Korean VLBI Network Calibrator Survey (KVNCS). 1. Source Catalog of KVN Single-dish Flux Density Measurement in the K and Q Bands

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Abstract

We present the catalog of the KVN Calibrator Survey (KVNCS). This first part of the KVNCS is a single-dish radio survey simultaneously conducted at 22 (K band) and 43 GHz (Q band) using the Korean VLBI Network (KVN) from 2009 to 2011. A total of 2045 sources are selected from the VLBA Calibrator Survey with an extrapolated flux density limit of 100 mJy at the K band. The KVNCS contains 1533 sources in the K band with a flux density limit of 70 mJy and 553 sources in the Q band with a flux density limit of 120 mJy; it covers the whole sky down to \(-32.5^\circ\) in decl. We detected 513 sources simultaneously in the K and Q bands; \(\sim76\%\) of them are flat-spectrum sources \((\sim0.5 < \alpha \leq 0.5)\). From the flux–flux relationship, we anticipated that most of the radiation of many of the sources comes from the compact components. The sources listed in the KVNCS are strong candidates for high-frequency VLBI calibrators.

Key words: catalogs – quasars: general – radio continuum: galaxies – surveys

Supporting material: machine-readable table

1. Introduction

A large proportion of compact radio sources have flat or inverted spectra (e.g., Kellermann & Pauliny-Toth 1981; Zensus 1997; Gurvits et al. 1999; Chen & Wright 2009; de Zotti et al. 2010; Mantovani et al. 2011; Massardi et al. 2011). This implies that these sources are optically thin at the observed radio frequencies. Very long baseline interferometry (VLBI) calibrators are also compact sources. The majority of sources in the Very Long Baseline Array (VLBA) Calibrator Survey (VCS) have flat spectra at 2.3 (S band) and 8.4 (X band) GHz (Beasley et al. 2002; Fomalont et al. 2003; Petrov et al. 2005, 2006; Kovalev et al. 2007; Petrov et al. 2008). However, VLBI calibrators at higher frequency (>20 GHz) are very rare compared to those at lower frequency. For example, 858 VLBI calibrators in the K band (<20 GHz) are known (Petrov et al. 2007; Lanyi et al. 2010; Petrov et al. 2011, 2012; Petrov 2012), while ~3800 sources are listed in the VCS in the S and X bands. High-frequency VLBI observations are useful to understand the physical processes in the vicinity of supermassive black holes of active galactic nuclei (AGNs) because it enables studying the optically thin region from the synchrotron radiation of compact radio sources. In addition, radio sources become more compact in structure so that astrometric errors in the celestial reference frame (CRF) would be minimized (e.g., Fey & Charlo 1997; Ma et al. 1998; Fey et al. 2004; Charlot et al. 2010; Lanyi et al. 2010). Together with the successful operation of the Gaia spacecraft during the first two years of sky survey, high-frequency VLBI sources that match Gaia samples will be important to compare the radio and optical reference frames (e.g., Bourda et al. 2010, 2011; Jacobs et al. 2014).

There is an extensive blind survey of the southern sky that identified 5808 sources at 20 GHz (AT20G) in order to support subtraction of foreground objects for the measurement of the cosmic microwave background (Murphy et al. 2010). In the northern sky, Righini et al. (2012) conducted the K-band Northern Wide Survey and identified 73 sources at decl. >72°3 (∼880 degree²). Recently, Jacobs et al. (2014) constructed a new compact radio survey at X/Ka (8.4/32 GHz) bands in order to improve the accuracy of CRF and detected 631 sources. However, the sky coverage of known K-band calibrators is about 49% of the whole sky by assuming the circles of 5° radius, as shown in Figure 1, while the VCS sources in the S and X bands cover the full sky above \(-40^\circ\) in decl. with this radius (Petrov et al. 2008). The critical separation angle, 5° was determined following Dodson et al. (2014). These authors showed that source frequency phase referencing in KVN is possible by considering a 5° separation angle between a target and a calibrator in the Korean VLBI Network (KVN). We therefore performed 21.7 (K band) and 42.4 (Q band) GHz single-dish survey observations in order to provide a wider sky coverage of possible VLBI target and calibrator sources at these frequencies (or even higher frequencies), particularly for the KVN.

