Accurate positions, fluxes and structure for 6603 southern radio sources.

by

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ABSTRACT

We present the results of a programme to measure accurate positions (s.e. <1 arcsec), radio fluxes and simple radio structure for 6603 sources drawn from the Parkes-MIT-NRAO (PMN) Southern Survey ($-87.5^{\circ} < \delta < -37^{\circ}$). The measurements were made using the Compact Array of the Australia Telescope National Facility at simultaneous frequencies of 4800 and 8640 MHz. We observed all objects in the PMN Southern point source catalogue (Wright *et al* 1994) which had flux densities at 4850 MHz ≥70 mJy, which lay in the declination range ($-87^{\circ} < \delta < -38.5^{\circ}$), and which had galactic latitudes greater than 2°. In addition, for the most southerly zone of our observations ($-87^{\circ} < \delta < -73^{\circ}$), the flux limit was lowered to 50 mJy. In all, we list a total of 7177 components for 6603 southern sources.

1. INTRODUCTION

The Parkes-MIT-NRAO (PMN) multi-beam radio surveys took place during 1990. They were a joint collaboration between institutions in Australia and the USA to survey the whole of the southern, and some of the northern, sky at a frequency of 4850 MHz. The survey limits were around 30 mJy for the most southerly zones, although dependant on declination. The PMN Surveys complemented and extended the northern surveys of Condon *et al* (1989) and increased the number of known, southern radio sources over those found in the earlier Parkes 2700 MHz and Molonglo 408 MHz surveys by almost an order of magnitude. A full description of the details of the PMN surveys and the data reduction techniques employed are contained in Griffith & Wright, 1993 (hereinafter Paper 1).

The point source catalogues resulting from the PMN surveys for the Southern zone ($-37^{\circ} < \delta < -87^{\circ}$), Tropical zone ($-29^{\circ} < \delta < -9.5^{\circ}$) and Equatorial zone ($-9.5^{\circ} < \delta < +10^{\circ}$) have been published, both in printed and machine-readable form (Wright *et al* 1994, Paper 2; Griffith *et al* 1994, Paper 3; Griffith *et al* 1995, Paper 6). In addition, FITS-format images of these survey zones are also available, as described in Condon *et al*, 1994; Paper 4 and Tasker *et al*, 1994; Paper 5. The point source catalogue and maps for the final survey zone, the Zenith zone ($-37^{\circ} < \delta < -29^{\circ}$) have recently been finalised and will be published shortly (Wright *et al* 1995, Paper 8; Tasker *et al* 1996, Paper 9). Point source catalogues for all zones are available for downloading via anonymous FTP from ***ftp.atnf.csiro.au*** in the area ***/pub/data/pmn/CA***.

The accuracy of the positions of the sources contained in the point source catalogues depends on the flux density, as described in Papers 2 & 3, but was typically around 15 arcsec (standard error) in each coordinate. However, in order to identify radio sources unambiguously with their optical counterparts, without regard to their optical colour or morphology, positions must be determined with a standard error of less than 2 arcsec — or even more accurately in regions of high star density.

With this goal in mind, we have undertaken a programme of re-measurements of the stronger sources contained in the Southern PMN survey. The criteria used to select sources are given in the following table (Table 1).

TABLE 1

Declination range (J2000)	Flux limits	Galactic latitude
($-87^{o} < \delta < -73^{o}$)	$S_{4850} \geq 50$ mJy	$\lvert b \rvert \geq 2^{o}$
($-73^{o} < \delta < -38.5^{o}$)	$S_{4850} \geq 70$ mJy	$\lvert b \rvert \geq 2$

These re-measurements have provided positions with a typical accuracy (standard error) of around 0.6 arcsec in each coordinate for the stronger compact sources, flux densities at both 4800 and 8640 MHz, and structural information for the individual source components which is sufficient to outline the gross morphology of the sources.

2. OBSERVATIONS

2.1 Observing method

All observations were made using the Compact Array of the Australia Telescope National Facility. Briefly, this array consists of six, 22-m telescopes arranged along an East-West baseline spanning 6 kilometres. The present observations were made in several sessions from 1992 to 1994. A variety of configurations ("6A", "6C" & "6D") was used, with minimum baseline separations ranging from 77 to 337m and maximum separations of close to 6000m.

Observations were made simultaneously centred on two frequencies of 4800 MHz and 8640 MHz. The total correlator bandwidth at each observing frequency was 128 MHz, although only the central 50% of each band was used so as to reduce "bandwidth smearing" of the synthesised images caused by frequency averaging. For each band, two orthogonal linear polarisations were combined and the data averaged on-line so as to provide a total intensity.

