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Accurate Optical Positions for Radio Source Identifications*

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Abstract

The optical identification of strong radio sources was a key step in establishing a grid of southern hemisphere calibrators, both for Parkes and for Molonglo. However, the measurement of precise positions for these optical counterparts presented some special astrometric problems and led to some novel solutions. This paper summarises the progress of optical position measurement from a radio astronomer's viewpoint and examines the role of the COSMOS database against this background. The source 0007−44, from the first Parkes catalogue, is used as a case study to illustrate the present-day approach to optical identifications.

1. Introduction

In the 1960s and early 1970s, the pointing calibration of radio telescopes was almost invariably based on accurate optical positions for identified radio sources. This situation arose because the techniques for measuring optical positions were well established and the positional accuracy was far higher than could be obtained in the radio. The procedure consisted simply of bootstrapping the radio positions to their optical counterparts and then searching for further identifications.

The 'eternal triangle' of radio telescope calibration is depicted in Fig. 1. In the early days it was necessary to use other props to increase the likelihood of making the correct identification. For instance, many of the earliest identifications were with bright catalogued galaxies and, later on, with quasars selected through their ultraviolet excess; in both areas John Bolton (1982, 1990) led the way. However, there is a complication arising from the path defined by Fig. 1. In adopting optical positions as radio calibrators we are making a tacit assumption that radio and optical positions coincide. While this assumption is probably reasonable for the most compact radio sources, it is almost certainly an oversimplification where the radio angular size is $> 10''$ or so. The way out of this dilemma has been to collect a sufficiently large number of calibrators and hope that, on average, there would be no overall systematic displacement between radio and optical centroids.

However, there were *never* enough calibrators, especially in the far south. This mattered more for the fully-steerable Parkes telescope than for the Molonglo pencil-beam cross telescope. Being a transit instrument, the Molonglo Cross

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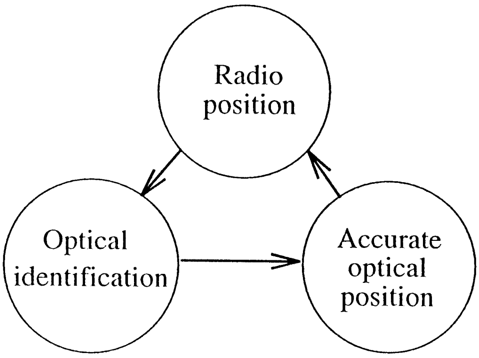


Fig. 1. Flowchart depicting the feedback path which led to progressive refinement of the pointing calibration of radio telescopes, especially through the 1960s and early 1970s.

was clearly less versatile than Parkes but compensated for this in having more accurate and predictable pointing. Early comparisons between Molonglo and Parkes positions (Hunstead 1969) revealed significant systematic errors in the Parkes right ascensions; John Bolton (personal communication) attributed these errors directly to the shortage of calibrators in some regions of the southern sky.

Section 2 gives an outline of the techniques used to obtain accurate ($<1''$) optical positions for southern radio source identifications through the 1960s and 70s, and some of the main results. A detailed account of the identification program at Parkes has already been given by Savage and Wall (1994). Section 3 uses the blank field source 0007–446 to highlight some of the issues to be considered in securing complete optical identifications for a radio-selected sample. Prospects for the future are discussed in the final section.

2. Optical Position Measurements—Historical

(2a) *Techniques*

While the benefits of an optically-based calibration grid are clear, the measurement of precise positions for the optical counterparts of strong radio sources presents some special astrometric problems. The most important problem arises from the faintness of the identifications themselves, a consequence of the strong evolution of the radio luminosity function (see Jasper Wall's paper, this issue p. 625). Two separate approaches were used through the 1960s: (i) special plates were taken at the large optical telescopes, requiring the use of dedicated measuring machines; and (ii) rough position estimates were obtained from the Sky Atlas of the National Geographic Society Palomar Observatory Sky Survey (Minkowski and Abell 1963), which was used almost exclusively as the initial search medium.