The KVN is composed of three 21 m telescopes in Seoul, Ulsan, and Jeju, Korea. Its notable characteristic is the multifrequency receiver system, which makes it possible to simultaneously observe the radio sources at four different frequencies [22 (K band), 43 (Q band), 86 (W band), and 129 (D band) GHz] (e.g., Han et al. 2008; Lee et al. 2011, 2014). In particular, this system is very efficient for high-frequency VLBI observations when the frequency phase transfer (FPT) method is applied to compensate for the atmospheric coherence loss; this method uses lower frequency phase solutions (e.g., in the K band) to compensate for higher frequency ones (e.g., in the Q, W, and D bands) because of the non-dispersive nature of the atmosphere with regard to radio systems (e.g., Jung et al. 2011; Rioja et al. 2014, 2015). As a result, noticeable improvements of coherence time and signal-to-noise ratio at high-frequency VLBI observations have been demonstrated (e.g., Jung et al. 2012, 2014).

For the practical use of the FPT for higher frequency (Q, W, and D band) VLBI observations with the KVN, increasing
available sources in the $K$ and $Q$ bands is very important in the northern sky because it is essential to detect target or calibrator sources at the lower frequencies (e.g., in the $K$ or $Q$ bands) as a reference for the atmospheric calibration. The increase in detection at high frequencies by the FFT will be able to extend our understanding of radio sources from centimeter to millimeter wavelengths in VLBI; for example, a statistical study of a spectral energy distribution of AGNs based on the simultaneously measured flux densities at a range from 20 to 130 GHz, and high-frequency astrometric applications (e.g., Rioja et al. 2015).

We therefore performed the KVN Calibrator Survey (KVNCs), which aims to simultaneously measure the single-dish flux densities of ~2500 selected sources in the $K$ and $Q$ bands in order to use them as VLBI calibrators of KVN.

In the next section, we explain the selection criteria for the ~2500 sources. The observations and data reductions are described in Section 3. In Section 4, the observational results and their analysis are presented. Finally, we summarize our findings and future prospects in Section 5.

2. Source Selection

A total of 2503 sources with an extrapolated total flux density (hereafter, $S_{\text{K+X}}$) greater than 100 mJy in the $K$ band were selected from VCS1 to VCS5 (Beasley et al. 2002; Fomalont et al. 2003; Petrov et al. 2005, 2006; Kovalev et al. 2007). As the most widely used catalog of VLBI calibrators, the VCS contains ~3800 radio sources that mostly show a compact structure and flat spectra sources with greater than ~40° in decl. $S_{\text{K+X}}$ was calculated, assuming a power-law spectrum from the total flux densities in the $S$ and $X$ bands (Sohn et al. 2009). The flux density limit of 100 mJy was a selection criterion, which gives >8σ at a baseline sensitivity of the KVN at $K$ band.4 A decl. limit of ~32°5 was determined so that all sources are observed at more than 20° above the horizon at transit. For the first observation as a pilot observation, 595 relatively bright sources that have $S_{\text{K+X}} >$ 500 mJy in the $K$ band were selected, and 493 sources (~83%) were successfully detected with the first single-dish observations from KVNCs1.0.1 to KVNCs1.1.3 in the $K$ and $Q$ bands. Then, we performed a single-dish observation toward 1450 of the remaining 1908 sources, the flux density of which ranges between 100 mJy and 1 Jy. In order to avoid concentrating on the specific regions, the 1450 sources were selected by considering the sky coverage of the detected source density, which was calculated by the Delaunay triangulation method whenever each observation was complete. We assumed that the calibrators are located on the vertex of the triangle in the triangulation method. The target is located in the center of the circumsphere of this triangle, and the radius of this circle become the maximum separation angle between the target and the calibrators.

