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THE SECOND VLBA CALIBRATOR SURVEY: VCS2

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ABSTRACT

This paper presents an extension of the Very Long Baseline Array Calibrator Survey, called VCS2, containing 276 sources. This survey fills in regions of the sky that were not completely covered by the previous VCS1 calibrator survey. The VCS2 survey includes calibrator sources near the Galactic plane, $-30° < \delta < -45°$, and VLA calibrators. The positions have been derived from astrometric analysis of the group delays measured at 2.3 and 8.4 GHz using the Goddard Space Flight Center CALC/SOLVE package. From the VLBA snapshot observations, images of the calibrators are available, and each source is given a quality code for anticipated use. The VCS2 catalog is available from the NRAO Web site.

Key words: astrometry — catalogs — quasars: general — radio continuum — reference systems — techniques: interferometric

On-line material: machine-readable table

1. INTRODUCTION

The Very Long Baseline Array (VLBA) Calibrator Survey produced the VCS1 catalog, which contained 1332 radio sources, and is described by Beasley et al. 2002. Most of these calibrator sources are suitable for phase referencing VLBI observations (Beasley & Conway 1995), and images for many of these sources are also available on-line. The radio positions were derived on the frame work of the International Celestial Reference System (ICRS) and the International Terrestrial Reference System (ITRS). The current realization of the ICRS and ITRS are the International Celestial Reference Frame (ICRF) and the International Terrestrial Reference Frame (ITRF 2000; Ma et al. 1998; Altamimi, Sillard, & Boucher 2002). In this paper we present a supplement to the VCS1 catalog, which includes sources near the Galactic plane,[1] at declinations between −30° and −45°, and from the VLA catalog of sources. This extension is called the VCS2 catalog. Since the observations, calibrations, astrometric solutions, and imaging are virtually identical to that of the VCS1, most of the details have been described in Beasley et al. 2002. In § 2 we describe the compilation of the VCS2 source list, in § 3 we list the catalog results, and in § 4 we summarize the results. Unlike the VCS1 observations, many of the radio sources in the VCS2 observing source list are weak, with unknown source structure. Hence, only 70% are usable as VLBA calibrators, and a quality code is attached to each VCS2 calibrator.

2. SOURCE SELECTION, OBSERVATIONS AND CALIBRATION

The ICRF and VCS1 catalogs cover the sky in a relatively uniform manner; however, two regions are relatively sparsely sampled: declinations south of −30° and the Galactic plane. The major goal of the VCS2 observations was to fill these regions with suitable calibrators. For the declination band −30° to −45°, we used the preliminary results from a VLA survey to locate gravitational lenses (J. N. Winn & J. E. Lovell 2002, private communication). We limited the VCS2 candidate sources from this survey to those with flat radio spectra and stronger than 80 mJy. In the declination range 0° to −30°, we also included the less frequently observed ICRF-Ext. 1 source list. For candidate sources near the Galactic plane, we used primarily the J-net Galactic Plane Survey for VLBI Exploration of Radio Astronomy (Honma et al. 2000). Finally, we searched the VLA calibrator source list and included those sources that were flat spectrum and unresolved, with no previous VLBI observations. The generated candidate source list for the VCS2 observations contained 276 sources.

The VCS2 observations were carried out in two 24 hr sessions: 2002 January 31 and 2002 May 14. The observations used the VLBA dual-frequency geodetic mode,

[1] Observations of sources within about 10° of the Galactic plane are often affected by Galactic scattering that makes their apparent angular size too large to be useful as calibrators for baselines longer than about 2000 km.

observing simultaneously at 2.3 GHz (S band) and 8.4 GHz (X band). The data for each of these two frequencies were separated into four 8 MHz channels, which spanned 140 MHz at 2.3 GHz and 490 MHz at 8.4 GHz, in order to provide precise measurements of the group delays for astrometric processing.

Nominally, each source was observed twice each for about 90 s. For sources north of -33°, the two observations were made on either of the two observing days and separated by at least 1 hr in order to improve the (u, v) coverage. More southern sources were observed once on both days, near transit. Because of the nonuniform distribution of the sources around the sky and some data editing, a few sources were observed three times and a few only one time. In addition to the targeted sources, three strong sources from a list of 32 sources taken from the ICRF catalog were observed every hour over the sky in order to allow estimation of the tropospheric path delay and to evaluate possible systematic errors of the VCS2 catalog.

