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Phase Calibration Sources in the Northern Sky at Galactic Latitudes $\mid b \mid < 2.5°$

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ABSTRACT

The Jodrell Bank - VLA Astrometric Survey (JVAS) of flat-spectrum sources yielded a catalog of 2118 compact radio sources in the northern sky. Those sources are being used as phase calibrators for many synthesis arrays. JVAS suffers from a zone of avoidance because Galactic confusion prevented selection of flat-spectrum sources at $\mid b \mid < 2.5°$. This confusion problem was overcome by selecting variable GB6 sources in the JVAS zone of avoidance. A subset of these sources were observed at 8.5 GHz with the NRAO VLA in the JVAS style, leading to 29 compact radio sources in the zone of avoidance whose positions have been measured to an rms accuracy of about 10 mas or less. This extension of the JVAS lists to lower Galactic latitudes (1) improves the prospects for VLBA phase-referencing of Galactic targets and (2) strengthens the lists' usefulness for studies of the Galactic interstellar medium.

Subject headings: astrometry – catalogs – radio continuum – techniques: interferometric

1. MOTIVATION

The Jodrell Bank - VLA Astrometric Survey (JVAS) of flat-spectrum sources yielded a catalog of 2118 compact radio sources (Patnaik et al. 1992; Browne et al. 1998; Wilkinson et al. 1998). Each compact source (a) has a peak flux density at 8.4 GHz $\geq$ 50 mJy at a resolution of 200 milliarcsecond (mas); (b) contains 80% or more of the total source flux density; and (c) has a position known to an rms accuracy of 12−55 mas. The 2118 sources are uniformly distributed in the northern sky at Galactic latitudes $\mid b \mid \geq 2.5^\circ$ (Figure 1). Although these sources are primarily intended for use as phase calibrators for the Jodrell Bank MERLIN, they are also suitable as phase calibrators for the NRAO Very Large Array (VLA) and can be considered as candidate phase calibrators for the NRAO Very Long Baseline Array (VLBA) and for millimeter arrays (Holdaway, Owen, & Rupen 1994; Peck & Beasley 1998).

JVAS suffers from a zone of avoidance because Galactic confusion prevented selection of flat-spectrum sources at $\mid b \mid < 2.5^\circ$. Fortunately, there is another way of selecting potential phase calibrators that is less susceptible to Galactic confusion: seek sources that vary with time and must, therefore, have significant contributions from compact components. A seven-beam receiver was used on the former NRAO 91-m telescope, during 1986 November and 1987 October, to survey repeatedly the declination band $0^\circ \leq \delta_{\rm B1950} \leq +75^\circ$ at 4.85 GHz with a resolution of $3.5'$ (Condon et al. 1994). Gregory et al. (2001) used this database [1] to extract variability information for sources in the GB6 catalog (Gregory et al. 1996), the large unbiased sample of 75,162 sources derived from the combined survey images. GB6 sources were selected with $S \geq 25$ mJy and with a flux density variation $\Delta S > 2.5\sigma$ between 1986 and 1987. The sky distribution of these long-term GB6 variables was dominantly isotropic, implying an extragalactic population. Imposing a further constraint of $\mid b \mid < 2.5^\circ$ on these GB6 variables leads to 97 potential phase calibrators in the JVAS zone of avoidance. New VLA observations in the JVAS style of these GB6 variables would help supplement the JVAS lists, thereby improving the prospects for VLBA phase-referencing of Galactic targets and strengthening the lists' usefulness for studies of the Galactic interstellar medium.

2. OBSERVATIONS AND IMAGING

The VLA (Thompson et al. 1980) was used 1999 June 18 UT in its A (36-km) configuration to observe 53 of the 97 GB6 variables. Some additional sources initially suspected of variability were also observed (Gregory, Scott, & Poller 1998). Data were acquired in dual circular polarizations with bandwidths of 25 MHz and at center frequencies of 4.5351, 4.8851, 8.1149, and 8.4851 GHz. Observations were made assuming a coordinate equinox of 2000. Phase calibration sources were selected from the International Celestial Reference Frame (ICRF) as realized by VLBI (Ma et al. 1998), with positions from the reference frame update of 1998-6 in the VLBA correlator database (T.M. Eubanks, private communication). The switching time between phase calibrator observations was 6 minutes. Additional astrometric check sources, also selected from Ma et al. (1998), were included to quantify the observed astrometric accuracy. Table 1 lists all phase calibrators and check sources used.

