are shown in Fig. 1. At this stage it was not clear whether the overall scatter about each fitted curve was intrinsic to the telescope or due to uncertainties in the calibrator positions themselves. A separate program was commenced, first to search for new optical identifications south of −40° and second, to measure more accurate optical positions for the identified sources north of −40°. This program is described in the following section.

Experience has shown that a choice of suitable calibration sources must be made with some knowledge of their radio structure. Whereas information on the angular structure of many northern sources was becoming available in the late 1960s, there were very few southern sources with comparable data. In order to compile a sufficiently large number of calibrators, a pragmatic decision was made to select sources which were unresolved in the pencil beams of the Molonglo Cross. The effective upper limit of ~40 arcsec was far from ideal, since asymmetric structure on this scale is quite common and could lead to real differences between radio and optical centroids. It turned out that there was sufficient redundancy in the determination of pointing corrections that the influence of such real offsets was minimal. Nevertheless, this emphasises a singular feature of the Cross (and, indeed, the MOST), namely the disparity between the ability to position a source accurately and to determine its small-scale structure.

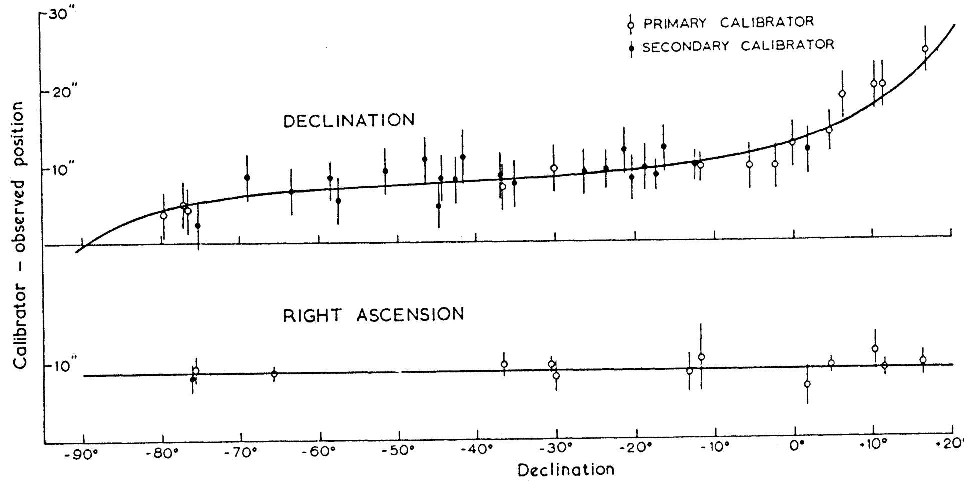

Fig. 1. Early calibration curves for the Molonglo Cross. Primary calibrators are occultation or optical positions; secondary calibrators are radio positions determined from other observing sessions *(from Hunstead 1969).*

(b) Optical Position Measurements

The pointing calibration of radio telescopes has traditionally been based on accurate optical positions for identified sources. This situation arose because the techniques for measuring optical positions were well-established, the accuracy being limited only by uncertainties in the fundamental star catalogues. However, the measurement of precise optical positions for radio source identifications presents some special astrometric problems, the most important resulting from the shape of the radio luminosity function: the strongest radio sources tend also to be the faintest optically, generally having $B < 17$. With this constraint, the Sky Atlas of the Palomar Observatory Sky Survey (POSS) was almost exclusively the initial search medium for optical identifications during the 1960s and 1970s.

Due to the widespread belief that the Sky Atlas prints were quite unsuitable for measuring optical positions to better than a few arcseconds (e.g. Dewhirst 1963), the much-needed astrometry was carried out (at a slow rate) on original plates taken specially for the purpose. On the other hand, our experience with a simple travelling microscope suggested that an accuracy of 1 arcsec was achievable on the Sky Atlas copies. As a result, Bob Shobbrook and I decided in 1968 to undertake the design and construction of a two-coordinate measuring machine specifically to accommodate both the Palomar prints and plates. The design work was carried out at the National Standards Laboratory, CSIRO, the instrument was constructed by John Horne, then a Technical Officer

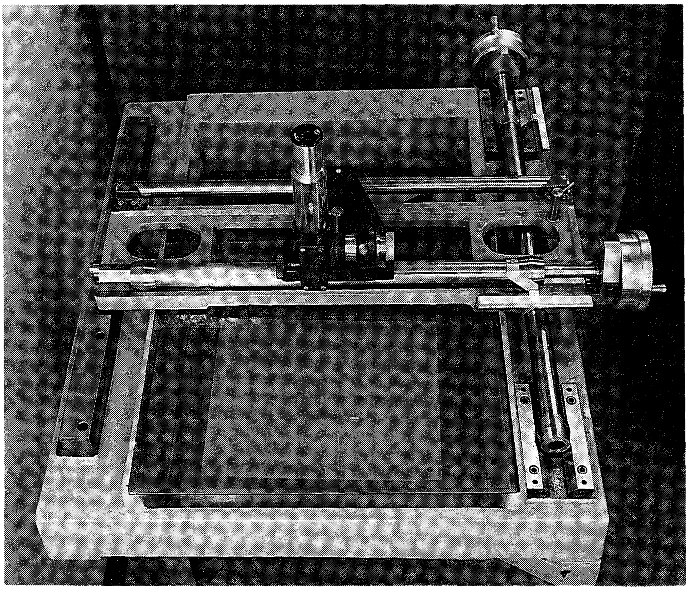

Fig. 2. The Molonglo two-coordinate measuring machine built in 1969 to measure accurate optical positions from the prints and plates of the Palomar Sky Survey.

in the Astrophysics Department, and a reduction program was written by Peter Shaver, then a co-Ph.D. student. A photograph of the measuring machine is shown in Fig. 2.