3. Observation and Data Reduction

3.1. Observation

We selected 2503 sources based on lower frequency VLBI flux density from VCS. Flux densities of 2045 of 2503 sources were simultaneously measured by single-dish observations in the $K$ and $Q$ bands using the KVN Yonsei and Ulsan radio telescopes from 2009 December to 2011 March. The observational information is summarized in Table 1. The cross-scan mode (cs-mode), a one-dimensional on-the-fly method, was used to obtain an accurate flux density measurement. A single cs-mode scan consists of two scans in azimuth (Az) and two in elevation (El). Each scan includes both forward and backward scans. We selected the parameters for the cs-mode considering the telescope beam size, timescales of the sky power variation, and the hardware and software limitations of the KVN system. The applied scan speed, the data sampling interval, and the

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3 KVN status report: http://kvn.kasi.re.kr/status_report/.
### Table 1
Observational Information

| Date          | Observation Code | Number of Sources [#] | Telescope  | On-source Integration Time (s) | Tsys \( (K) \) | \( \tau_0 \) | Conversion Factor (Jy K\(^{-1} \)) |
|---------------|------------------|-----------------------|------------|-------------------------------|--------------|---------|-----------------------------------|
| 2009 Dec      | KVNCS1.0.1       | ...                   | KYS        | 40(K), 20(Q)                  | 96.2(K), 181.7(Q) | 0.053(K), 0.097(Q) | 12.95(K), 12.99(Q) |
| 2010 Feb      | KVNCS1.1.1       | ...                   | KYS        | 40(K), 20(Q)                  | 74.3(K), 157.4(Q) | 0.027(K), 0.088(Q) | 12.78(K), 11.82(Q) |
| 2010 Mar      | KVNCS1.1.2       | ...                   | KYS        | 40(K), 20(Q)                  | 97.0(K), 168.9(Q) | 0.068(K), 0.104(Q) | 13.11(K), 12.88(Q) |
| 2010 May      | KVNCS1.1.3       | 595\(^a\)            | KYS        | 40(K), 20(Q)                  | 220.4(K), 397.1(Q) | 0.103(K), 0.111(Q) | 12.97(K), 12.45(Q) |
| 2010 Jun      | KVNCS1.2.1       | 396                   | KYS        | 80(K), 40(Q)                  | 124.7(K), 184.0(Q) | 0.111(K), 0.116(Q) | 12.97(K), 12.45(Q) |
| 2010 Dec      | KVNCS1.2.2       | 670                   | KUS        | 80(K), 40(Q)                  | 95.8(K), 119.4(Q) | 0.051(K), 0.086(Q) | 13.67(K), 15.33(Q) |
| 2011 Jan      | KVNCS1.3.1       | 573                   | KUS        | 160(K), 80(Q)                 | 82.9(K), 137.5(Q) | 0.034(K), 0.092(Q) | 13.85(K), 16.24(Q) |
| 2011 Mar      | KVNCS1.3.2       | 182                   | KYS        | 160(K), 80(Q)                 | 88.3(K), 180.2(Q) | 0.042(K), 0.091(Q) | 12.99(K), 13.51(Q) |

**Notes.**

\(^a\) KYS: KVN Yonsei Radio Observatory, KUS: KVN Ulsan Radio Observatory.

\(^b\) Mean system temperature of each observation.

\(^c\) Mean zenith optical depth of each observation.

\(^d\) Total number of sources from KVNCS1.0.1 to KVNCS1.1.3 is 595.

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Figure 2. Flux density distributions of measured sources (≤5 Jy) in K (top) and Q (bottom) bands. Red arrows indicate the median flux densities, 397 and 587 mJy in the K and Q bands, respectively, whereas the mean flux densities are 707 and 1,103 mJy, respectively.