[1] http://pulsar.physics.ubc.ca/gregory/index.html

Each source, whether a GB6 variable, a phase calibrator, or an astrometric check source, was scheduled in 2-minute observations. Separate observations were needed to acquire 4.5351 and 4.8851 GHz simultaneously, and 8.1149 and 8.4851 GHz simultaneously. Allowing for telescope drive and electronics settling time, this gives about 1 to 1.5 minutes of integration time per observation per source. Additional observations of J0137+3309 (3C 48), J0521+1638 (3C 138), J0542+4951 (3C 147), and J1331+3030 (3C 286) were used to set the flux density scale to an accuracy of 3% and to fix electric-vector position angles to an accuracy of 3°. Instrumental polarizations were determined to an accuracy of 0.1% through observations of the phase calibrator sources J0359+5057, J0547+2721, J1928+0848, J1935+2031, J2007+4029, and J2322+5057. Information on all Stokes parameters was obtained at all four frequencies. This paper tabulates astrometric and photometric results for Stokes I only, and at the highest possible angular resolution at 8.4851 GHz. Polarimetric and spectral information at matched, and lower, angular resolutions at all four frequencies will be presented elsewhere (T. E. Clarke, in preparation). The GB6 variables were observed at *a priori* positions taken from, in order of preference, the VLBA correlator database, Condon et al. (1998), or Gregory et al. (1996). All data were calibrated using the 1999 October 15 release of the NRAO AIPS software.

The 1999 December 31 release of AIPS was used to image all phase calibrators, astrometric check sources, and GB6 variables. The data were handled as described by Patnaik et al. (1992). Briefly, an automatic script was employed which first located the source by making a large image with a field of view 82″, from which the source position was obtained by fitting a quadratic to the brightest component using the program MAXFIT. If the fitted peak was less than 40 mJy per beam area (mJy/b), then the procedure was halted and the source was abandoned from further analysis. This 40-mJy filter passed all phase calibrators and check sources but only 30 of the GB6 variables. The automatic script next determined the source structure, by performing two iterations of phase only self-calibration and imaging. The final CLEANed images of Stokes I were convolved with a Gaussian of 200 mas FWHM and used to derive a total flux density $S_{\rm total}$, a peak flux density $S_{\rm peak}$, and an rms noise level σ. The error in $S_{\rm peak}$ is the quadratic sum of a 3% amplitude error and σ. For one GB6 variable that passed the 40-mJy filter, the VLA pointing position was $> 40''$ from the derived position and, because it is then difficult to distinguish source structure from delay smearing, that source was abandoned from this study.

Table 2 gives the astrometric and photometric results for the 29 GB6 variables that survived the automatic script and its quality control. A code "nvss" in the notes for 25 GB6 variables means that the *a priori* observed position was from Condon et al. (1998) and the position in Table 2 was derived from the script prior to self-calibration. A code "icrf" in the notes for 4 GB6 variables means that the *a priori* observed position was from the VLBA correlator database and the position in Table 2 is from that database. For these 4 GB6 variables and the 5 astrometric check sources in Table 1, the positions derived with the script can be compared to those from the VLBA correlator database. This comparison leads to a standard deviation in right ascension of about 4 mas and in declination of about 9 mas, which when combined in quadrature give a 2-dimensional astrometric error of about 10 mas. Only a few of the GB6 variables show interesting structure at 200-mas resolution (Figure 2).

Each compact source in the JVAS lists (a) has a peak flux density at 8.4 GHz $\geq$ 50 mJy at a resolution of 200 mas; (b) contains 80% or more of the total source flux density; and (c) has a position known to an rms accuracy of 12−55 mas (Patnaik et al. 1992; Browne et al. 1998; Wilkinson et al. 1998). Each GB6 variable in Table 2 has very similar properties: it is a compact source with (a) a peak flux density at 8.5 GHz $\geq$ 40 mJy; (b) 80% or more of the total source flux density; and (c) a position now known to an rms accuracy of about 10 mas (25 sources) or less (4 sources). These GB6 variables therefore effectively extend the JVAS lists of compact sources into the zone of avoidance at Galactic latitudes $\mid b \mid < 2.5°$. This has two important consequences. First, these GB6 sources can be considered as candidate phase calibrators for the VLBA, thereby improving the prospects for VLBA phase-referencing of Galactic targets. Second, the addition of these GB6 sources to the JVAS lists strengthens the lists' usefulness for studies of the Galactic interstellar medium, including scintillation (eg, Cordes & Rickett 1998), angular broadening (eg, Desai & Fey 2001), Faraday rotation (eg, Wrobel 1993), and both molecular and atomic absorption (eg, Liszt & Lucas 1998).