The Palomar Sky Survey covers the sky north of declination $-33°$ on 935 pairs of plates in the red and the blue, reaching limiting magnitudes of 20·0 and 21·1 respectively (Minkowski and Abell 1963). The southern extension to the Sky Survey carried out in 1964 and 1965 by Dr John Whiteoak (Bolton *et al.* 1965) provides single colour (orange) coverage down to $-45°$ with a slight reduction in limiting magnitude to 19·5.

At the time, there was a widespread belief that the Sky Atlas prints were unsuitable for measuring positions to better than a few arcseconds. Our measurements with a simple travelling microscope, however, suggested that an accuracy of 1 arcsecond could be achieved. This was enough to trigger the construction in 1970 of a purpose-built X–Y measuring machine at Sydney University, specifically to accommodate the 35×35 cm prints and second negative glass plates of the Palomar Sky Survey (Hunstead 1991). The accuracy we achieved ($\sim 0 \cdot 3$ arcsec errors in each coordinate; Hunstead 1971) was far higher than expected, and directly comparable with that obtained by Kristian and Sandage (1970) using special plate material from Palomar and a more sophisticated measurement and reduction technique.

Most importantly, the establishment of the Palomar Sky Survey as a viable astrometric medium was a crucial step in giving radio astronomers ready access to accurate optical positions. Shortly after the publication of this first sky-survey-based optical position paper (Hunstead 1971) a request was received from John Bolton at Parkes for copies of all the drawings for the measuring machine.* The Parkes copy of the Sydney machine confirmed the claimed accuracies, as did similar measurements made at the Institute of Astronomy, Cambridge (see the Discussion at the end of Hunstead 1974).

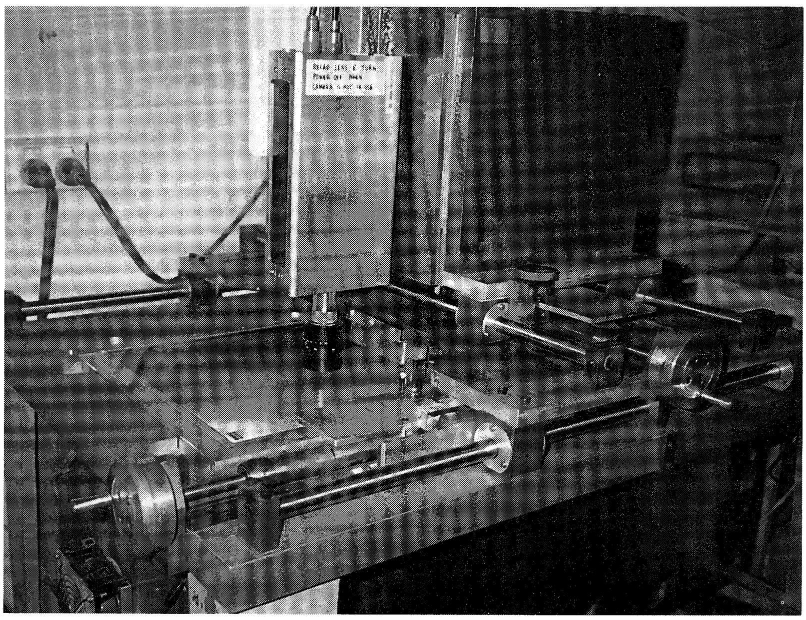


Fig. 2. The Sydney University version of the Bolton Machine, showing the movable carriage which rides on cylindrical rails and carries the TV camera. The carriage can be moved rapidly to any location on a Schmidt plate or film and then clamped in position. The carriage can then be driven by handles attached to the leadscrews, and its x, y position measured using Inductosyn linear transducers.

Not content with the limitations of the very basic Sydney measuring machine, John Bolton took the design a stage further with the construction at Parkes of what became known as the 'Bolton Machine'. This used a TV viewing system instead of an eyepiece, and had digital encoders on the two axes. Several clones of the Bolton Machine were built, including one for Sydney University which was

* Jasper Wall (personal communication) reports that Bolton's initial reaction to the paper was anything but complimentary!

used for all radio source identification programs through the 1980s (see Fig. 2). Although its accuracy did not quite match that of the original machine, this was more than compensated by the lack of eye strain and the convenience in being able to interface the encoders directly to a PC. Four Bolton Machines were made: for Parkes, Sydney University, the Anglo-Australian Observatory and the UK Schmidt telescope on Siding Spring mountain. Graeme White has written a brief history of each machine, along with a discussion of their measurement errors (White 1984).