The amplitude and initial phase calibration of the observations was made using the Astronomical Image Processing System (AIPS; Greisen 1988). Fringe-fitting and determination of the group delays for each observation was made by the Goddard Space Flight Center (GSFC) VLBI group, also using AIPS. The software package CALC/SOLVE for the astrometric analysis was then used to determine accurate estimates of the position for all of the candidate sources. Estimates of the temporal changes in the clocks, the troposphere path delays, and other geodetic information were also determined. The ionospheric delays were removed by the appropriate difference of the measured group delays at the two frequencies. For some of the weaker and resolved sources, only 8.4 GHz data was used to determine the source position. Errors of all parameters were also determined. See Beasley et al. 2002 for more details concerning the astrometric methods used for the solutions.

Comparison of common source positions of the VCS2 catalog and the ICRF Ext. 1 catalog revealed significant systematic errors of the VCS2 catalog. These errors increase with decreasing declination and are given in Tables 1 and 2. We believe these errors are caused by unmodeled variations of the troposphere path delay, which become more significant at low elevations, and preferentially for sources in the south. We used these tables of errors for computation of the source position uncertainties:

$$\sigma_\alpha = \sqrt{(1.5\sigma_\alpha^r)^2 + E_\alpha^2(\delta)/\cos^2\delta}\ ,$$
$$\sigma_\delta = \sqrt{(1.5\sigma_\delta^r)^2 + E_\delta^2(\delta)}\ , \qquad (1)$$

where σ_α^r and σ_δ^r stand for the formal uncertainties, $E_\alpha(\delta)$ and $E_\delta(\delta)$ are the declination-dependent additive reweighting parameters for right ascension and declination, respectively, taken from Tables 1 or 2.

TABLE 1
ERRORS OF THE VCS2 X/S POSITIONS

Decl. Zone (deg)	$\Delta\alpha^*\cos\delta$ (mas)	$\Delta\delta$ (mas)	No. of Pts.
(+90, +20).............	0.3	0.3	12
(+20, −30).............	0.3	0.6	15
(−30, −46).............	0.6	1.1	11

TABLE 2
ERRORS OF THE VCS2 X-BAND–ONLY POSITIONS

Decl. Zone (deg)	$\Delta\alpha^*\cos\delta$ (mas)	$\Delta\delta$ (mas)	No. of Pts.
(+90, +20).............	1.9	1.1	49
(+20, −20).............	1.3	1.9	29
(−20, −30).............	1.0	6.2	15
(−30, −40).............	2.9	8.2	79
(−40, −46).............	4.7	9.3	9

The data at each frequency were imaged at NRAO using the Caltech package DIFMAP (Shepherd 1997). Starting with a point-source model, progressively better images were obtained for each source and frequency using the deconvolution, editing, and self-calibration algorithms in DIFMAP. Since many of the sources were relatively weak, natural weighting, with some loss of resolution, was used to produce the images. Some sources were so weak and resolved that the images were dominated by noise. The faintest unresolved component that could be detected was $\approx$0.07 Jy at both frequencies.

During the source position determination at GSFC and the source mapping at NRAO, it was clear that a significant minority of the sources would not make good calibrators for VLBI phase-referencing experiments. Hence, we decided to include a quality code at both frequencies for each source, and these are listed in the VCS2 catalog given below. These quality codes are somewhat subjective, and the use of any calibrator depends on the sensitivity, resolution, and frequency of the VLBI observations. The amplitude versus projected spacing properties of a source provide the best information for the appropriate choice of calibrators.

3. THE VCS2 CATALOG

A sample of the VCS2 catalog is listed in Table 3. The first four columns give the source names and the position at epoch J2000.0, with estimated 1 σ errors as described above. Column (5) gives the number of baseline observations used to derive the position. For a source observed two times using all 45 VLBA baselines, 90 observations would be made. Column (6) gives the solution type: X/S means that an ionosphere free linear combination of the X-band and S-band data was used for the position determination; X+ and X-o mean that only X-band group delays were used due to the poor quality of the S-band data (X+) or because no fringes at the S-band were detected (X-o). Column (7) gives the average correlated flux density at 2.3 GHz for the source at the *shorter* VLBA spacings, and column (8) gives the quality. Columns (9) and (10) are similar to columns (7) and (8), except at 8.4 GHz.

The calibrator qualities are indicative of their strength and resolution at VLBA baselines. Those sources with a quality factor of 5 should not be used. They are large-diameter and weak sources and are included in the list for completeness. The quality factors have the following meaning:

1: *Excellent quality*.— Little change of signal over all baselines and stronger than 0.4 Jy.