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... (continued from previous page)

scan length are mainly \(65'' \) s\(^{-1} \), 0.1 ms, and 13', respectively, which yield a 4 s (K band) and 2 s (Q band) full-beam cross time. We can remove sky power variation with timescales longer than the full-beam cross time by fitting off-source data. Assuming a Gaussian beam pattern, the on-source integration time of a cross scan are 8 and 4 s in the K and Q bands, respectively. The total on-source time for each source is considered based on the estimated source flux density and is calculated by multiplying by the number of scans. The main-beam sizes of the KVN telescopes are around 126'' and 63'' in the K and Q bands, respectively (see footnote 4). The mean beam sizes in the K and Q bands are quite consistent with the known sizes. However, the estimated beam sizes and pointing offsets have large errors for faint sources and under bad weather conditions or rapid sky variation (e.g., Fante 1975). We used them to eliminate low-quality data with 30% differences in beam size from the known ones and with the pointing offsets larger than 25'' arbitrarily. The standard deviations in the beam size and pointing offset data are 7% (K) and 20% (Q) and 4'' (K) and 4'' (Q) in Az and 10% (K) and 19% (Q) and 6''4 (K) and 6''0 (Q) in El, respectively. The observing frequencies were 21.7 GHz for the K band and 42.4 GHz for the Q band with a 512 MHz bandwidth. A measured root mean square (rms) error is an order of magnitude higher than the estimated thermal error. This is usual in practice. Hot/cold load calibration was performed in order to determine the antenna temperature scale from KVNCS1.0.1 to KVNCS1.2.1. For hot/cold load calibration, we used two microwave absorbers, one at room temperature of ~292 K and the other immersed in liquid nitrogen of 80K, as hot and cold loads, respectively. For KVNCS1.2.2 we used the chopper-wheel method, which uses the sky as a cold load together with a microwave absorber at room temperature (Kutner & Ulich 1981; Mangum 2000). The results from these two
calibration methods were consistent with each other to within \(\sim 2\%\) uncertainty. The system temperature and zenith optical depth of each observation are presented in Table 1. The sky opacity was corrected using the sky-dipping method based on observations every hour. The source 3C 286 was observed as a flux calibrator every 1.5 h to convert the measured antenna temperature into the flux. The flux densities of 3C 286 are 2.64 and 1.51 Jy in the \(K\) and \(Q\) bands, respectively. These were measured with a brightness model of Mars at the KVN Yonsei observatory (B.W. Sohn et al. 2017, in preparation).

### 3.2. Data Reduction

We developed an analysis program for the KVN single-dish flux density measurements, and the following procedures were applied: (a) Extraction of bad scans due to the weather

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**Table 2**

Examples from the KVNS Catalog

| IAU name (J2000) | R.A. (hh:mm:ss) | Decl. (°:′″) | Obs. Code | Flux Density (±1σ) | Redshift (z) |
|------------------|----------------|-------------|-----------|-------------------|--------------|
| J0007+5706       | 00:07:48.47    | 57:06:10.44 | KVNS1.3.1 | 0.34 (±0.04)      | ...          |
| J0008+2339       | 00:08:00.37    | 23:39:18.00 | KVNS1.3.1 | 0.16 (±0.03)      | ...          |
| J0008+6837       | 00:08:33.47    | 68:37:22.08 | KVNS1.3.1 | 0.21 (±0.02)      | ...          |
| J0009+0628       | 00:09:03.93    | 06:28:21.25 | KVNS1.3.1 | 0.22 (±0.03)      | ...          |
| J0010+4001       | 00:09:04.17    | 04:01:46.56 | KVNS1.3.1 | 0.29 (±0.04)      | ...          |
| J0010+1058       | 00:10:31.00    | 10:58:29.64 | KVNS1.0.1 | 2.15 (±0.12)      | 1.601        |
| J0011+1724       | 00:10:33.99    | 17:24:18.72 | KVNS1.3.1 | 0.50 (±0.04)      | ...          |
| J0011–2157       | 00:10:53.65    | 21:57:04.32 | KVNS1.3.1 | 0.41 (±0.03)      | ...          |
| J0011–2612       | 00:11:01.25    | 26:12:33.48 | KVNS1.2.2 | 0.45 (±0.05)      | ...          |
| J0011–7045       | 00:11:31.90    | 70:45:31.68 | KVNS1.3.1 | 0.47 (±0.05)      | ...          |