The 1980s saw the introduction of a new generation of high-speed automatic measuring machines such as APM (Kibblewhite *et al.* 1984) and COSMOS (MacGillivray and Stobie 1984). From a radio astronomer's viewpoint the major impact of these new machines has been the recent release of the object listing from the COSMOS digitised southern sky survey (Yentis *et al.* 1992). This includes positions, magnitudes, shapes, sizes and star/galaxy classifications of all objects found on the plates of the UK (now AAO) Schmidt southern sky survey. The COSMOS database is discussed further in Section 4.

(2b) Results

The first Parkes catalogue (Bolton *et al.* 1964) contained a number of identifications with bright galaxies ($V < 12{\cdot}5$). The first attempt at identifying the fainter, more distant counterparts of the majority of southern radio sources was carried out by Westerlund and Smith (1966) using deep plates taken with the Mt Stromlo 74-inch telescope. Because of the limited field of view of these plates it was necessary to employ a two-stage reduction using short-exposure transfer plates taken with the Uppsala Schmidt telescope. Positions were measured to an accuracy of $0{\cdot}5$ arcsec. Of the 18 sources studied south of declination $-35°$, 11 identifications were claimed, all with galaxies having $V < 17$. Although QSOs had been discovered more than two years before this paper was submitted for publication, it seems that only galaxies were considered as radio source counterparts, possibly because of the much higher chance rates for associations with stellar objects. Amongst the 18 sources in the Westerlund and Smith sample there are now known to be three QSOs (PKS 0125–41, 0251–67 and 2204–54; Hewitt and Burbidge 1987). The *only* unidentified source is PKS 0007–44 which is the subject of further investigation in Section 3.

Bolton (1968) determined accurate optical positions for 78 identified sources between declinations of $-33°$ and $+20°$ using special plates taken at the Palomar Schmidt telescope. Measurements were made using a semi-automatic measuring machine giving quoted (random) errors ranging from $\sim 0{\cdot}3$–$1{\cdot}0$ arcsec. However, the positions of Bolton's reference stars were not updated to the plate epoch by applying proper-motion corrections, with the result that systematic errors of a similar magnitude were introduced.

Ekers (1970) extended the earlier work of Westerlund and Smith (1966), using the same techniques, and classified the fields of 46 sources south of $-44°$. Seven new identifications were proposed, including the peaked-spectrum radio galaxy 1934−63, which has become the primary calibrator for the Australia Telescope and most other southern hemisphere radio telescopes.

Hunstead (1971) reported accurate optical positions for 87 identified sources between declinations $+19°$ and $-80°$ using the new two-coordinate measuring machine described above. Measurements for 76 of the sources were made on the paper print and glass copies of the Palomar Sky Survey. New identifications were proposed for nine sources south of $-40°$, again using plates from Mt Stromlo, most of which had been taken some years earlier by Ron Ekers and Bob Shobbrook. The more accurate Molonglo 408 MHz positions (Hunstead 1972) allowed radio–optical associations to be established on the basis of positional agreement alone, marking a major shift in the approach to optical identifications. One of the southern QSOs identified in this program, 1610−77, was the source used in 1988 to record the first fringes from the compact array of the Australia Telescope.

Hunstead *et al.* (1971) reported identifications for a further ten sources south of $-45°$ with accurate Molonglo 408 MHz positions, using deep image-tube plates taken with the 60-inch reflector at the Cerro Tololo Interamerican Observatory in Chile. Transfer plates were taken with the Curtis Schmidt at CTIO.

Wall (1973) measured accurate optical positions for 39 QSOs and five radio galaxies between declinations of $+24°$ and $-68°$, mostly on specially taken plates from Palomar, Mt Stromlo or Siding Spring. Some of these measurements were made with the Parkes copy of the Sydney two-coordinate machine. Further position measurements with the Parkes machine, this time using the blue prints of the Palomar Sky Survey, were reported by Vander Haegen (1976).