Phase and position calibration of the target sources was performed using standard ATNF Compact Array calibrator sources, which were observed once every 30 target sources (see below). We flux calibrated the data using daily observations of the standard source PKSB1934-638, for which we have adopted flux densities of 6.33 Jy (at 4800 MHz) and 2.59 Jy (at 8640 MHz).

Our observing method made brief "cut" observations of the target sources, each lasting about 45 seconds. Every source was observed 3 times: once approximately 4 hours East of transit, once near transit, and once approximately 4 hours West of transit. The profile resulting from each cut observation was reduced and displayed in real time, thus permitting data quality to be continuously monitored. When 3 cuts had been obtained at the three different hour angles, the profiles were reduced and combined to produce positions and fluxes for all source components.

2.2 Scheduling

For efficient observing, we divided the Southern survey sources into declination bands. Each band had a width defined such that it contained an average of 60 sources per hour of right ascension. This permitted the telescope control system to move the dishes between sources at a regular rate of 1 source per minute while remaining at almost exactly the same hour angle in the sky.

For each band, we further divided the sources into "packets" of 30 target sources plus one nearby phase-calibrator source. Typically, the calibrator source lay within 10 degrees of the centre of the source group. The calibrator was observed at the start of each packet and this information used to calibrate the positions of the associated target sources in the *CASNAP* program (see below).

In principle, 4 hours of observing in the East could be followed by 4 hours near transit and then 4 hours in the West, so that three days of continuous observing would complete a declination band. In practice, however, we had to vary the times spent observing in each sky "window" so as not to return to a part of the sky which had already been observed 24 hours earlier.

Approximately 10% of the target objects had to be re-observed in order to obtain satisfactory data. Where this occurred, we tried to re-observe all three cuts for the source on the same day so that any possible variability would not influence the data quality.

2.3 Data Reduction

We developed two special reduction programs specifically for our observing programme. The first, *CASNAP*, read the bandwidth-averaged data from the array correlator computer and produced and displayed the CLEAN-ed cuts while the observing was taking place.

The principle steps in the *CASNAP* reduction were:

1: We calibrated each of the target fields in a 30-source "packet" for both amplitude and position using the associated calibrator observed at the start of the packet.

2: The calibrated visibilities were averaged over the 45s observing time for each source.

3: We flagged sources which had anomalously high or low visibilities relative to the median amplitude over all baselines. However, we ignored anomalously high visibilities on the shortest baseline (either 75 or 300m, depending on the array configuration) because of the possibility of extended emission.

4: For each snapshot or "cut", we determined both a "dirty source" cut profile and the related "dirty beam" cut profile. The dirty source cut profile was determined by Fourier transforming the observed visibilities. We applied a scaling factor for both the beam and source cut during this process to account for the fore-shortened baseline spacings.

5: We deconvolved each source cut using a standard implementation of the Högbom CLEAN algorithm, and accumulated the CLEAN components. The CLEAN was terminated either when the residuals converged or when the maximum number (500) of CLEAN iterations was reached.

6: Based on the known half-power beam width (HPBW) of the array, we tested whether any of the CLEAN components were unrealistically close to each other. If so, we re-combined them into a single component.

7: We sorted the CLEAN-ed components for each cut into flux order and retained only the two most significant. This, we justified as follows: at the flux levels at which we were working, the statistics of the source counts showed that there was very little chance of two *un*related sources occurring in the same field. And our three-cut observing method did not permit us to delineate accurately the structure of sources which had more than two components.

8: We optimised the position and flux values of each of the "cut-components" by minimising the square of the difference between the modelled and observed visibilities.

9: We displayed the *CASNAP* results on-line in order to monitor the data quality and logged the modelled cut-component values to a database for further processing by the *POSNAP* program. This completed the *CASNAP* reduction.

The *POSNAP* program combined the reduced cut-component data from the individual cuts and automatically determined source component parameters once sufficient cuts had been obtained.

The main steps in the *POSNAP* procedure were:

1: The program checked that the cuts contributing to each source were separated in hour angle by at least 10 degrees and were well distributed across the sky. Experience convinced us that at least three cuts were required for adequate source fitting.

2: We modelled the positional uncertainty for each cut-component as a normal distribution whose dispersion was the quadrature sum of both a flux-independent and flux-dependent contribution. The component's uncertainty in position orthogonal to the cut was approximated as a uniform distribution of width equal to the processed field size, 120 arcsec.

3: We used the positional uncertainties and cut-component widths to model the probability that a cut-component appearing in each of the cuts was produced by a real source component. To do this, all possible cut-component combinations were determined and a probability product computed for each combination.