TABLE 3

The VCS2 Source List

Source Name						2.3 GHz		8.4 GHz	
IAU (1)	IVS (2)	R.A. (J2000.0) (3)	Decl. (J2000.0) (4)	No. (5)	SOL (6)	$S_{2.3}$ (7)	Q (8)	$S_{8.4}$ (9)	Q (10)
J0000−3221	2357−326	00 00 20.39995 ± 0.00007	−32 21 01.2343 ± 0.0014	40	X/S	0.43	3	0.12	3
J0001+6051	2358+605	00 01 07.09961 ± 0.00064	+60 51 22.8034 ± 0.0036	11	X/S	0.12	4	0.07	4
J0004+2019	0002+200	00 04 35.75831 ± 0.00003	+20 19 42.3170 ± 0.0005	68	X/S	0.19	3	0.24	3
J0005−3445	0002−350	00 05 05.92510 ± 0.00030	−34 45 49.6414 ± 0.0085	19	X-o	0.09	4	0.07	4
J0006−2955	0003−302	00 06 01.12325 ± 0.00023	−29 55 50.0978 ± 0.0055	16	X/S	0.10	5	<0.05	5
J0008+1144	0005+114	00 08 00.83833 ± 0.00006	+11 44 00.7741 ± 0.0013	40	X/S	0.12	4	0.09	4
J0009+0628	0006+061	00 09 03.93187 ± 0.00002	+06 28 21.2394 ± 0.0007	72	X/S	0.15	2	0.23	2
J0010+2047	0007+205	00 10 28.74312 ± 0.00016	+20 47 49.7886 ± 0.0018	31	X-o	<0.05	5	<0.05	5
J0010−3054	0008−311	00 10 34.91052 ± 0.00123	−30 54 15.2772 ± 0.0417	4	X-o	0.09	5	0.07	5
J0010−3027	0008−307	00 10 35.74240 ± 0.00018	−30 27 47.4157 ± 0.0044	17	X/S	0.11	4	0.16	3
J0010−4153	0008−421	00 10 52.51774 ± 0.00033	−41 53 10.7799 ± 0.0124	14	X/S	0.49	5	0.09	5
J0012−3954	0010−401	00 12 59.90986 ± 0.00007	−39 54 26.0553 ± 0.0013	43	X/S	1.15	1	0.94	1
J0014+6117	0012+610	00 14 48.79215 ± 0.00022	+61 17 43.5417 ± 0.0008	18	X/S	0.09	4	0.26	2
J0019−3031	0017−307	00 19 42.67533 ± 0.00006	−30 31 19.3500 ± 0.0013	47	X/S	0.24	3	0.16	3
J0024+2439	0021+243	00 24 27.33055 ± 0.00003	+24 39 26.2299 ± 0.0006	69	X/S	0.15	3	0.11	3
J0024−4202	0022−423	00 24 42.98922 ± 0.00023	−42 02 03.9379 ± 0.0097	17	X/S	1.13	1	0.31	4
J0025−2602	0023−263	00 25 49.15625 ± 0.00008	−26 02 12.6168 ± 0.0019	28	X/S	0.54	4	0.14	4
J0026−3512	0023−354	00 26 16.38710 ± 0.00029	−35 12 48.7796 ± 0.0082	49	X-o	0.10	5	0.20	3
J0027+0929	0024+092	00 27 05.79366 ± 0.00005	+09 29 57.7632 ± 0.0011	28	X/S	0.10	3	0.12	3
J0031−3922	0028−396	00 31 24.33167 ± 0.00241	−39 22 49.3865 ± 0.0524	4	X/S	0.07	5	<0.05	5
