THE KCAL VERA 22 GHz CALIBRATOR SURVEY

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ABSTRACT

We observed a sample of 1536 sources with correlated flux densities brighter than 200 mJy at 8 GHz with the very long baseline interferometry (VLBI) array VLBI Exploration of Radio Astrometry at 22 GHz. One half of the target sources has been detected. The detection limit was around 200 mJy. We derived the correlated flux densities of 877 detected sources in three ranges of projected baseline lengths. The objective of these observations was to determine the suitability of given sources as phase calibrators for dual-beam and phase-referencing observations at high frequencies. Preliminary results indicate that the number of compact extragalactic sources at 22 GHz brighter than a given correlated flux density level is two times less than that at 8 GHz.

Key words: astrometry – catalogs – surveys

Online-only material: color figures, machine-readable and VO tables

1. INTRODUCTION

Currently, very long baseline interferometry (VLBI) astrometry is the best tool for measuring distances and motions of sources located at kiloparsec (kpc) scales and hence for exploring the structure of the Milky Way on the Galactic scale. For instance, the Japanese VERA project (VLBI Exploration of Radio Astrometry; Honma et al. 2000) has been conducting astrometric monitoring of positions of Galactic maser sources with respect to reference compact extragalactic objects, yielding a handful of measurements of parallaxes and proper motions of maser sources (e.g., see the recent PASJ special issue on VERA: Honma et al. 2011, Nagayama et al. 2011, and others). The Very Long Baseline Array (VLBA) is actively used for astrometry of Galactic maser sources (e.g., Reid et al. 2009 and the currently ongoing Bar and Spiral Structure Legacy (BeSSeL) survey), and the European VLBI Network (EVN) conducts astrometric observations of methanol maser sources (e.g., Rygl et al. 2010).

In order to measure the parallax and proper motion of a radio source at kiloparsec scales, observations are conducted in the phase-referencing mode by frequent switching pointing between the target and a calibrator source. This technique significantly reduces phase variations caused by tropospheric fluctuations. To do this effectively, calibrators must be located close to target sources, typically within 1–2′ separation. This requires a high density of calibrator sources in the sky, and hence, there is still a strong demand for finding many calibrator sources.

To date, there have been several massive surveys of compact calibrators, such as the VLBA Calibrator Surveys (Petrov et al. 2008, and references therein), the Long Baseline Array Calibrator Survey for the southern hemisphere (Petrov et al. 2011b), the VLBA Image and Polarization Survey (Helmboldt et al. 2007; Petrov & Taylor 2011), and several ongoing programs such as the program of study for Fermi active galactic nuclei (AGNs) at parsec scales3 (Y. Y. Kovalev et al. 2011, in preparation), the program for observing radio-loud Two Micron All Sky Survey galaxies4 (Condon et al. 2011), the program for observing optically bright quasars (Bourda et al. 2008, 2011; Petrov 2011), and the recent VLBA calibrator search for the BeSSeL survey (Immer et al. 2011).

Together with regular geodetic VLBA observations of 1000 sources (Petrov et al. 2009, the RDV program), by 2011 June, positions of 6455 sources at a milliarcsecond level of accuracy were derived from analysis of these massive surveys. The sources were compact enough to be detected with VLBI, i.e., they have cores of milliarcsecond scale. However, in most cases these surveys were conducted in relatively low frequencies such as 2 (S band), 5 (C band), or 8 GHz (X band), at which the telescope performance is the best. On the other hand, recent VLBI maser astrometry is often done at frequencies higher than 10 GHz. For instance, VERA's main bands are 22 (K band) and 43 GHz (Q band) for H2O and SiO maser sources. Maser astrometry with VLBA is mainly conducted at 12 GHz for CH3OH masers and 22 GHz for H2O masers. Therefore, calibrator information at high frequencies (such as K and higher bands) is of great importance for ongoing and future astrometric observations. Compact calibrators, which are the cores of radio-bright AGNs, have a wide variety of spectra: for the majority of sources the correlated flux density decreases with the frequency, although some sources may have spectra growing with frequency or peaking within the GHz regime. Hence, the extrapolation of the correlated flux densities from the S and X band to 22 or 43 GHz is highly unreliable. For successful phase-referencing or dual-beam observations, the correlated flux density should be known with an accuracy of at least 30% in order to correctly predict the signal-to-noise ratio (SNR). Therefore, it is necessary to conduct a systematic survey of the K-band flux densities for the compact sources which were already detected in the S and X bands.