4: We ranked all products and iteratively processed the data to attempt to remove any degeneracy within an East-Transit-West cut-component combination. Such degeneracy would occur, for example, when the hour angle at which a particular cut observation was made was very similar to the relative orientation of two or more source components on the sky. The probability products were recomputed and surviving combinations re-ranked.

5: If the highest-ranked probability product allowed a non-degenerate, and significant, estimate of integrated flux, we noted this combination as representing a "real" source component. We then removed the cut-components contributing to the real source component from any other combinations and the residual fluxes were re-assigned. Steps 4 and 5 were repeated until either all the cut-components were "used" or the maximum allowable number of real sources components was reached.

6: We computed the best position and position error for each real source component using the spatial location and extent of its associated probability product. The integrated flux for a source component was computed as the noise-weighted average of the non-degenerate cut-component contributions. The maximum and minimum widths for a source component were determined directly from the CASNAP cut profiles.

7: We cross-correlated source components found at both of our observing frequencies (4800 and 8640 MHz) based on positional coincidence within a "3-sigma" region of combined uncertainty and computed spectral indexes based on the integrated fluxes where appropriate.

8: Finally, we manually inspected the source list and removed a few anomalies produced by the automated reduction procedure by combining multiple components into a single component for a few extended sources. In the great majority of cases, however, we have preferred to list the direct output from the automated process so that the user can make up his or her own mind as to the complexity or otherwise of the sources.

This completed the POSNAP reduction.

The main reason we were led to produce our own reduction software was that the reduction of data for several thousand sources using conventional, manual methods, such as *AIPS* or *MIRIAD*, is a very onerous task. Furthermore, conventional methods do not permit data quality to be assessed during observing. The main advantages of our method were that it was much faster and more automated than conventional methods. Its main disadvantage was that it did not combine the data from each cut prior source to fitting. This resulted in a poorer signal-to-noise on each source component.

As mentioned earlier, the Compact Array observations and our automated reduction method produced a result in approximately 82% (=6603/8068) of the sources observed. In the majority of cases we concluded that the reason no result was obtained in the other 18% of cases was that the sources were very extended and had been completely resolved by the Compact Array. This conclusion was reinforced by plotting the proportion of missing sources as a function of galactic latitude. As expected, the missing sources were located preferentially towards the galactic plane where such extended radio sources as HII regions and supernovae remnants predominate. However, we were also interested to know if more conventional reduction techniques would increase the number of detected sources. We therefore re-reduced the data for a small, representative group of objects using *MIRIAD*. Based on this sample, we conclude that a further 3% of objects would be detected if all the data was analysed using the more laborious method and this work may be undertaken some time in the future.

3. RESULTS

The PMN Southern Survey catalogue (Paper 2) lists a total of 8078 sources which conform to the criteria of Table 1. During the present programme of observations we observed 8068 of these objects, the 10 sources missed being caused by observing difficulties or errors in scheduling.

Presenting data for 6603 objects in tabular form presents a serious challenge. In addition, such large collections of data are increasingly required in "electronic" form, rather than as "hard copy". Therefore, we decided to publish the results from our work on the Australia Telescope's FTP server, which can be accessed using the account ***anonymous*** as:

ftp.atnf.csiro.au and in the area ***/pub/data/pmn/CA***.

In "hard copy" versions of this paper we present only a sample page of the main data table. The table may be downloaded in full from the above server, in plain-text ("ASCII") format, as:

table2.txt.

This directory area also contains a ***READ.ME*** file which should be read first for the latest information.

A typical ***ftp*** session might be as follows:

`ftp ftp.atnf.csiro.au`	(connect to the Australia Telescope National Facility's FTP server)
login: **`anonymous`**	(log in as an anonymous user)
password: *your password*	(supply your email address as a password)
`cd /pub/data/pmn/CA`	(change to the appropriate directory)
`ls`	(list all available files as a check)
`get READ.ME`	(to download the ***READ.ME*** file)
`get table2.txt`	(to download the ***table2*** data file)

where the commands to be typed are shown in a **`bold, monospaced`** typeface.

This paper, and the data, may also be read and downloaded from the Parkes World Wide Web HomePage, Surveys HomePage at:

http://wwwpks.atnf.csiro.au/databases/surveys/surveys.html

Table 2 lists the individual components for each PMN source observed. In this table, Column 1 contains the name of the PMN survey source from which the component is derived. Where multiple components were found for the same “parent” survey source, they have been indicated by an asterix. Note that there is no guarantee that these components are always physically associated, since there is a small, but finite, chance that two unrelated sources may close together on the sky.