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Table 1. Calibrators Used

Name	Name
J0102+5824 check	J0603+1742 check
J0228+6721 phase	J0725−0054 phase
J0306+6243 check	J1928+0848 phase
J0359+5057 phase	J1935+2031 phase
J0423+4150 phase	J1953+3537 phase
J0443+3441 phase	J1957+3338 check
J0547+2721 phase	J2007+4029 phase
J0559+2353 check	J2322+5057 phase

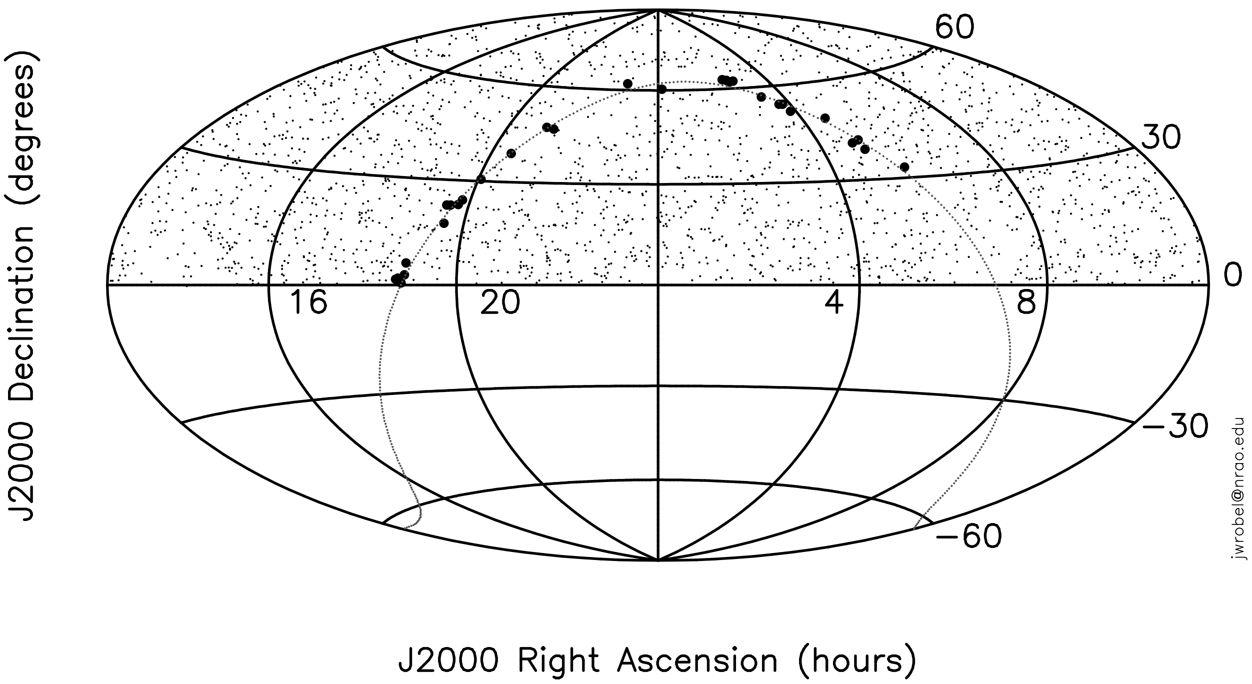
Table 2. GB6 Variable Sources at 8.5 GHz