J0036+1434	0033+142	00 36 35.10909 ± 0.00004	+14 34 03.6198 ± 0.0010	46	X/S	0.08	4	0.15	3
J0040−3243	0037−329	00 40 17.54073 ± 0.00012	−32 43 27.8246 ± 0.0024	19	X/S	0.09	4	0.13	3
J0040−3225	0038−326	00 40 30.65493 ± 0.00049	−32 25 20.3364 ± 0.0168	9	X/S	0.12	4	0.08	4
J0045−3900	0043−392	00 45 30.50924 ± 0.00042	−39 00 02.9051 ± 0.0104	15	X-o	0.13	5	0.06	5
J0049−3116	0046−315	00 49 22.90073 ± 0.00037	−31 16 27.3203 ± 0.0142	10	X/S	0.12	4	0.07	4
J0051−4226	0048−427	00 51 09.50184 ± 0.00008	−42 26 33.2919 ± 0.0014	36	X/S	0.81	2	0.39	2
J0058−3234	0055−328	00 58 02.23031 ± 0.00012	−32 34 20.7470 ± 0.0036	20	X/S	0.11	4	0.05	4
J0058−3347	0055−340	00 58 15.64184 ± 0.00055	−33 47 57.4885 ± 0.0204	5	X-o	0.11	5	0.05	4
J0059+5812	0056+579	00 59 52.20898 ± 0.00013	+58 12 23.6836 ± 0.0005	39	X/S	0.12	3	0.12	3
J0100−3337	0057−338	01 00 09.38767 ± 0.00376	−33 37 32.0234 ± 0.0984	3	X-o	0.09	4	0.05	4
J0109+6133	0106+612	01 09 46.34439 ± 0.00013	+61 33 30.4557 ± 0.0003	60	X/S	0.26	2	0.47	2
J0110+5632	0107+562	01 10 57.55198 ± 0.00634	+56 32 16.9830 ± 0.1780	2	X/S	<0.05	5	<0.05	5
J0119+0829	0116+082	01 19 01.27437 ± 0.00007	+08 29 54.6926 ± 0.0019	15	X/S	0.28	?	0.13	?
J0120−2701	0118−272	01 20 31.66333 ± 0.00003	−27 01 24.6523 ± 0.0009	48	X/S	0.43	4	0.19	4
J0124−3416	0122−345	01 24 21.45944 ± 0.00029	−34 16 21.4461 ± 0.0108	17	X/S	0.14	4	0.08	4
J0134−3843	0132−389	01 34 32.03008 ± 0.00008	−38 43 33.3824 ± 0.0016	28	X/S	0.31	4	0.19	3
J0134−0931	0132−097	01 34 35.66684 ± 0.00014	−09 31 02.8734 ± 0.0031	16	X+	0.10	5	0.11	4
J0140+6346	0137+635	01 40 43.07794 ± 0.00051	+63 46 06.8918 ± 0.0007	16	X/S	0.22	4	0.19	4
J0143−3200	0140−322	01 43 10.13154 ± 0.00006	−32 00 56.6511 ± 0.0013	31	X/S	0.15	3	0.20	3
J0144−3938	0142−398	01 44 54.09346 ± 0.00034	−39 38 10.5064 ± 0.0085	17	X+	0.12	4	0.11	4
J0151−3435	0149−348	01 51 23.48911 ± 0.00007	−34 35 13.8768 ± 0.0015	35	X/S	0.16	3	0.11	4
J0153−3310	0150−334	01 53 10.12167 ± 0.00009	−33 10 25.8571 ± 0.0030	24	X/S	0.35	4	0.23	4
J0155−4048	0153−410	01 55 37.05928 ± 0.00020	−40 48 42.3488 ± 0.0075	15	X/S	0.51	4	0.18	4