The accuracy of direct measurements on the second-generation copies of the POSS was assessed by multi-way comparisons with other published lists of accurate optical positions (Hunstead 1971). The external comparisons indicated that positional errors were only ~0·3 arcsec in each coordinate, directly comparable with the accuracy achieved by Kristian and Sandage (1970) using original plates from Palomar and a far more sophisticated measurement and reduction technique. The success of our venture was attributed in part to the high quality of construction of our measuring machine and in part to the stability of the plate material itself which was kept in a controlled environment. Most importantly, however, we demonstrated that the POSS was a viable astrometric medium for radio source identifications, a fact that radio astronomers at other observatories were quick to recognise and take advantage of.

The search for far southern identifications was carried out on plates taken by Bob Shobbrook and Ron Ekers at the Mt Stromlo 74-inch telescope. Due to the small angular field of these plates, the final optical positions had to be defined relative to secondary reference stars measured on a companion Uppsala Schmidt plate; both sets of plates were measured on the new two-coordinate machine. Amongst the early identifications from this program were 0637–75, a flat-spectrum QSO studied extensively with VLBI over the past decade, and 1610–77, another flat-spectrum QSO which was used in 1988 for the first detection of fringes from the Compact Array of the Australia Telescope.

(c) Results and Comparisons

The improved accuracy and declination coverage of the optical positions described in *(b)* permitted the use of bootstrap procedures to refine the telescope pointing corrections. This process revealed a small systematic error in the radio R.A.s which could be explained most simply by an error of 1·0 arcsec in the assumed azimuth of the EW arm. A plot of the radio–optical discrepancies in R.A. as a function of declination is shown in Fig. 3 together with the adopted correction curve. The magnitude of the azimuth error lies within the survey limits quoted by Sutton (1968), and is entirely consistent with the possibility, mentioned by John Sutton in his Ph.D. thesis, that the whole eastern arm may be displaced by ~3 mm to the north.

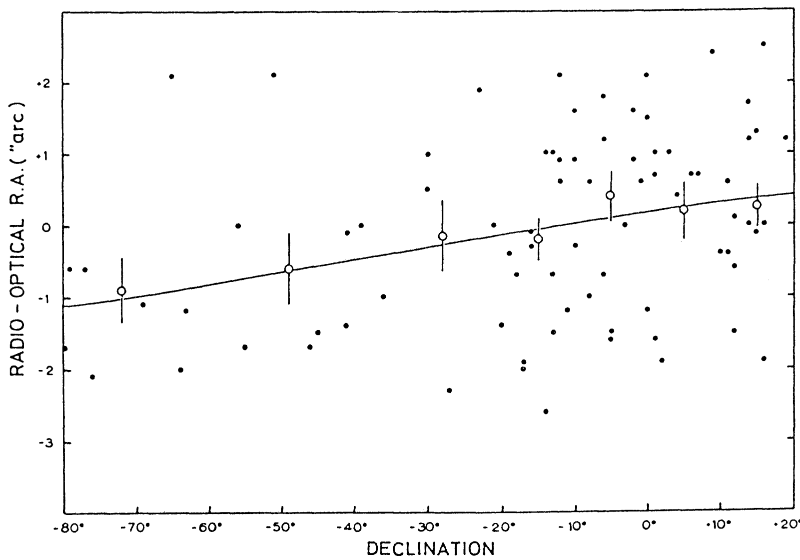

Fig. 3. Differences between the 408 MHz radio and optical right ascensions for the calibration sources plotted as a function of declination. The open circles refer to group means and standard errors, and reveal a subtle systematic error in the assumed azimuth of the EW arm. The best-fit curve of the correct form is shown *(from Hunstead 1972b).*

The end product from these exhaustive calibrations was a list of positions and flux densities for 314 small-diameter sources spanning the declination range +20° to −80° (Hunstead 1972*b*). The accuracy of the final source positions was influenced by a number of factors, most notably the assumptions built in to the pointing corrections. Statistical tests were applied to the ~1500 individual scans and showed that the internal error estimates determined for different sources were consistent with a single global value. These global standard deviations were $\sigma_\alpha = 2\cdot9$ arcsec and $\sigma_\delta = 3\cdot4 \sec z$ arcsec (z = zenith angle), each amounting to ~1·9% of the beamwidth.