By the mid-1970s the measurement of optical positions for radio source identifications had become a routine matter, especially with the introduction of the 'Bolton Machine'. The next major advance came with the southern sky survey carried out by the UK/AAO Schmidt telescope at Siding Spring Observatory. Reaching more than two magnitudes fainter than the northern survey, and with excellent image quality, the southern Schmidt plates were a revelation to those of us accustomed to the fuzzy images from the Palomar Sky Survey.

However, even with these deeper plates there were still many strong sources with no optical counterpart. In the following section, one such blank-field source is examined in greater detail.

3. Digression—0007–446: A Case Study

(*3a*) *Pre-1990 data*

The strong, high Galactic latitude source 0007−446 (≡PKS 0007−44 ≡ MSH 00−4*3*) is the third entry in the first Parkes catalogue (Bolton *et al.* 1964, hereafter BGM). It has a steep radio spectrum ($\alpha = -1\cdot1$; $S \propto \nu^{-\alpha}$) from 408–2700 MHz and has remained unidentified for three decades. It is listed by BGM as being extended $\sim 1'$ NS although, as we will see later, this is not supported by recent observations at higher resolution.

The first attempt at an optical identification was by Westerlund and Smith (1966), based on the BGM catalogue position and using a deep 103a-D plate taken with the Mt Stromlo 74-inch telescope (see Fig. 3*a*). 0007−446 was also included in the identification paper by Ekers (1970) and its optical field was classified as containing a star of unknown colour within a 3σ error rectangle of an accurate 2650 MHz position determined by Shimmins *et al.* (1966)—see

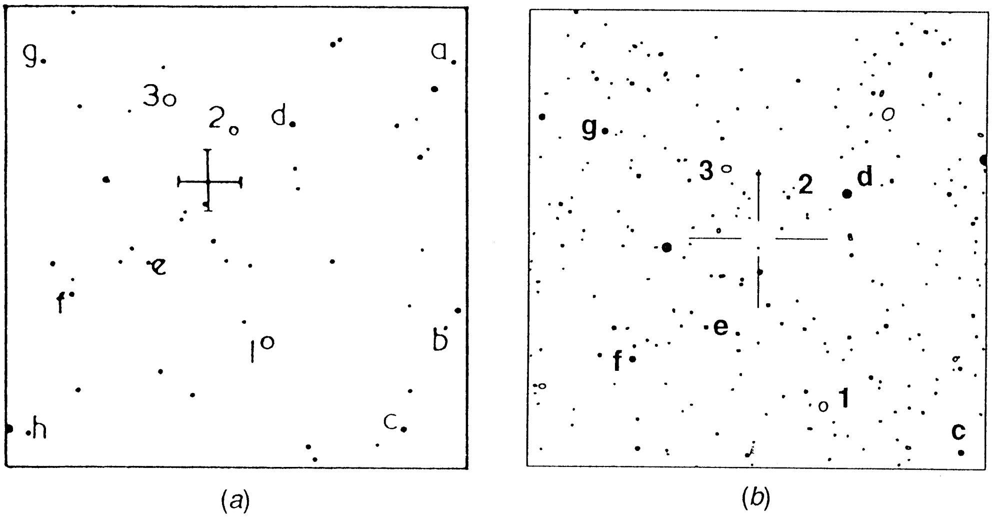


Fig. 3. Finding charts ($15' \times 15'$) for the optical field of 0007−446; north is up and east is to the left. Stars are plotted as filled dots and galaxies as open circles or ellipses. (*a*) Chart reproduced from Westerlund and Smith (1966); the cross marks the BGM radio position and the lengths of the arms define the maximum errors. Reference stars are labelled with letters and galaxies with numbers. (*b*) Chart generated from the COSMOS database. The same labels are used but the field is now centred on the MOST centroid position; the MOST error box is about the size of the star dot immediately south of the field centre.

Fig. 4*a*. A later Parkes position by Bolton and Shimmins (1973), as part of the 2700 MHz survey, did not change the story, nor did a more accurate position from the Molonglo Reference Catalogue (MRC) at 408 MHz (Large *et al.* 1981).