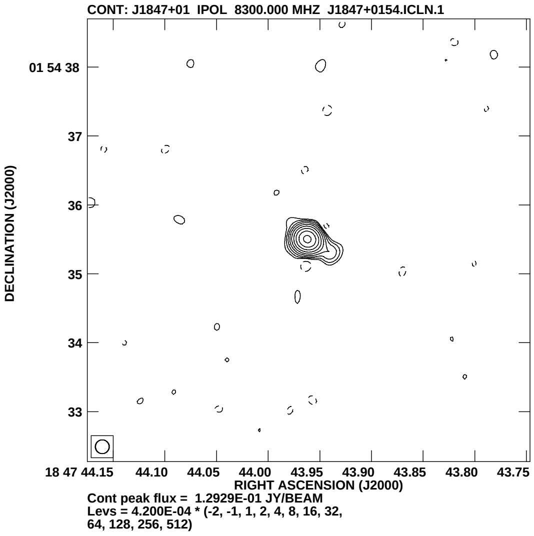
Name	b (°)	l (°)	α_{J2000} (h,m,s)	δ_{J2000} (°,′,″)	$S_{\rm total}$ (mJy)	$S_{\rm peak}$ (mJy/b)	σ (mJy/b)	Notes
J0008+6024	−2.0	117.6	00 08 19.0524	+60 25 01.254	52	44	0.18	nvss
J0223+6307	+2.1	133.1	02 23 29.6078	+63 07 17.298	106	98	0.17	nvss
J0231+6250	+2.2	134.1	02 31 59.1568	+62 50 34.202	125	122	0.16	nvss
J0235+6216	+1.8	134.7	02 35 20.6398	+62 16 02.334	76	74	0.17	nvss
J0244+6228	+2.4	135.6	02 44 57.6969	+62 28 06.515	765	751	0.22	icrf
J0317+5644	−0.6	142.0	03 17 54.9423	+56 43 57.795	147	143	0.18	nvss
J0340+5405	−1.0	146.1	03 40 06.4897	+54 05 38.771	50	53	0.16	nvss
J0346+5400	−0.5	146.9	03 46 34.5031	+54 00 59.100	449	443	0.21	nvss
J0350+5138	−2.0	148.8	03 50 25.0508	+51 38 38.721	118	117	0.15	nvss
J0438+4848	+1.3	156.4	04 38 59.1064	+48 48 46.628	335	308	0.19	nvss
J0450+4056	−2.2	163.7	04 50 43.6790	+40 56 13.986	367	376	0.23	nvss
J0502+3849	−1.8	166.8	05 02 32.4916	+38 49 54.937	212	199	0.17	nvss
J0502+4139	+0.0	164.6	05 02 37.9876	+41 39 19.343	795	792	0.24	nvss
J0541+3301	+1.4	176.1	05 41 49.4341	+33 01 31.909	89	93	0.16	nvss
J1844+0137	+2.2	33.6	18 44 50.9635	+01 37 17.548	52	62	0.19	nvss
J1847+0154	+1.7	34.2	18 47 43.9620	+01 54 35.500	154	127	0.19	nvss
J1851+0035	+0.2	33.5	18 51 46.7231	+00 35 32.348	972	872	0.39	nvss
J1855+0250[a]	+0.4	35.9	18 55 35.4366	+02 51 19.548	202	189	0.20	nvss
J1856+0610	+1.7	39.0	18 56 31.8384	+06 10 16.757	311	303	0.20	nvss
J1931+2243	+1.9	57.6	19 31 24.9168	+22 43 31.259	406	398	0.16	icrf
J1934+1732	−1.3	53.4	19 34 50.2056	+17 32 14.154	121	103	0.20	nvss
J1936+2246	+0.9	58.2	19 36 29.3042	+22 46 25.859	119	111	0.18	nvss
J1946+2300	−0.9	59.5	19 46 06.2515	+23 00 04.415	201	191	0.18	icrf
J1949+2421	−0.9	61.1	19 49 33.1432	+24 21 18.252	116	124	0.18	nvss
J2003+3034	−0.3	68.0	20 03 30.2448	+30 34 30.779	387	380	0.18	nvss
J2028+3833[a]	−0.2	77.5	20 28 54.0288	+38 32 48.144	42	49	0.16	nvss
J2102+4702	+0.3	87.9	21 02 17.0563	+47 02 16.254	170	159	0.15	icrf
J2114+4634	−1.5	89.0	21 14 32.8774	+46 34 39.296	78	74	0.16	nvss
J2254+6209	+2.3	109.7	22 54 25.2918	+62 09 38.727	86	76	0.16	nvss

[a] Initial suspicion of long-term variability was not confirmed (Gregory et al. 2001).