Comparisons with accurate interferometer positions for known small-diameter sources measured at NRAO and RRE (Wade 1970; Adgie *et al.* 1972) confirmed that the Molonglo positions were reliable at the quoted levels, typically

$1 \cdot 5$ arcsec in R.A. and $2 \cdot 0$ arcsec in declination, with a Gaussian error distribution. A comparison with the optical calibrator positions is shown in Fig. 4. Although the mean offset is zero and the standard deviations are reasonable ($\sigma_\alpha = 1 \cdot 66$ arcsec, $\sigma_\delta = 1 \cdot 95$ arcsec), there is a statistical excess of large offsets (occasionally too large to be shown in Fig. 4) and this is interpreted as being due to real differences between the optical positions and the 408 MHz centroids. The radius-vector offset amounts to ~$2 \cdot 0$ arcsec rms—not surprising for structures that may be as large as 40 arcsec—and *must* be taken into account when making optical identifications based on Molonglo 408 MHz positions.

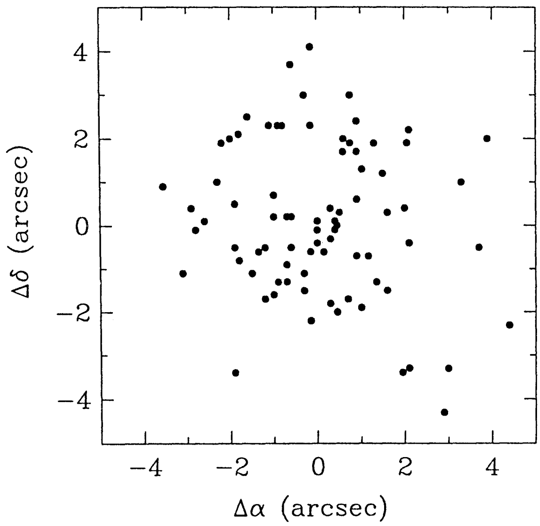

Fig. 4. Cross plot showing the final distribution of radio–optical differences in each coordinate for the Molonglo Cross calibrators *(from Hunstead 1972b).*

3. Flux Density Calibration at 408 MHz

(a) Calibration Procedures

The flux density scale at 408 MHz was defined by absolute measurements by Wyllie (1969*a*) and transferred to secondary standards using the fan-beam response of the EW arm alone (Wyllie 1969*b*). Pencil-beam flux densities were measured relative to a reference noise signal injected into the centre module of the NS arm. However, it was soon found that the flux density corresponding to this noise signal was not constant but varied in an oscillatory manner with zenith angle, probably as a result of interference between the main and back-lobe responses (Shaver 1970).

The main calibration task was to determine the form of the zenith-angle gain dependence as accurately as possible. This was done by determining relative gains (to ~1%) for each of five selected observing sessions and then forming a combined set of relative flux densities for 200 sources. These relative flux densities were then correlated with the EW fan beam measurements of Wyllie (1969*b*), assuming a particular functional form for the zenith-angle gain dependence. The rms scatter about the final fitted curve was 5% for the scale calibrators and 8–9% for the secondary calibrators; the latter value is boosted by the effects of confusion in the EW fan beam at the lower flux density levels involved.

The same statistical analysis used for the positions was applied to the flux densities from ~1100 scans of 290 sources, yielding a global standard deviation, σ_S/S of 3·7%. This error, which refers only to the repeatability within and between observing sessions, is dominated by gain fluctuations; in comparison, receiver noise and confusion are negligible.

(b) Variability: The Puzzling Bonus

One factor which had not been considered initially when redetermining the flux density calibration was the possibility of genuine temporal variations in flux density. This was a reasonable assumption at the time, because even though variations in flux density had been reported at frequencies from 750 MHz to > 15 GHz, the fluctuations were most intense at the highest frequencies. A common pattern was a rapid outburst seen first at high frequency and appearing some time later at lower frequencies, with a marked reduction in amplitude. An extrapolation to frequencies ~400 MHz predicted an effect that would be practically unmeasurable.

When finalising the flux density calibration, my suspicions were raised by discordant flux densities for one of the scale calibrators, 2230+11 (CTA 102), which appeared to be 30% stronger in 1968 August than in 1967 July. Although 2230+11 had previously been reported as a periodic variable at 32·5 cm (Sholomitskii 1965), this report was subsequently discredited by a number of negative results at similar frequencies. However, by assembling further data for this source spanning the period 1967·5–1971·0, I was able to show that the 408-MHz variations were significant.

Although the declination-dependent gain of the NS antenna limited the *external* accuracy of Molonglo flux densities, it was the *internal* consistency that determined the significance of changes in flux density. As noted above, external errors in flux density were ~5% rms, whereas scaling factors between different observing sessions were defined typically to 1–2% rms. Discrepancies of individual flux-density ratios from a session mean therefore provided a sensitive indication of source variability, and this method was used to select candidate variables for further investigation.