0007−446 belongs to a sample of 232 strong southern radio sources—the Molonglo Southern 4 Jy (MS4) sample (Burgess and Hunstead 1994)—being studied by Ann Burgess. As part of this study the source was observed at 843 MHz with the Molonglo Observatory Synthesis Telescope (MOST) in 'snapshot' mode (Hunstead 1991). The new information provided by MOST was that the source was slightly extended, with a deconvolved gaussian size of 33″ FWHM in position angle 65°.

It was hoped that the more accurate MOST centroid position would help to secure the optical identification. Such was not the case. The finding chart from Westerlund and Smith (1966) is shown in Fig. 3*a*, alongside a computer-generated finding chart from the COSMOS digitised southern sky survey (Yentis *et al.* 1992) in Fig. 3*b*. Both charts have the same scale but slightly different centres; Fig. 3*b* is centred on the MOST position. Despite the fact that the blue-sensitive Schmidt survey plate reaches fainter magnitudes than the Mt Stromlo plate in Fig. 3*a*, the optical counterpart of 0007−446 is still too faint (or too red) to be recorded.

A summary of all the radio position measurements for 0007−446 is given in Table 1, ordered by date. In the span of three decades the positional accuracy has improved by more than a factor of 100, and it is encouraging to note that the positions are all self-consistent.

(*3b*) *Probing Deeper*

It has been known for many years that the steepest spectrum sources from low-frequency surveys tend to fall in blank optical fields. However, it was only after follow-up spectroscopy on some of the steepest spectrum 4C sources that they were revealed to be high-redshift galaxies (up to $z = 3 \cdot 8$) with unusual aligned radio and optical structures (Miley *et al.* 1989). The radio morphologies are typically FR II (Fanaroff and Riley 1974), as expected for high-luminosity radio galaxies. For reasons which are still not well understood, the optical continuum images are usually elongated roughly in the direction of the radio axis and sometimes extend as far as the radio lobes.

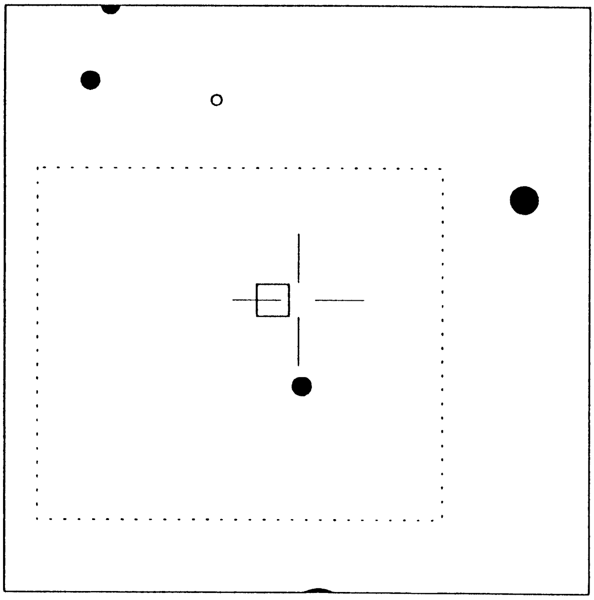
Table 1. Position for 0007–446

	Right Ascension (B1950)				Declination (B1950)				Frequency	Reference*
	h	m	s	s	°	′	″	″	MHz	
Radio:										
	00	08	12	±12	−44	40		±4′	85·5	MSH60
	00	07	58	±3·4	−44	40	00	±36	1400	BGM64
	00	08	00	±1·3	−44	39	47	±12	2650	SCE66
	00	07	59·6	±2·5	−44	39	40	±27	5009	SB72
	00	07	58·9	±1·3	−44	39	37	±14	2700	BS73
	00	07	59·7	±0·3	−44	39	41	±3	408	MRC81
	00	07	59·6	±0·8	−44	39	36	±7	4850	GVSC94
	00	07	59·39	±0·09	−44	39	38·1	±1	843	MOST centroid
Optical:										
	00	07	58·90	±0·05	−44	39	37·1	±0·5	—	This paper