We have identified ~2000 sources previously observed with VLBI with δ > −30° with correlated flux densities >200 mJy in the X band at baselines longer than 900 km. Analysis of the dependence of the number of sources N with the correlated flux density exceeding S as a function of S suggests that this sample is complete at the 95% level (Y. Y. Kovalev 2010, private communication). Of these sources, 511 have been previously observed in large K-band surveys: the VERA Fringe Search Survey (Petrov et al. 2007), KQ survey (Lanyi et al. 2010), VLBI Galactic Plane Survey (VGaPS; Petrov et al. 2011a), and

3 http://astrogeo.org/faps
4 http://astrogeo.org/v2m
in the EVN Galactic Plane Survey (Petrov 2012), and their correlated flux densities at 22 GHz have been measured. The K-band brightness of other objects was not known.

We conducted a dedicated survey of the remaining 1536 sources at 22 GHz with VERA in the K-band Calibrator Survey (KCAL) campaign. The goal of these observations was to check the detectability of the sources in the K band and to measure their correlated flux densities at baselines of 1000–2000 km.

The first objective of this campaign was to provide a complete list of calibrators suitable for VERA observations of faint targets. According to our prior observations, the detection limit of the VERA network for 2 minutes of integration time is around 200 mJy, depending on weather conditions. Therefore, the list of sources observed in this and the previous K-band surveys is expected to approach completeness at the 200 mJy level, provided that the spectra of compact cores are flat or falling. According to Massardi et al. (2011) who analyzed simultaneous ATCA spectra at 4.8, 8.4, and 20 GHz, the share of sources with growing spectra that may be missed in our sample does not exceed 8%.

The second objective of this campaign is to collect information for a population analysis of a large complete sample. In particular, the analysis of the data set that combines existing and new data will help to answer the questions of what the distributions of spectral indices of the core regions and the source compactness at high frequencies are, whether the spectral index at parsec scales is systematically different than the spectral index at kiloparsec scales, and whether the compactness in the K band is systematically different than that in the X and S bands.

In this paper, we present the results of the survey. In Section 2, we describe the observations, their design, and scheduling. In Section 3, we discuss our analysis technique. The catalog of correlated flux densities of detected sources accompanied by analysis of flux density uncertainties is presented in Section 4 followed by concluding remarks that are given in Section 5.

2. OBSERVATIONS

Observations were carried out using the VERA network of four 20 m antennas in the K band. The primary task of the array is to perform parallax measurement of maser sources. In order to maximize the throughput of the instrument, observing time for the KCAL experiments was allotted in blocks that fill gaps between parallax measurement observing sessions or during periods of time when one of the antennas was under maintenance.

A monthly observing plan for VERA parallax measurements was usually finalized by at least one week before the beginning of the month. When there were suitable gaps for KCAL experiments and there were enough magnetic tapes in the Mitaka correlation center, we ran calibrator survey experiments during these gaps. The parallax measurement requires the participation of each of the four VERA stations in order to achieve required astrometric accuracy. If any station other than Ogasawara could not join regular observations because of maintenance or instrumental problems, the KCAL experiments were scheduled with three stations during that time.

The left circular polarization in the 21.97–22.47 GHz band was received, sampled with two-bit quantization, and filtered using the VERA digital filter (Iguchi et al. 2005) before being recorded onto magnetic tapes. The digital filter split the data within the 500 MHz band into 16 frequency channels of 16 MHz width each, equally spaced with 16 MHz wide gaps.