The data on four suspected variables were included in the initial detection paper (Hunstead 1972*c*). Radio data for the best studied source, 2251+15 (3C 454·3), are shown in Fig. 5. Although a well-known variable at short cm wavelengths, no significant variations had previously been reported at frequencies below 1400 MHz. For this source the Molonglo 408 MHz data were augmented by data from Jodrell Bank at 408 and 610 MHz, and the excellent agreement between these independent measurements was most reassuring. For comparison, Fig. 5 shows the radio light curve at 2700 MHz, demonstrating one of the most puzzling aspects of this new phenomenon: the changes at 408 MHz appeared to be unconnected with the changes seen at higher frequencies, suggesting that a completely different mechanism was responsible.

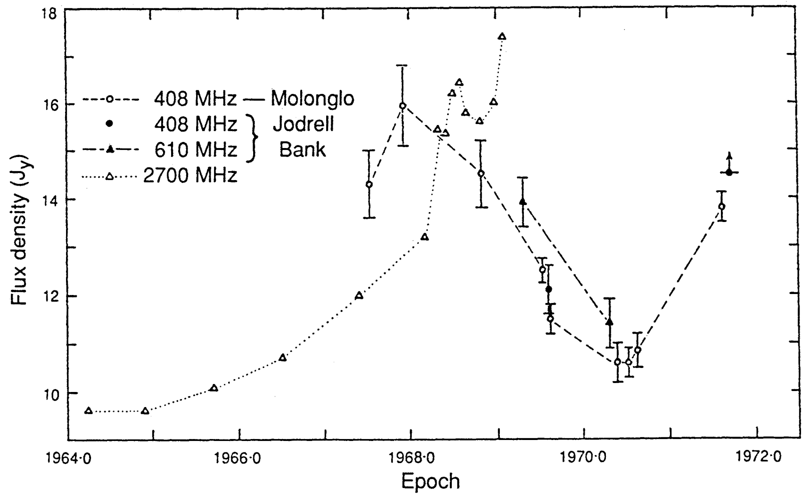

Fig. 5. Variations in the 408 MHz flux density of 2251+15 (3C 454·3) measured at Molonglo, together with additional low-frequency data from Jodrell Bank. The data at 2700 MHz are shown for comparison *(from Hunstead 1972c).*

Ten years later (Cotton and Spangler 1982) there was general acceptance of the reality of low-frequency variability but still no generally-accepted description of the phenomenon or an explanation of the underlying astrophysics. However, it had been recognised that the very high inferred brightness temperatures ($\sim 10^{16}$ K) posed fundamental problems for an intrinsic origin within the framework of incoherent synchrotron radiation, and alternative explanations were sought in terms of scintillation of a *very* small-diameter source in the local interstellar medium. The latter possibility is now considered the most plausible explanation (at least for the rapid variations), and when the properties of the ISM are better understood, the study of low-frequency variability may eventually serve as a useful tool for detecting source structures on much smaller angular scales than is possible with earth-based long-baseline interferometry.

4. Calibration of the MOST at 843 MHz

(a) Radio Calibration Procedures

The evolution of the 408-MHz Molonglo Cross to the 843-MHz Molonglo Observatory Synthesis Telescope (MOST) in 1981 presented a new set of calibration problems. Initially, the position calibration was tied to a subset of strong sources with optical identifications measured from earlier work. However, with the higher resolution at 843 MHz, many of these calibrators were found to be slightly resolved and therefore unsuitable for the purpose.

Flux density calibration was based initially on interpolation between 408 MHz Molonglo values and 2700 MHz Parkes values for strong sources with power-law spectra. This interpolated scale was later refined by Calabretta (1985) to make it self-consistent, and further sources were included as potential calibrators. To investigate the systematic accuracy of the Calabretta scale, Caganoff (1984) obtained absolute flux density measurements at 843 MHz using a standard-gain horn antenna in combination with the two arms of MOST, a technique similar to that used by Wyllie (1969*a*). The unweighted mean ratio of absolute and