Columns 2—7 refer to data at our lower observing frequency of 4800 MHz. Columns 2 and 3 list the source component right ascension and declination (equinox and equator J2000). Column 4 gives the peak flux (S_{peak}) measured for the source component (in mJy) while Column 5 gives the corresponding integrated, or total, flux (S_{tot}). Columns 6 and 7 give the major (W_{max}) and minor (W_{min}) half-power widths for the component measured from the three cuts. These have been normalised to the sizes of the telescope's synthesised beams, which were 1.5 arcsecs at 4800 MHz and 0.8 arcsecs at 8640 MHz. Thus, an unresolved source would have a width of 1.0 at either frequency.

Columns 8—13 list data similar to Columns 2—7, but refer to the higher observing frequency of 8640 MHz. Finally, in Column 14, we provide a spectral index for each component where this could be determined, defined between 4800 MHz and 8640 MHz and computed from the total fluxes, S_{tot}.

4. DATA QUALITY

In this section, we assess the quality of the data for the 7177 source components reported here. We also provide a brief comparison of the Compact Array data with the data for the corresponding sources found in the original PMN Southern Survey.

As mentioned in Section 2.1, positional calibration of the target sources was performed using 141 standard Compact Array compact calibrator sources of accurately known position. Since they are also catalogued in the PMN Southern Survey, they were also observed as ordinary target sources. Thus the positions measured for them during our programme could be compared with the more accurately known positions to provide an indication of the overall survey positional accuracy.

The results of this comparison suggest that standard errors of about 0.6 arcsec indicate the accuracy of the measured source components in each coordinate, at least for these stronger sources. The positional accuracy of the weakest sources is expected to be somewhat poorer (perhaps ~1.0 arcsecs) although we have not been able to determine this value accurately.

We have also compared the measured positions of 103 strong sources in our sample with those listed in PKSCAT90 (Wright & Otrupcek, 1990) as having accurate (s.e. <1 arcsec) positions. The dispersions are again consistent with standard errors ~0.6 arcsecs.

Estimating the flux density accuracy is difficult because extended objects may have been resolved by our high-resolution Compact Array observations. On the other hand, compact sources may have varied between the epochs of the original PMN surveys (circa 1990.5) and the Compact Array re-measurements (circa 1994). Despite this problem we thought it worthwhile to produce a comparison of the 4800 MHz Compact Array fluxes (after combining adjacent components where appropriate) with the original PMN fluxes (measured at 4850 MHz).

The resulting flux-flux plot is shown in Fig. 1. As expected, the plot shows the effects of resolution, with the higher-resolution, Compact Array fluxes being appreciably smaller than the Parkes 64-m telescope PMN fluxes in many cases. On the other hand, a few objects have *larger* fluxes when measured with the Compact Array, presumably as a result of variability between the epochs of the two surveys. However, there also appears to be a well-defined upper envelope to the majority of the data, which probably results from sources which have not varied appreciably between the two epochs. This envelope has a slope close to +1.0 in the logarithmic flux-flux plot and suggests that there is no appreciable systematic flux differences between the two sets of data.

In summary, we estimate that the standard error of the flux densities is given by:

$$\textit{standard error in flux}^2\ (mJy) = (5)^2 + (0.05.S)^2 \qquad \text{(4800 MHz) and}$$

$$= (8)^2 + (0.07.S)^2 \qquad \text{(8640 MHz),}$$

where S is the source flux density in mJy. The constant term in each equation originates from the noise on each source measurement whereas the flux-proportional term arises primarily from the uncertainties in the zenith angle gain calibration of the array dishes.

5. CONCLUSIONS & FUTURE WORK

We have observed 8068 of the stronger radio sources catalogued in the PMN Southern Survey using the Australia Telescope Compact Array. The selection criteria for these sources are defined in Table 1. Ten objects which satisfy these criteria were missed from our programme because of scheduling problems.

Of the 8068 sources observed, we detected at least one source component in 6603 of them. These sources revealed a total of 7177 individual source components. The 1465 sources which satisfied the PMN criteria but which were not detected by the Compact Array observations presumably have very extended structure and were totally resolved by the instrument.

The reduction of the data was made essentially automatically using two computer programs, *CASNAP* and *POSNAP*, which were developed specifically for our programme of observations. These programs were capable of producing fully-reduced data in real time.

The positional accuracy of the data reported here is about 0.6 arcsec for each component and in each coordinate at both frequencies. The flux density accuracy varies from about 5mJy for the weaker sources up to about 50mJy for a 1Jy source at 4800MHz.

The data is available as a table describing the individual source components. This table can be downloaded using "anonymous" FTP from the Australia Telescope National Facility's server, ***ftp.atnf.csiro.au*** .