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In this paper, we present the results of the survey. In Section 2, we describe the observations, their design, and scheduling. In Section 3, we discuss our analysis technique. The catalog of correlated flux densities of detected sources accompanied by analysis of flux density uncertainties is presented in Section 4 followed by concluding remarks that are given in Section 5.

2.1. Scheduling

The scheduling software sur_sked selected sources from the pool of candidate objects in a sequence that minimized slewing time. In a given experiment, each source was observed in one scan of 120 s long. Every 30 minutes a scan of a strong source with the brightness distribution map produced from VLBA observations under the KQ observing campaign (Lanyi et al. 2010) was inserted into the schedule. The purpose of including these scans in the schedule was to compare our measurements of the correlated flux densities of sources with known images considered as the ground truth in order to evaluate gain corrections. The target sources, which were observed in one scan, were returned to the pool for scheduling in a second scan in subsequent experiments.

In total, 36 experiments were scheduled. However, six experiments were canceled for various reasons. In three observing sessions two stations either failed or did not observe; these experiments were excluded from analysis. The dates and durations of the 27 VLBI experiments under the KCAL program over the period 2007–2009 that were used in the analysis are shown in Table 1.

The scheduling goal of the campaign was to have each target source observed in two experiments—one scan in each observing session. Due to the nature of scheduling in a fill-in mode, it was difficult to reach this goal. As seen from Table 2, one-third of the sources was observed in one scan. In total, 1536 target sources were observed for 143 hr. The antennas spent...
71% of the time on target sources. The remaining time was spent observing the amplitude calibrators and slewing.

### 3. DATA ANALYSIS

#### 3.1. Fringe Fitting

The data were correlated on the Mitaka FX correlator (Chikada et al.
1991). Correlation output was written in FITS-IDF format. Consecutive analysis was performed with the computer program PIMA. The procedure of data analysis is described in detail in Petrov et al. (2011a). Here only a brief outline is given. After applying a fringe amplitude correction for digitization, the spectrum of the cross-correlation function was presented as a two-dimensional array with the first dimension running over frequency channels and the second dimension running over time. The two-dimensional Fourier transform of the spectrum over frequency and time cast the spectrum of the cross-correlation function into the domain of group delay and phase delay rate. A set of estimates of delays, phase delay rates, and fringe amplitude for a given scan at a given baseline is thereafter called an observation. In the presence of a signal in the data, the Fourier transform of the cross-spectrum exhibits a sequence of peaks. The amplitude of the major peak is proportional to the fringe amplitude of the signal. The fringe-fitting process locates the peaks and determines the group delay, delay rate, and fringe amplitude that correspond to the main maximum of the Fourier transform of the cross-correlation spectrum.

In order to determine the detection threshold, first we had to measure the noise level. To do this, we computed the ratios of the fringe amplitudes to mean amplitudes of the Fourier transform of the cross-correlation spectrum. The mean amplitude was computed by averaging 32,768 randomly selected samples of the cross-spectrum Fourier transform after iteratively excluding the amplitudes that were greater than 3.5 times the variance of amplitudes in the sample, in order to be sure that no samples with a signal were selected by accident. This procedure ensured that the mean amplitude of the noise was determined with an accuracy no worse than 1%.

Even in the absence of a signal, the fringe-fitting procedure will find a peak, but the amplitude of this peak will not be related to the fringe amplitude. The distribution of the achieved SNRs consists of the contribution of the population of observations with a signal detected and the population of observations without a signal. The SNR probability density in the absence of a signal is described (e.g., Petrov et al. 2011a) as

\[
p(s) = \frac{2}{\pi} \frac{n_{\text{eff}}}{\sigma_{\text{eff}}} s e^{-\frac{s^2}{\pi}} \left(1 - e^{-\frac{s^2}{\pi}} \right)^{n_{\text{eff}} - 1},
\]

where \(n_{\text{eff}}\) is the effective number of independent samples and \(\sigma_{\text{eff}}\) is the effective noise variance.