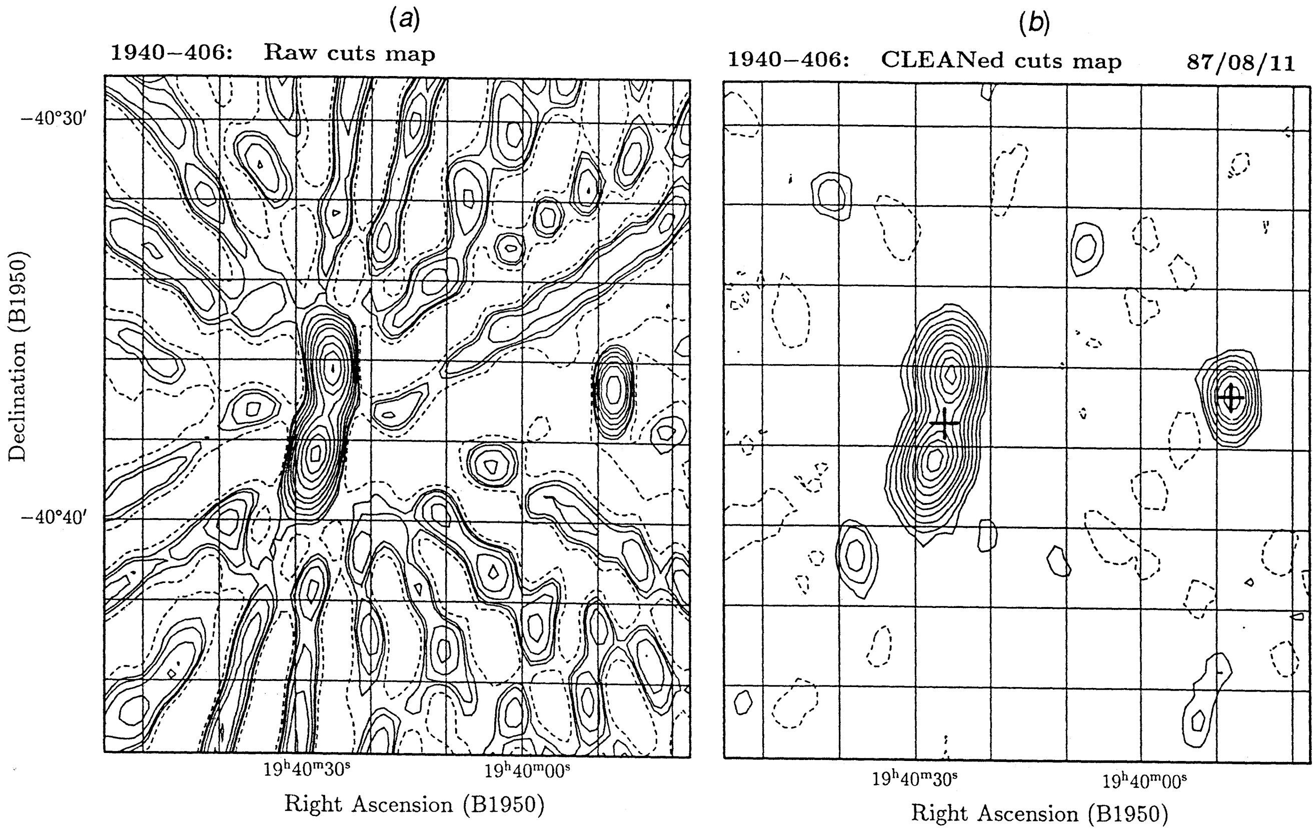

Fig. 6. *(a)* Raw and *(b)* CLEANed 'cuts' images of the source 1940–406 obtained with MOST at 843 MHz. The total integration time was 32 minutes, consisting of eight 4-minute cuts spaced uniformly in hour angle and spanning 9 hours. Contour levels on both maps are: −15, 15, 30, 60, 100, 150, 200, 300, 400, 500, 600 mJy. The galaxies identified with the main double source and its neighbour to the west are marked in *(b)* with crosses.

relative flux densities for the best seven of Caganoff's sources was $0 \cdot 99 \pm 0 \cdot 03$, indicating that the 843 MHz scale is probably correct to within 5%.

In 1985, a mode of synthesis known as 'cuts' was introduced by C. R. Subrahmanya, a post-doctoral fellow in the Astrophysics Department. By using time multiplexing, it was feasible to image ~10–15 sources in a single 11- or 12-hour observing run, the main penalty being poorer *uv* coverage and correspondingly poorer dynamic range. By choosing well-concentrated groups of sources ($\Delta\alpha \le 2$ h, $\Delta\delta \le 30°$) the on-source duty cycle was >50%. Following the commissioning of 'cuts' mode, I undertook an 843 MHz survey of all sources listed in the Molonglo Reference Catalogue (MRC) with $S_{408} \ge 4$ Jy, $\delta \le -30°$ and $|b| > 10°$ with the aim of generating an expanded list of point-source calibrators for MOST. This project (dubbed initially the Southern 3C survey, and later the Southern Strong-source [SS] survey) took two years to complete and resulted in images for ~200 MRC sources, a source density comparable with the northern hemisphere 3C survey.

An example of raw and CLEANed 'cuts' images of one of the SS sources, 1940–406, is shown in Fig. 6, demonstrating the good image quality obtained with eight 4-minute cuts spaced evenly in hour angle. The 'dirty' beam used in CLEANing a 'cuts' map is generated directly from the measured 'transit' beam defined by a nearby calibration source. The dynamic range in the CLEANed map is limited principally by the cumulative effects of confusing sources in the fan beam response of each 'cut' and is typically ~10 mJy rms. For sources with $S_{843} \ge 0 \cdot 6$ Jy peak, the dynamic range is limited at present to ~50 : 1 by fluctuations in telescope gain and beamshape on timescales of minutes to hours.

Forty five sources from the SS catalogue were found to be suitable as calibrators. The primary selection criterion was an angular size < 10 arcsec, determined readily from deconvolution of the individual one-dimensional 'cuts'. A secondary criterion was the absence of nearby strong sources likely to cause serious confusion at particular hour angles.

(b) Accuracy of Calibration

The initial list of 45 calibrators was augmented by seven flat-spectrum sources from a study by Tzioumis (1987) and three of the original calibrators north of −30°. All 55 sources were then observed in two sessions, 1987 November 6–8 and 1988 January 9–11, with some overlap between the two sessions. Positions and flux densities were measured from CLEANed 'cuts' maps using the source-fitting program FIND.