Notes.—Table 3 is presented in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

2: *Good quality*.—Some decrease of signal at shorter baselines, but stronger than 0.2 Jy at all baselines.

3: *Average quality.*—Decrease of signal at the shorter baselines, but stronger than 0.10 Jy everywhere.

4: *Fair quality*.—Less than 0.10 Jy on the longer baselines, but more signal on the shorter baselines. These calibrators should be checked before using.

5: *Poor quality*.—Less than 0.10 Jy on most baselines. These calibrators should *not* be used. The positions could be even more in error than indicated. Most sources within about 10° of the Galactic plane are significantly broadened by interstellar scattering at 2.3 GHz.

The complete VCS2 catalog is available on the World Wide Web.[2] Contour plots of the images and of the visibility amplitude versus projected spacing can also be found on the VLBA calibrator Web search page.[3]

Examples of the correlated flux density and image of the sources with different qualities are shown in Figure 1. Each line shows the 2.3 and 8.4 GHz visibility amplitude and contour representation of the image. The sources

[2] See http://www.nrao.edu/vlba/VCS2.

[3] See http://magnolia.nrao.edu/vlba_calib.

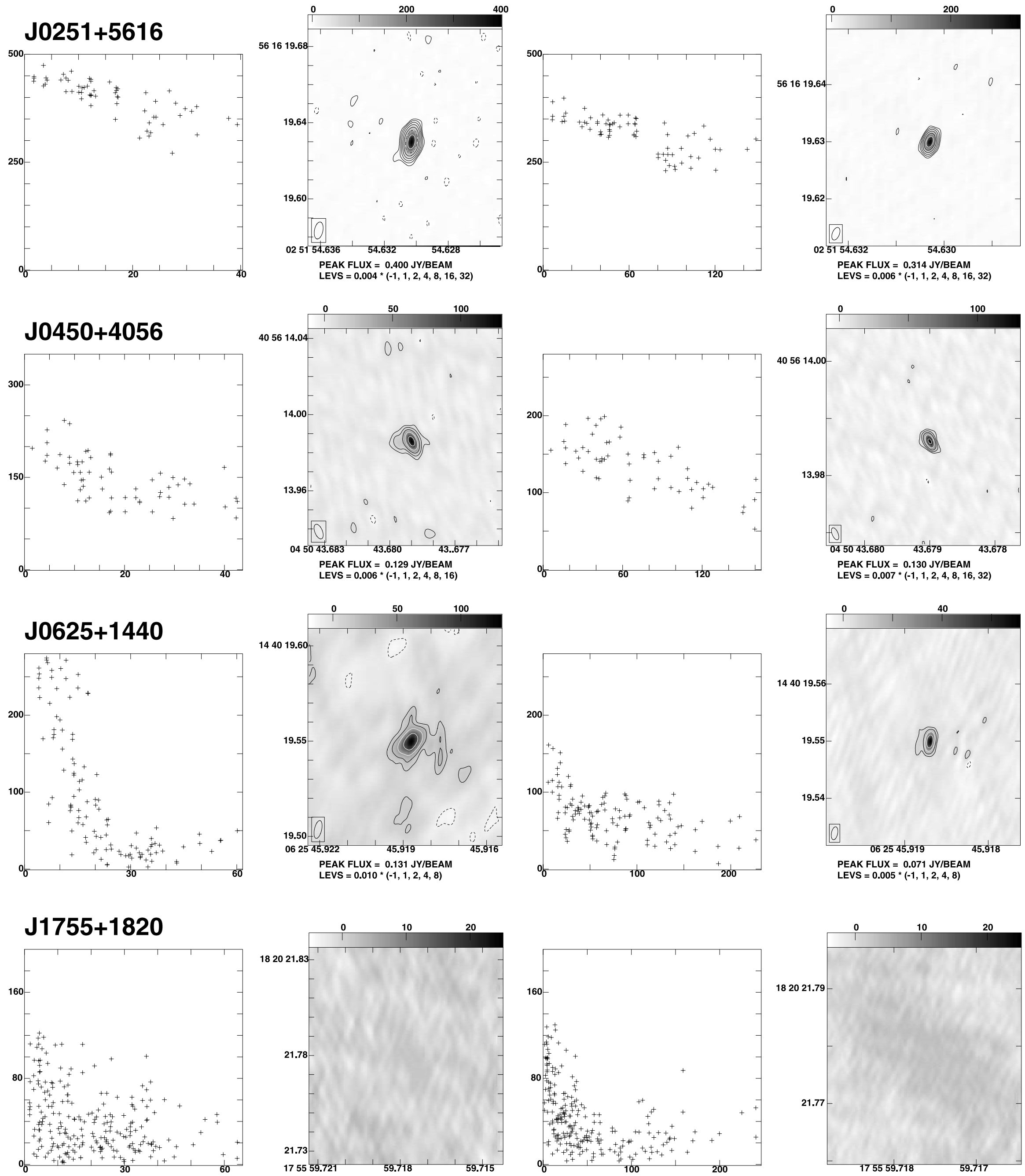

Fig. 1.—Samples of high-to-low quality calibrators. Each line from left to right shows: 2.3 GHz visibility amplitude vs. projected spacing; 2.3 GHz image; 8.4 GHz visibility amplitude vs. projected spacing; and 8.4 GHz image. The four lines show these plots for four sources in decreasing order of calibration quality. The visibility plot ordinates are in millijanskys, the abscissa in millions of wavelengths. The image contour plots are labeled with the right ascension and declination (epoch J2000.0), the gray-scale levels (in millijanskys) are given at the top of each image plot, the peak flux density (in janskys) and contour levels are given at the bottom of each image plot.

J0251+5616 and J0450+4056 have quality factors of 2 and 3, respectively, and are suitable for calibrators, even at the longest earth baselines. Source J0625+1440, with quality factor 4, has significant large-scale structure, and any small-diameter radio component is weak. This calibrator should be used with caution and, perhaps, checked before observations if possible. The source J1755+1820 is very resolved and is not a useful calibrator. The image is dominated by noise, and the position is derived only from the very shortest spacings where some signal was detected.

4. CONCLUSION

The VCS2 survey has added 276 new sources in the VLBA calibrator catalog. These additional sources are preferentially near the Galactic plane and in the range $-30° > \delta > -45°$, where the density of calibrators was relatively low. It is beneficial to have a high density of calibrators in the sky since the closer a calibrator is to the target source, the smaller its residual phase error will be. This will improve the quality of the image and the accuracy of the relative position between the calibrator and the target. The use of multiple calibrator sources for a target also demands a high density of calibrator sources.

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