In order to determine \(n_{\text{eff}}\) and \(\sigma_{\text{eff}}\), we computed the histogram of the achieved SNR in the KCAL experiments in the range of [3.8, 6.5] (see Figure 1) and fit it with the theoretical curve \(p(s)\) of the fringe amplitude distribution in the absence of a signal. The left tail of the SNR histogram is dominated by non-detected sources. The right tail is dominated by detected sources. The breakdown occurs with SNR in a range of [5, 6.5]. There is some fraction of detected sources with an SNR within the range of [5, 6.5], and they may potentially cause a bias in our estimates of \(n_{\text{eff}}\) and \(\sigma_{\text{eff}}\). We varied the range of SNRs used for fitting and found that the estimates are stable at a level of \(10^{-3}\), i.e., the bias is negligible.

After determining \(n_{\text{eff}}\) and \(\sigma_{\text{eff}}\), we can find the probability that an observation with a given SNR belongs to the population of observations without a signal, i.e., the probability of false detection, by integrating expression (1) over \(s\), which can be easily done analytically. Specifically, we found that the probability of false detection is less than 0.001 when the SNR > 6.03. We considered a source as detected if the SNR in at least two observations at different baselines of the same scan was above the detection limit 6.03. In the absence of a signal, the probability of finding two peaks exceeding the threshold limit in the data of different observations is in the range of \(10^{-3}\) to \(10^{-6}\) depending on whether the errors are completely correlated or completely uncorrelated. In practical terms, this means that our catalog may have no more than one or two falsely detected objects.

#### 3.2. Amplitude Calibration

System temperatures including atmospheric attenuation were measured with the chopper-wheel method (Ulich & Haas 1976). At the beginning of each scan, a microwave absorber at ambient temperature was inserted just in front of the feed horn, and the received total power was measured with a power meter. Using the measured total power for the blank sky and the absorber, the temperature scale automatically corrected for the atmospheric

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5 Available at http://astrogeo.org/pima.
attenuation was determined. We estimate the uncertainty in the temperature scale to be around 10%, mainly due to the assumption that the ambient temperature is the same as the air temperature.

The initial amplitude calibration was made by scaling fringe amplitudes, determined with the fringe-fitting process, by the measured system temperature and dividing them by the antenna gain. Then, the antenna gains were adjusted by comparing the calibrated fringe amplitudes of the observed calibrator sources with the correlated flux densities predicted on the basis of their $K$-band brightness distributions\(^6\) produced from the analysis of observations from KQ (Lanyi et al. 2010) and VGaPS (Petrov et al. 2011a):

$$F_{\text{corr}} = \sum_j c_j(x, y) e^{\text{imag}(u x + v y)},$$

(2)

where $c_j$ is the correlated flux density of the $j$th CLEAN component with coordinates $x$ and $y$ with respect to the center of the image; $u$ and $v$ are the projections of the baseline vectors onto the tangential plane of the source.

Then we built a system of equations for all observations of calibrators:

$$F_{\text{corr}} = \sqrt{g_i g_j} A_{\text{corr}},$$

(3)

that relates the calibrated amplitude $A_{\text{corr}}$, gain corrections $g$ for stations $i$ and $j$ of a baseline, and the predicted correlated flux of the amplitude calibrator. After taking logarithms from the left- and right-hand sides, we solved for average gain corrections for all stations using the least-squares (LSQ) technique. Then an iterative procedure of outlier elimination was performed. At each step of the iterations, we computed the root mean square (rms) of the ratio of observed and predicted correlated flux densities. We searched for an observation with a maximum by module logarithm of this ratio. If the ratio for that observation exceeded $3.5\sigma$ rms, we excluded the observation from the system of equations and ran a new LSQ solution. The process was repeated until no observation with a maximum by module logarithm exceeding $3.5\sigma$ rms was found.