Of the 55 sources, 39 had optical counterparts visible on the UK Schmidt/SERC sky survey films. Optical positions were measured with an upgraded version of the prototype measuring machine (Fig. 2), with digital position encoders and a TV viewing system. The optical reference frames were defined by the Cape Photographic Catalogue for $\delta < -64°$, the Sydney Southern Star Catalogue for the range −51° to $-63 \cdot 5°$ and the Smithsonian Catalogue north of −51°. The distribution of radio–optical differences is shown in Fig. 7. Excluding the two largest offsets (radius-vector differences $> 3 \cdot 0$ arcsec), the mean differences are sensibly zero, with $\sigma_\alpha = 0 \cdot 64$ arcsec and $\sigma_\delta = 0 \cdot 59$ arcsec (referred to the pole). These standard deviations are considerably smaller than those found in a similar comparison with the Molonglo 408 MHz positions (Fig. 4).

Flux density calibration was tied to the previously listed values (Calabretta 1985) for eight sources: 0407–658, 0409–752, 1215–457, 1308–220, 1422–297, 1827–360, 1934–638 and 2259–375. Radio positions within each 'cuts' run were adjusted so that they agreed *on average* with the positions of optical counterparts; it was assumed that telescope geometry was accurately known and, therefore, that pointing errors were independent of declination. Sources with anomalously large radio–optical offsets were not included.

The results of the comparison between positions and flux densities obtained in the two calibration sessions are given below. It is important to emphasise that, due to the need to cover the full R.A. range, a *different* set of calibration sources was used for each session and that the optical positions were used only to set zero points.

	Mean offset	σ	N
Right Ascension (arcsec)	$-0\cdot12\pm0\cdot09$	$0\cdot31$	13
Declination (arcsec at pole)	$+0\cdot02\pm0\cdot08$	$0\cdot27$	13
Flux density (ratio)	$0\cdot991\pm0\cdot005$	$0\cdot017$	13

This limited comparison indicates that systematic errors in R.A. and Dec. are probably $< 0\cdot1$ arcsec and random errors are $\sim 0\cdot2$ arcsec rms; the corresponding errors in flux density are $\sim 1\cdot0$–$1\cdot5$%. With such high positional accuracy it is clear that the radio position errors have a negligible effect on the scatter seen in Fig. 7 ($\sigma \sim 0\cdot6$ arcsec in each coordinate). On the other hand, it is unlikely that the scatter is due entirely to errors in optical positions, so again we must invoke real offsets between radio and optical centroids. The formal errors in the optical positions are $\sim 0\cdot4$ arcsec rms, leaving $\sim 0\cdot5$ arcsec rms for real offsets. The latter value is 1/20 of the minimum detectable source size, a ratio similar to that found at 408 MHz.

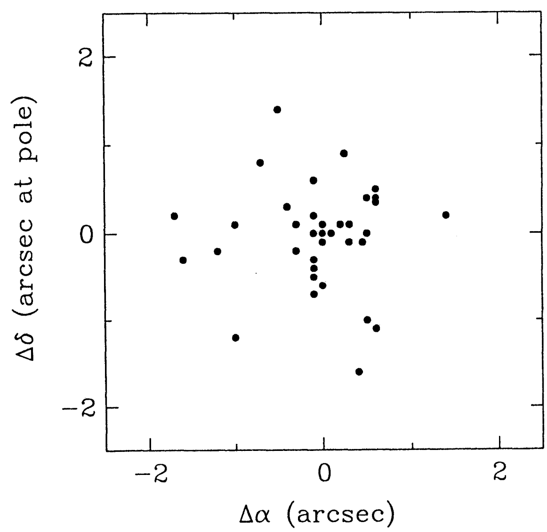

Fig. 7. Cross plot showing the distribution of radio–optical differences in each coordinate for the MOST calibrators. Differences in declination have been multiplied by sinδ.

5. Discussion

(a) Ramifications of the 408 MHz Calibration

The list of 314 positions and flux densities (Hunstead 1972*b*) was the basic calibration resource for all Molonglo Cross observations through the 1970s. Most importantly, it formed the backbone for calibrating the Molonglo Reference Catalogue and most of the other Molonglo catalogues.

Our ability to measure accurate optical positions also led to several productive collaborations. In particular, accurate radio positions from the interferometer at the Royal Radar Establishment plus optical positions from the Molonglo measuring machine led the way in showing that identifications could be made solely on the basis of close positional agreement, without resort to the colour or morphology of the candidate object (Gent *et al.* 1973). This led in turn to the discovery of new high-redshift QSOs—notably 1442+101 at $z = 3\cdot53$—which tended to be redder in colour than lower-z QSOs and therefore more difficult to distinguish from galactic stars.

Another position-based project was directed at seeking optical identifications of radio sources from the northern 3C catalogue. The first paper from this collaboration (Spinrad *et al.* 1975) reported observations of a radio galaxy, 3C 411, with a redshift of 0·469, just greater than the record redshift set by Minkowski (1960) for 3C 295. In this and subsequent papers the Molonglo radio and/or optical positions were needed to confirm a faint identification before the long spectroscopic integrations could be undertaken.