Fig. 1.— Sky plot for 2118 compact radio sources from JVAS (small dots) plus 29 GB6 variable sources from this work (big dots) in the JVAS zone of avoidance. Grey dotted line shows $b = 0°$.

Fig. 2.— VLA images of Stokes I emission at 8.3 GHz from 4 resolved GB6 variables. Boxed circle shows the Gaussian restoring beam at 200-mas FWHM. Negative contours are dashed and positive ones are solid. These images were made from data at 8.1 and 8.5 GHz, improving upon the script images described in Table 2. *Upper left:* J1847+0154. *Upper right:* J1851+0035. *Lower left:* J1934+1732. *Lower right:* J1946+2300.


60
30
0
−30
−60
16
20
4
8
J2000 Declination (degrees)
J2000 Right Ascension (hours)
jwrobel@nrao.edu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RIGHT ASCENSION (J2000)
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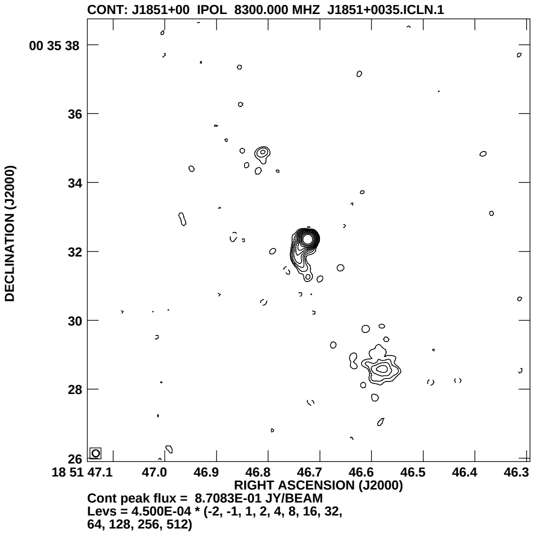
64, 128, 256, 512)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RIGHT ASCENSION (J2000)
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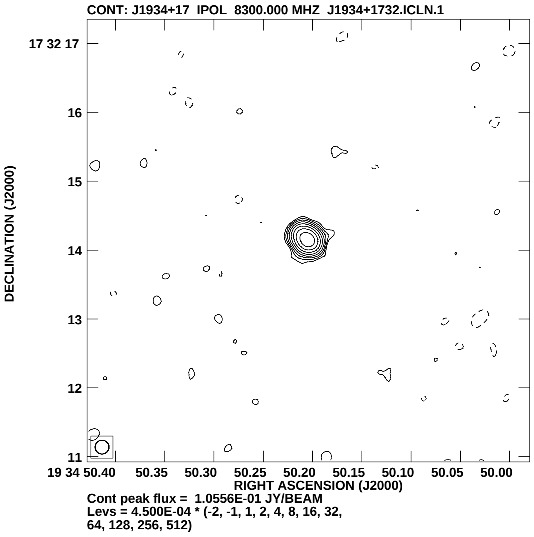
64, 128, 256, 512)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RIGHT ASCENSION (J2000)
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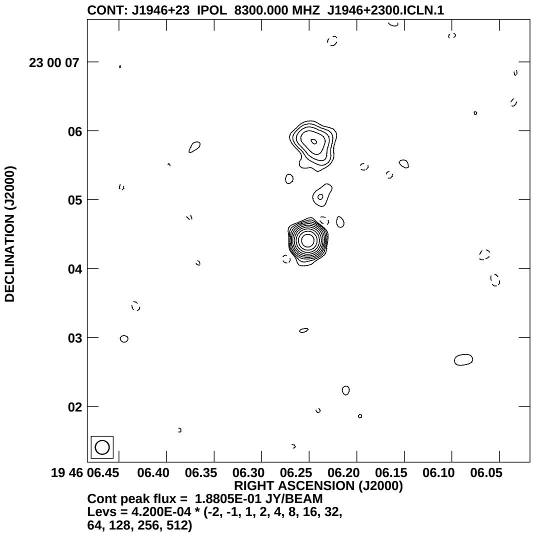
64, 128, 256, 512)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64, 128, 256, 512)