The number of calibrators in each individual experiment varied. On average, nine calibrators were used for gain correction adjustment in each experiment. If the model brightness distributions were perfect, and gain corrections were stable over an experiment, calibration adjustment would have been below the noise level. Several factors can degrade the quality of calibration using this method. First, the images of calibrator sources were produced using observations at different sampling of spatial frequencies than the analyzed observations. Computation of the predicted correlated flux densities is equivalent to an interpolation of visibilities measured in the KQ and VGaPS VLBA campaigns to $u$ and $v$ baseline projections in the KCAL experiments. Errors of this interpolation may be significant, except for sources with very simple structure. Second, both source structure and the peak brightness evolve with time. Since the time difference in epochs between the KQ, VGaPS, and KCAL experiments is 2–6 years, the changes in source brightness distribution may be significant. The sampling bias and the source variability are expected to cause only random errors in gain, but not a systematic bias. Some calibrator sources may become brighter, some dimmer, but the average flux density of the ensemble should be rather stable. Third, we assumed that gain corrections are constant over the time of an individual experiment, since we do not have enough information to model their time variability.

### Table 3

The First 12 Rows of the Catalog of Correlated Flux Densities of 877 Sources with at Least Two Detections in the VERA KCAL Observing Campaign

| Source Name | IAU Name | IVS Name | Flag | No. of Exp | No. of Det | Corr. Flux Density | Errors of $F_{\text{corr}}$ | Source Coordinates |
|-------------|----------|----------|------|------------|------------|--------------------|--------------------------|-------------------|
|             | (1)      | (2)      | (3)  | (4)        | (5)        | (6) $F_{\text{corr}}$ | (7) $E_{\text{corr}}$ | (8) $E_{\text{corr}}$ |
| J0001 + 1914 | 2358 + 189 | 1 | 4 | 0.221 | 0.322 | 0.216 | 0.055 | 0.070 | 0.051 | 0.0108 62 + 19 14 33.8 |
| J0005 + 3820 | 0003 + 380 | 2 | 8 | -1.000 | 0.608 | 0.526 | -1.000 | 0.136 | 0.116 | 0.05 57.17 + 38 20 15.1 |
| J0006 + 0623 | 0003–066 | 2 | 9 | 1.027 | 1.120 | 1.212 | 0.104 | 0.205 | 0.176 | 0.06 13.89 - 06 23 35.3 |
| J0008 + 6387 | 0005 + 683 | 1 | 2 | -1.000 | 0.353 | -1.000 | -1.000 | 0.080 | -1.000 | 0.08 33.47 + 68 37 22.0 |
| J0010 + 1058 | III2Z2 | C | 2 | 6 | -1.000 | 1.193 | 1.442 | -1.000 | 0.239 | 0.289 | 0.10 31.00 + 10 58 29.5 |
| J0011 + 1724 | 0007 + 171 | 1 | 2 | -1.000 | 0.340 | 0.266 | -1.000 | 0.078 | 0.060 | 0.10 33.99 + 17 24 18.7 |
| J0011 + 1257 | 0008–222 | 1 | 2 | -1.000 | 0.236 | -1.000 | -1.000 | 0.052 | -1.000 | 0.10 55.64 - 21 57 04.2 |
| J0011 + 7045 | 0008 + 704 | 2 | 8 | 0.440 | 0.405 | 0.542 | 0.043 | 0.088 | 0.064 | 0.11 31.90 + 70 43 54.6 |
| J0012 + 3954 | 0010–401 | 1 | 3 | 0.505 | 0.494 | -1.000 | 0.120 | 0.103 | -1.000 | 0.12 59.90 -39 54 26.0 |
| J0013 + 4051 | 0010 + 405 | 2 | 7 | 0.531 | 0.534 | 0.492 | 0.065 | 0.119 | 0.115 | 0.13 31.13 + 40 51 37.1 |
| J0013 – 0423 | 0011–046 | 2 | 7 | 0.552 | 0.406 | 0.445 | 0.071 | 0.094 | 0.101 | 0.13 54.13 -04 23 52.2 |
| J0017 + 5312 | 0015 + 529 | 1 | 2 | -1.000 | 0.270 | -1.000 | -1.000 | 0.067 | -1.000 | 0.17 51.75 + 53 12 19.1 |

Notes. The table columns are explained in the text. IVS: International VLBI Service.