Finally, we are undertaking a programme to produce high quality optical identifications for the 6603 sources listed above. This programme is now essentially complete (Tasker & Wright, 1993; Tasker, 1996). In addition, the accurate positions for the radio sources reported in this paper are being used to produce cross-correlations with catalogues compiled at other wavelengths. The results of this work will be reported in the near future.

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	4800 MHz						8640 MHz						
NAME	**RA**	**DEC**	**Speak**	**Stot**	**Wmax**	**Wmin**	**RA**	**DEC**	**Speak**	**Stot**	**Wmax**	**Wmin**	**SI**
	J2000	J2000	mJy	mJy	norm	norm	J2000	J2000	mJy	mJy	norm	norm	
J0000-4722	00:00:29.85	-47:21:47.2	6	64	11.5	1.0							
J0000-8539	00:00:12.04	-85:39:19.9	101	108	1.1	1.0	00:00:12.04	-85:39:19.9	69	70	1.0	1.0	**-0.7**
J0001-3931	00:01:43.08	-39:30:43.6	1	56	6.8	5.8							
J0001-4630	00:01:26.89	-46:30:12.4	85	106	1.2	1.0							
J0001-6715	00:01:20.90	-67:15:37.1	2	40	10.6	1.6	00:01:21.09	-67:15:38.3	7	16	1.9	1.2	**-1.6**
J0001-6849	00:01:50.63	-68:49:18.9	9	58	3.4	1.8	00:01:50.13	-68:49:22.1	2	28	9.1	1.3	**-1.2**
J0001-7051	00:01:01.92	-70:51:07.8	8	42	5.1	1.1							
J0001-7511	00:01:01.82	-75:12:00.2	79	97	1.2	1.0							
J0001-7609	00:01:23.23	-76:09:11.3	56	70	1.3	1.0	00:01:22.89	-76:09:12.8	8	29	3.4	1.0	**-1.5**
J0001-7702	00:01:04.21	-77:01:55.7	6	35	5.6	1.1							
J0002-5025	00:02:42.30	-50:24:46.9	96	96	1.0	1.0	00:02:42.29	-50:24:46.9	38	39	1.0	1.0	**-1.5**
J0002-5621	00:02:53.58	-56:21:11.4	245	310	1.3	1.0	00:02:53.59	-56:21:11.3	129	135	1.0	1.0	**-1.4**
J0002-6122	00:02:17.22	-61:22:16.1	6	111	4.8	3.8	00:02:17.42	-61:22:15.8	1	46	9.3	4.4	**-1.5**
J0003-4114	00:03:53.47	-41:15:00.0	72	79	1.1	1.0							
J0003-5444 *	00:03:11.91	-54:45:08.0	5	223	14.4	3.2							
J0003-5444 *							00:03:10.16	-54:44:55.4	1	122	21.6	6.8	
J0003-5905	00:03:13.29	-59:05:48.0	91	156	1.5	1.1	00:03:13.30	-59:05:47.9	38	77	1.6	1.3	**-1.2**
J0004-4033	00:03:57.85	-40:32:46.5	39	58	1.5	1.0							
J0004-4144	00:04:32.40	-41:43:54.1	43	84	1.7	1.1	00:04:32.39	-41:43:53.8	15	39	2.1	1.2	**-1.3**
J0004-4345	00:04:07.26	-43:45:09.5	77	156	1.9	1.0	00:04:07.26	-43:45:10.1	192	201	1.0	1.0	**0.4**
J0004-4736	00:04:35.66	-47:36:19.6	725	748	1.0	1.0	00:04:35.66	-47:36:19.7	715	736	1.0	1.0	**0.0**
J0004-5254	00:04:14.14	-52:54:58.4	32	52	1.6	1.0	00:04:14.15	-52:54:58.6	20	38	1.9	1.0	**-0.5**
J0004-5546	00:04:21.97	-55:46:56.2	7	86	6.3	1.9							
J0004-6413	00:04:17.18	-64:13:38.9	7	57	3.9	2.1	00:04:17.10	-64:13:38.7	2	26	5.3	2.2	**-1.3**
J0005-5049	00:05:08.13	-50:49:16.0	2	30	5.2	2.6							
J0005-5428	00:05:39.19	-54:28:31.7	2	74	9.4	4.3	00:05:39.07	-54:28:31.9	4	58	5.3	2.6	**-0.4**
J0005-5751	00:05:24.72	-57:51:53.3	107	164	1.5	1.0	00:05:24.72	-57:51:53.3	41	69	1.6	1.0	**-1.5**

Fig 1. Comparison of fluxes measured with the Compact Array (CA) and the original