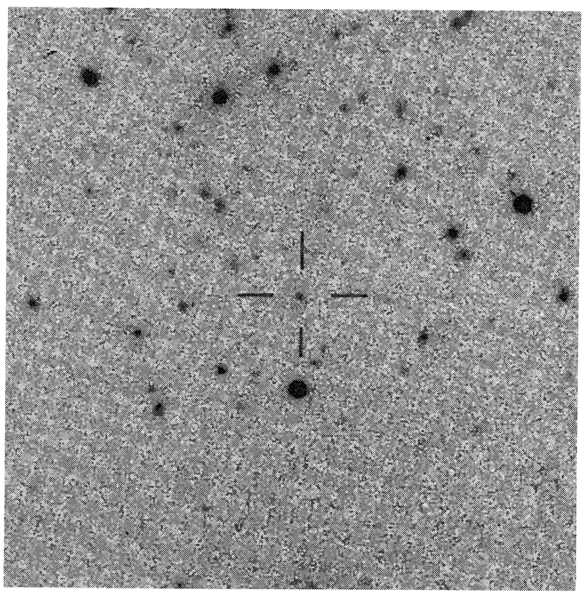
* MSH60 = Mills, Slee and Hill (1960); BGM63 = Bolton, Gardner and Mackey (1964); SCE66 = Shimmins, Clarke and Ekers (1966); SB72 = Shimmins and Bolton (1972); BS73 = Bolton and Shimmins (1973); MRC81 = Large *et al.* (1981); GVSC94 = Gregory *et al.* (1994).

Three observational ingredients were needed to test whether 0007−446 belonged to this class of high-z radio galaxies: a high-resolution radio image, a much deeper optical image and an optical spectrum. A 'snapshot' image of 0007−446 at 4·8 GHz was obtained in August 1990, during one of the first scheduled observing runs with the five-element Australia Telescope compact array. A deep R-band CCD image of the field was obtained in a 300 s exposure at the prime focus of the 3·9 m Anglo-Australian Telescope in August 1993. This revealed a non-stellar object close to the radio positions in Table 1 with an estimated magnitude of $R = 23$; a second image, taken in better seeing, was obtained in May 1994. As yet we have no spectroscopic data.

A comparison between the COSMOS finding chart and the deep (May 1994) CCD image, at the same scale, is shown in Fig. 4. With the field of view now reduced to $2' \times 2'$ the COSMOS field in Fig. 4*a* is rather empty, while the R-band AAT image in Fig. 4*b* reveals many faint galaxies not seen on the Schmidt plate, including one which is very close to the MOST centroid. The position of the proposed galaxy identification, measured relative to the two closest objects in the COSMOS finding chart, is given in Table 1.

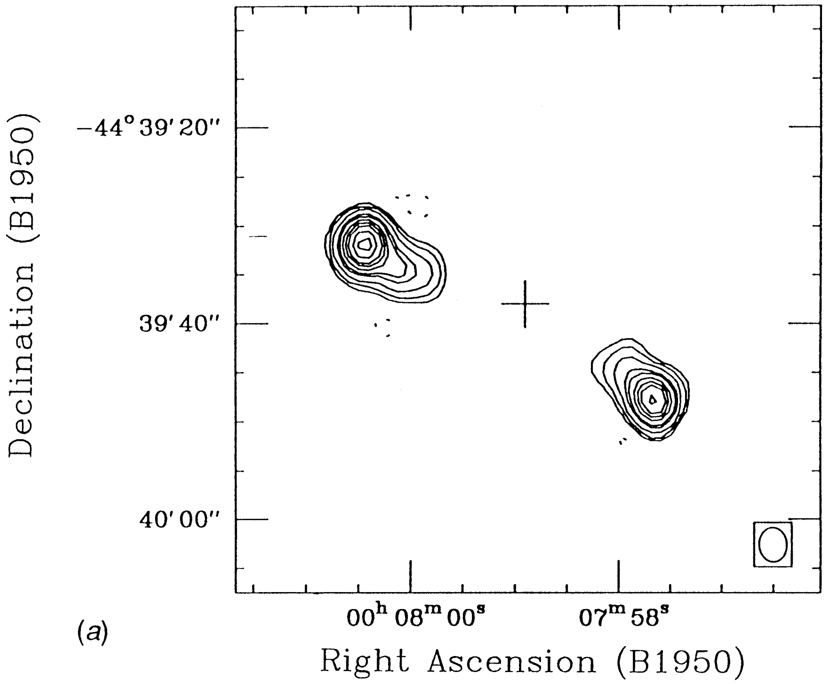


(*a*)