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

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\(^6\) Available at http://astrogeo.org/vlbi_images.
imaging procedure in the case where there are too few measurements.

The catalog of correlated flux densities of 877 observed sources, including 750 targets and 127 calibrators, is presented in Table 3. Objects with at least two detections were included in the catalog. Columns 1 and 2 show IAU and International VLBI Service source names. Column 3 shows the source status: C stands for an amplitude calibrator and blank stands for a target object. Column 4 shows the number of experiments in which a source was detected and Column 5 shows the total number of detections. Columns 6–8 present the estimates of the average correlated flux density in three ranges of the projected baseline lengths. Columns 9–11 show the estimates of correlated flux density uncertainty:

\[
\sigma (F_{\text{corr}}) = A_{\text{corr}} \cdot \sqrt{\frac{0.22}{\pi}} + \frac{(2/\pi)(1/\text{SNR}^2)}{\text{corr}}.
\]

Columns 12 and 13 show right ascensions and declinations. A value of −1,000 in Columns 6–11 indicates a lack of results for these baseline projections.

Of 1536 observed sources, including both targets and calibrators, 407 were not detected at all and 252 were detected in only one observation. The detections from the latter group were considered unreliable and were not included in the catalog.

4.1. Error Analysis

Errors in correlated flux density estimates are due to (1) the thermal noise in estimates of fringe amplitude, (2) the uncertainties in system temperature measurements, (3) the uncertainties in antenna gain measurement, (4) the sampling bias in predicted correlated flux densities of calibrators, and (5) the variability of calibrator sources.

The uncertainty due to the thermal noise can be easily evaluated as \( \sqrt{2/\pi} (\sigma_n / \bar{a}) \), where \( \sigma_n \) is the average amplitude of the noise computed by the fringe-fitting procedure and \( \bar{a} \) is the fringe amplitude. As we already mentioned, the uncertainty in the system temperature measurement is around 10%. The aperture efficiency of VERA antennas is measured every year and known within 10% accuracy (see VERA status report\(^7\)). We assume these two uncertainties are uncorrelated, and therefore, these two factors would introduce an uncertainty of the a priori gain calibration at a \( \approx 14\% \) level.

Since on average, nine amplitude calibrators were used for gain adjustments, this redundancy can be exploited for the evaluation of the gain correction uncertainties. We computed the average and the rms of the residual mismatches between observed correlated flux densities of calibrators after applying gain corrections \( A_{\text{corr}} \) from the LSQ fit and the predicted correlated flux densities from the brightness distributions:

\[
\text{Avr} = \left( \prod_i \frac{F_{\text{corr},i} \sqrt{\frac{\text{SNR}_i^2}{\bar{a}}} A_{\text{corr},i}}{A_{\text{corr},i}} \right)^{1/n}
\]

\[
\text{rms} = \sqrt{\frac{\sum_i \left( \frac{F_{\text{corr},i} \sqrt{\frac{\text{SNR}_i^2}{\bar{a}}} A_{\text{corr},i}}{A_{\text{corr},i}} - 1 \right)^2}{n}}.
\]

We found \( \text{Avr} = 0.994 \) and \( \text{rms} = 0.21 \). The first statistic describes the systematic bias and the second statistic is the measure of the contribution of uncertainties in the gain adjustments to the uncertainty of our estimate of the correlated flux density.

\(^7\) Available at http://veraserver.mtk.nao.ac.jp/.