(b) The 843 MHz Calibration Sources

The upgrade to 843 MHz has brought a significant improvement in positional accuracy, due collectively to the different method of forming images, the higher angular resolution and the substantial reduction in the effects of ionospheric refraction. In fact, the radio positional accuracy obtained with MOST is somewhat better than that achievable at present with optical positions, the opposite situation to that pertaining at 408 MHz. It has therefore been decided to adopt the MOST positions for routine calibration at Molonglo. This has the obvious advantage that we have a uniform set of calibrators for both position and flux density, and the issue of individual radio–optical offsets is no longer a problem.

The properties of this calibration set are interesting in their own right. Restricting the sample to the 45 MRC sources meeting the original selection criteria, it is worth noting that 1/3 are in blank optical fields, 1/3 are identified with (mostly) faint galaxies and 1/3 are identified with QSOs. A similar sample selected at high frequency would have a much higher identification rate and be dominated by QSOs. The distribution of radio spectral indices, shown in Fig. 8, contains no surprises; the median spectral index is $\alpha = 0\cdot8$ ($S \propto \nu^{-\alpha}$) and, as expected, the flat-spectrum tail comes from the QSOs (mostly with $z < 2$), and the blank-field sources tend to have the steepest spectra.

More is revealed by a radio two-colour diagram, shown in Fig. 9, which emphasises a general tendency for the spectra to be curved, in the sense that they steepen towards higher frequencies. This effect is too large to be explained by systematic errors in the 843 MHz flux density scale (see Section

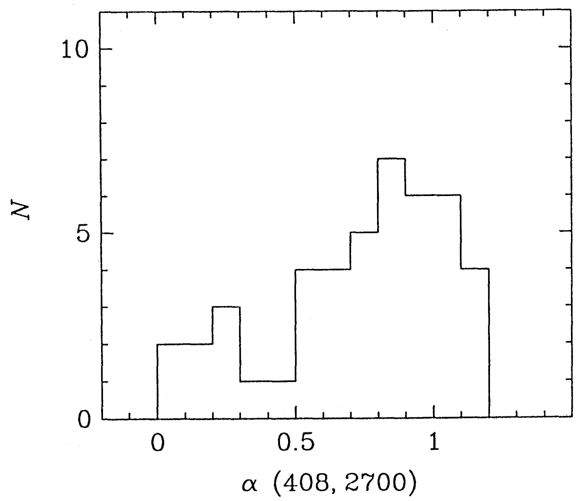

Fig. 8. Distribution of two-point spectral indices between 408 and 2700 MHz for the 45 MOST calibrators satisfying the criteria: $S_{408} > 4 \cdot 0$ Jy, $\delta < -30°$, $|b| > 10°$, FWHM ≤ 10 arcsec.

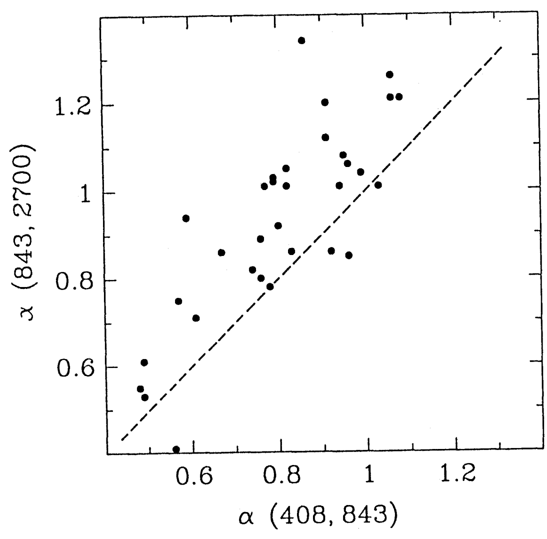

Fig. 9. Radio 'two-colour' plot for the 45 MOST calibrators in Fig. 8. The two-frequency spectral index between 843 and 2700 MHz is plotted against the the two-frequency spectral index between 408 and 843 MHz. Sources with straight spectra would lie on the dashed line of slope unity.

4*a*) and, in any case, the curvature is supported by measurements for some sources at frequencies below 408 MHz and above 2700 MHz. A very similar result was found by Tielens *et al.* (1979; Fig. 3) for a sample of 4C sources with data at 178, 1415 and 4995 MHz. Follow-up optical spectroscopy on some of the steepest-spectrum sources from the Tielens *et al.* sample has revealed them to be high-redshift galaxies (up to $z = 3 \cdot 8$) with unusual aligned radio and optical structure (Miley *et al.* 1989).

The obvious conclusion to draw is that many of the MOST calibrators fall into the same class of distant, high-luminosity galaxies as those discovered by McCarthy *et al.* (1987) and Chambers and Miley (1990). It is only in the past 5–10 years that it has become possible to obtain spectra of such faint objects, using high-efficiency spectrographs and CCD detectors on 4-m class telescopes. We now have the opportunity of contributing to this expanding and exciting field using a sample of sources intended for a far more mundane purpose.