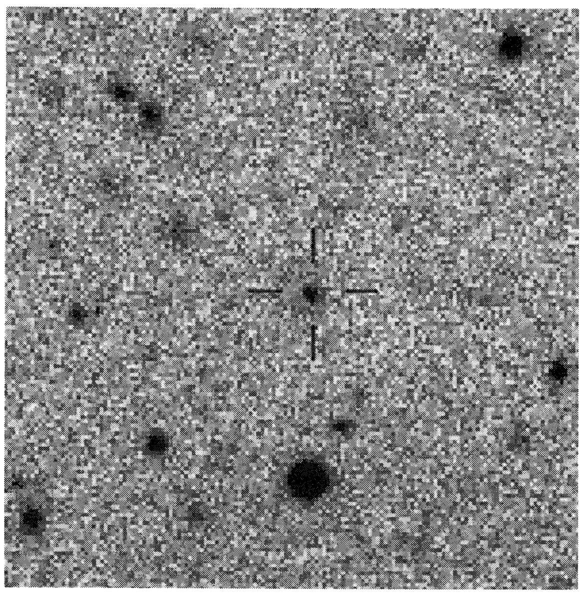


(*b*)

Fig. 4. Finding charts ($2' \times 2'$) for 0007−446 prepared from (*a*) the COSMOS database (see Fig. 3), and (*b*) a 300 s AAT *R*-band CCD image. In (*a*) the 3σ error region from Ekers (1970) is shown dotted, while the corresponding MOST error rectangle is drawn with a solid line. The location of the proposed galaxy identification is marked in each panel with an open cross.



(a)



(b)

Fig. 5. (*a*) AT radio image of 0007−446 at 4·8 GHz. Contour levels are at −2, 2, 4, 8, 15, 20, 30, 40, 50, 70 and 90 per cent of the peak flux density of 114 mJy/beam; the synthesised beam is shown in the SW corner. The map area is $1' \times 1'$ and the cross marks the position of the proposed galaxy identification. *(b)* The AAT *R*-band CCD image reproduced to the same scale as *(a)*. The galaxy image, marked with a cross, is compact but clearly non-stellar, showing slight elongation in a position angle close to that of the radio axis.

Have we located the correct identification? In Fig. 5 we zoom in to a still smaller field of view of $1' \times 1'$. Fig. 5*a* shows the AT radio image (resolution $4''$) which has a classic FR II morphology showing compact lobes with back-flow extensions pointing along the source axis towards the central engine. The proposed galaxy identification lies on this axis (which is slightly bent), closer to the midpoint of the lobes than the centroid. It is also worth noting that the galaxy image in Fig. 5*b* is slightly elongated (by $\sim 2''$) in a position angle close to that of the radio axis.

The radio lobe separation of $34''$ in position angle 62° is consistent with the deconvolved MOST estimate but disagrees with the earlier BGM value. Without a redshift we can only obtain a rough estimate for the corresponding linear size. Assuming an Einstein–de Sitter cosmology with $H_0 = 50\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, and $z \sim 0{\cdot}5$ (based on the R magnitude), the linear size is $\sim 0{\cdot}25$ Mpc, close to the median value at this redshift (Kapahi 1987). The unequal lobe strengths could readily account for the MOST centroid falling $\sim 5''$ east of the galaxy position.

The message that emerges from this case study is that it is not at all straightforward to define objective criteria for automatically accepting or rejecting a radio–optical association. Each case needs to be examined on its merits. Radio structural information is crucial in directing the search for an identification, but so too is a deep optical image.