In order to evaluate the representativeness of these statistics, we computed the median correlated flux densities in three ranges of projected baseline lengths of two experiments of the 24 GHz VLBA VGaPS campaign using two methods: (1) rigorous self-calibration imaging and (2) the same simplified method used for processing KCAL experiments. In order to closely mimic analysis of the KCAL experiments, we used the brightness distributions from the KQ campaign made at epochs at least one year prior to observations for our test. We obtained \( \text{Avr} = 0.996 \) and \( \text{rms} = 0.24 \). Then we computed the rms of the scatter of the ratios of the correlated flux density \( F_{\text{corr}}^\ast \) determined by the simplified method to the flux density \( F_{\text{corr}}^\ast \) determined by the rigorous method: \( \text{rms} = \sqrt{\sum_i (F_{\text{corr},i}^\ast / F_{\text{corr},i}^\ast - 1)^2} \). We found an rms equal to 0.15. Considering the brightness distributions from the self-calibration analysis procedure as the ground truth, we conclude that the accuracy of the median correlated flux density obtained by the simplified method is at a level of 15% for the VGaPS campaign. Thus, the rms statistics give us an upper limit of gain errors.

Another way to evaluate the average uncertainty of correlated flux densities is to compute the rms of the scatter of ratios of the correlated flux densities of a given source with respect to the mean value for all the KCAL sources which have three or more observations. We obtained an rms value of 0.20, which is close to the rms statistic. Therefore, we conclude that the average uncertainty of calibration error is 20%. Since the uncertainty in fringe amplitude caused by the thermal noise and calibration errors is independent, we compute the multiplicative uncertainty of reported correlated flux density as a sum of these two contributions in quadrature: 0.2 and \( \sqrt{(2/\pi)(1/\text{SNR})} \).

5. CONCLUDING REMARKS

Using VERA at 22 GHz we observe a subset of the complete sample of continuum compact extragalactic sources with correlated flux densities \( \geq 200 \text{ mJy} \) in the X band at declinations \( \geq -30^\circ \). The subset excluded sources previously detected in the K band by large VLBA and VERA surveys. Of 1536 target sources, approximately one half has been detected. The errors of the correlated flux densities are a level of 20%.

Figure 2 shows the distribution of the KCAL correlated flux densities. Assuming that the parent population of sources is uniform in the range of flux densities \( 1-1000 \text{ mJy} \), we explain the sudden drop in the number of sources with correlated flux
densities below 200 mJy as an indication of underrepresentation of sources weaker than that limit in the catalog because they are not reliably detected with VERA. Thus, the KCAL is incomplete at flux densities below 200 mJy. This result is in agreement with our analysis of previous VERA observations (Petrov et al. 2007) where we estimated the probability of detection of a source with a correlated flux density of 200 mJy at a level of 70%.

The detection limit of VERA at 22 GHz, 200 mJy, corresponded to the lowest correlated flux density of the input source list, 200 mJy, at 8 GHz. The majority of the sources from the input list were previously observed with VLBI at both 8.6 and 2.3 GHz. The distribution of spectral indices ($F(\nu) \sim \nu^\alpha$) of the compact component of these sources shows a peak near spectral index 0 (see Figure 3). Among 1536 sources from the input list, 48% had a spectral index greater than zero, and therefore, their extrapolated flux density at 22 GHz was greater than 200 mJy, the average detection limit of the KCAL survey. Although a measured correlated flux density at 22 GHz for an individual source may be less than the flux density extrapolated from 8.6/2.3 GHz, if the entire population is considered as a whole, the measured flux density at 22 GHz turned out to be on average very close to the extrapolated one.

Results of the KCAL survey augmented with results of prior K-band surveys form the list of objects with known correlated flux densities. By 2011 June, this list8 contained 1161 objects. Among these sources, 766 objects have correlated flux densities greater than 200 mJy at baselines shorter than 70 Mλ, and 608 objects are brighter than 200 mJy at baselines longer than 100 Mλ. These sources are considered as a pool of calibrators for VERA in 2011. After completion of a planned sensitivity upgrade, even weaker sources can be used for calibrators.

We reserve a rigorous population analysis for a future publication. Preliminary results indicate that the number of compact extragalactic sources in the K band brighter than a given correlated flux density level is two times less than in the X band.

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