6. Conclusions

The pointing and flux density calibration at Molonglo have presented a number of challenges and returned some important dividends. Far from being the boring and unrewarding task conjured up by the name, the calibration process has led to innovations in the measurement of optical positions and in our understanding of radio source variability. It has also been the vehicle for making reliable optical identifications in the far south, an essential step in pursuing the astrophysics of different classes of radio source. Of particular interest in this regard are radio sources in clusters of galaxies and the very high luminosity galaxies which will undoubtedly show up amongst the MOST calibration sources. Finally, it has assured the quality of the various surveys carried out over the past 25 years and, in the case of the MRC, enabled the detection for the first time of significant local structure in the distribution of extragalactic radio sources (Shaver 1991, present issue p. 759).

Acknowledgments

It is a pleasure to acknowledge the advice and encouragement of Bernard Mills over the past 25 years. The calibration of a telescope as complex as Molonglo required input from many people—academic and technical staff, fellow students and colleagues from other observatories—and I am grateful for the assistance and willing cooperation I received.

References

Adgie, R. L., Crowther, J. H., and Gent, H. (1972). *Mon. Not. R. Astron. Soc.* **159**, 233.
Caganoff, S. (1984). Physics IV Honours Report, The University of Sydney.
Calabretta, M. R. (1985). Ph.D. Thesis, The University of Sydney.
Chambers, K. C., and Miley, G. K. (1990). *In* 'The Evolution of the Universe of Galaxies: the Edwin Hubble Centennial Symposium' (Ed. R. G. Kron), p. 373 (Astronomical Society of the Pacific).
Cotton, W. D., and Spangler, S. R. (Eds) (1982). *Proc. NRAO Workshop on* 'Low Frequency Variability of Extragalactic Radio Sources' (National Radio Astronomy Observatory: Green Bank, WV).
Davies, I. M., Little, A. G., and Mills, B. Y. (1973). *Aust. J. Phys. Astrophys. Suppl. No. 28*, 1.
Dewhirst, D. W. (1963). *In* 'Radio Astronomy Today' (Eds H. P. Palmer *et al.*), p. 178 (Harvard University Press).
Gent, H., Crowther, J. H., Adgie, R. L., Hoskins, D. G., Murdoch, H. S., Hazard, C., and Jauncey, D. L. (1973). *Nature* **241**, 261.
Hunstead, R. W. (1969). *Proc. Astron. Soc. Aust.* **1**, 231
Hunstead, R. W. (1971). *Mon. Not. R. Astron. Soc.* **152**, 277.
Hunstead, R. W. (1972*a*). Ph.D. Thesis, The University of Sydney.
Hunstead, R. W. (1972*b*). *Mon. Not. R. Astron. Soc.* **157**, 367.
Hunstead, R. W. (1972*c*). *Astrophys. Lett.* **12**, 193.
Kristian, J., and Sandage, A. (1970). *Astrophys. J.* **162**, 391.

Large, M. I., and Murdoch, H. S. (1967). *Proc. Astron. Soc. Aust.* **1**, 32.
Large, M. I., Mills, B. Y., Little, A. G., Crawford, D. F., and Sutton, J. M. (1981). *Mon. Not. R. Astron. Soc.* **194**, 693.
McCarthy, P. J., van Breugel, W. J. M., Spinrad, H., and Djorgovski, S. G. (1987). *Astrophys. J. Lett.* **321**, L29.
Miley, G., Chambers, K., Hunstead, R., Macchetto, F., Roland, J., Rottgering, H., and Schilizzi, R. (1989). *ESO Messenger No. 56*, p. 16.
Mills, B. Y. (1981). *Proc. Astron. Soc. Aust.* **4**, 156.
Minkowski, R. (1960). *Astrophys. J.* **132**, 908.
Shaver, P. A. (1970). Ph.D. Thesis, The University of Sydney.
Shaver, P. A. (1991). *Aust. J. Phys.* **44**, 759.
Sholomitskii, G. B. (1965). *Sov. Astron. AJ* **9**, 516.
Spinrad, H., Smith, H. E., Hunstead, R., and Ryle, M. (1975). *Astrophys. J.* **198**, 7.
Sutton, J. M. (1966). Ph.D. Thesis, The University of Sydney.
Sutton, J. M. (1968). *Aust. J. Phys.* **21**, 221.
Tielens, A. G. G. M., Miley, G. K., and Willis, A. G. (1979). *Astron. Astrophys. Suppl.* **35**, 153.
Tzioumis, A. K. (1987). Ph.D. Thesis, The University of Sydney.
Wade, C. M. (1970). *Astrophys. J.* **162**, 381.
Westerlund, B. E., and Smith, L. F. (1966). *Aust. J. Phys.* **191**, 181.
Wyllie, D. V. (1969*a*). *Mon. Not. R. Astron. Soc.* **142**, 229.
Wyllie, D. V. (1969*b*). *Proc. Astron. Soc. Aust.* **1**, 235.

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