4. Optical Position Measurements—Future Prospects

The faint limiting magnitude and high image quality of the UK/AAO Schmidt sky survey have certainly eased much of the pain formerly associated with identifications in the south. However, the better images have not led to significant improvements in positional accuracy. In the 20–30 years between the northern (Palomar) and southern surveys, the star positions in the reference catalogues have become progressively contaminated due to the propagation of errors in stellar proper motions. There are also known to be significant warps in the the fundamental catalogues, especially in the south. It is hoped that the database now being assembled from the *Hipparcos* astrometric mission will iron out both these problems and, in conjunction with the *Hubble Space Telescope*, establish a direct tie to the VLBI extragalactic reference frame (see White *et al.* 1990 and references therein).

In the meantime we have COSMOS, which has proven to be an extremely valuable resource, but one requiring a certain amount of care in its use. In a paper dealing with the automatic optical identification of radio sources, Unewisse *et al.* (1993) pointed out some of the shortcomings of COSMOS, including

(a) missed objects, generally due to errors in the deblending routines;
(b) inaccurate positions, including significant systematic errors;
(c) misclassification, mostly of galaxies as stars; and
(d) no data in regions of high star density (Galactic plane $|b| < 10°$, Magellanic clouds).

To deal with (a) and (c) there is ultimately no alternative but to inspect the plate or film copies; this can now be done electronically using the NASA/STScI digitised sky survey which is available in compressed form on CD ROM. In the case of (b) significant progress has been made in the last two months. It was discovered, as the result of an extensive series of inter-comparisons, that the systematic errors arose from an incorrect precession routine used at ROE to generate the COSMOS positions. We are still left with the random errors, however. These are typically $\sim 1 \cdot 3$ arcsec rms, significantly worse than can be achieved using, say, the Bolton Machine. On the other hand, the COSMOS positions are based on whole-plate solutions, and it is likely that at least some of the random error is the result of plate distortions which have not been adequately parametrised. It may be possible to achieve higher accuracy by recovering the original COSMOS x, y values and carrying out *local* plate solutions over areas of 3 $\deg^2$ or less, preferably using only the fainter reference stars, which are less likely to have their centroid positions affected by asymmetric ghosts (M. Drinkwater, personal communication).

The next generation automatic measuring machine, SUPERCOSMOS (Dodd and MacGillivray 1991), is about to be commissioned at the Royal Observatory, Edinburgh. Offering improved speed and positional accuracy over COSMOS, the new machine is expected to meet the foreseeable future demand for highly accurate positions for multi-object spectroscopy, and for direct or transfer positions for radio source identification programs.

At present, we can be confident of the registration of radio and optical frames at the $0 \cdot 3$–$0 \cdot 5$ arcsec level in most parts of the sky. With the expected improvements to star positions and proper motions from the *Hipparcos* mission it is anticipated that registration can be tightened to around $0 \cdot 1$ arcsec. However, the accurate alignment of radio and optical images at a level of $0 \cdot 01$–$0 \cdot 1$ arcsec—already a pressing need for the comparison and interpretation of VLA (and MERLIN) and *HST* images—is unlikely to be achieved routinely for several years to come.

Finally, it is worthwhile recalling the transition that has occurred over the past 30 years, from the early days when radio telescopes relied on optical positions for their calibration, to the present where radio positional accuracy has far outstripped optical. The balance has shifted to the point where the science is now being compromised. To rectify this situation we need further space missions like *Hipparcos*, and a change in attitude among astronomers and funding agencies to recognise the crucial rôle of astrometry in extracting the best science from existing (and future) ground and space facilities.

Acknowledgments

It is a pleasure to thank Ann Burgess for permission to include her AT and AAT images of 0007−446, and for her assistance in preparing them for publication. I also thank Graeme White, Ann Savage and Jasper Wall for collectively twisting my arm to present this paper, and also for jogging my memory of those early halcyon days. The MOST is supported by grants from the Australian Research Council, the University of Sydney Research Grants Committee, and the Science Foundation for Physics within the University of Sydney. Observing trips to the AT and AAT have been supported by grants from the ARC Small Grants Scheme.

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