**Note.** (1) IAU name (J2000), (2) IVS names, (3) and (4) are the R.A. and decl. taken from the VCS1-5, respectively, (5) and (6) are an observation code and the source flux density with 1σ error in the blanket in the \(K\) band, respectively, (7) and (8) are the same as (5) and (6) only in the \(Q\) band, (9) redshifts (z) of 1137 sources come from NASA/IPAC Extragalactic Database (NED) and the Sloan Digital Sky Survey (SDSS) DR13. (This table is available in its entirety in machine-readable form.)

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**Figure 3.** Luminosity distribution of 1137 sources as a function of redshift (z). The z values were taken from the NASA/IPAC Extragalactic Database (NED) and the Sloan Digital Sky Survey (SDSS) DR13. These luminosities are calculated with \(\alpha = 0\) as the criteria for flux densities. Top right: The number of sources according to their luminosities at \(\alpha = -1.0\) (gray filled circles, 0: black circles). The red lines indicates the luminosity distribution at \(\alpha = 0\) with a brightness model of Mars at the KVN Yonsei observatory (B.W. Sohn et al. 2017, in preparation).
conditions or instrumental spuriousness, (b) linear baseline fitting to estimate the rms noise level and to eliminate sky level, (c) Gaussian fitting to measure the antenna temperature and to correct pointing offsets deviating from the Gaussian fitted center position using Equations (1) and (2) (Fuhrmann 2004).

\[
(T'_{\alpha,Az})' = T'_{\alpha,Az} \cdot \exp \left[ 4 \ln 2 \frac{\chi^2}{\theta_{\text{EL}}^2} \right]
\]  

(1)
We denote spectra as steep, flat, and inverted, respectively. Furthermore, $x_{\text{Az}}$ and $x_{\text{El}}$ are pointing offsets, and $\theta_{\text{Az}}$ and $\theta_{\text{El}}$ are the half-power beam width in arcseconds. After the pointing correction, $(T'_{a,\text{Az}})$ and $(T'_{a,\text{El}})$ were averaged. (d) The error propagation of the antenna temperature was calculated using Equation (3).

$$\sigma_{(T'_{a})} = (T'_{a})^{\frac{1}{2}} \sqrt{\frac{\sigma_{\Delta G}^2}{\Delta G^2} + \frac{\sigma_{T}^2}{(T'_{a})^2}}$$  \hspace{1cm} (3)$$

$(T'_{a})$ is the corrected and averaged $T'_{a}$ for the pointing offset and in Az and El. $\sigma_{T'}$ represents the uncertainty of $T'_{a}$. $\Delta G$ is the temporal variation of the antenna gain, and its uncertainty is written as $\sigma_{\Delta G}$. The gain curves of the KVN radio telescopes are very flat for elevations of $20^\circ$–$80^\circ$ in the K and Q bands. The gain variation along each elevation were 2.5% (K) and 2.0% (Q) at KYS and 1.5% (K) and 4.5% (Q) at KUS (see footnote 4). The elevation dependence of the gain variation was therefore ignored. $\Delta G$ was obtained by using the ratio of the mean $(T'_{a})'$ to $(T'_{a})$ of 3C 286. However, the error was dominated by the thermal random noise. The flux density conversion factors were determined from the ratio of the flux densities to $(T'_{a})$ of 3C 286 in the K and Q bands (see Table 1), which were obtained using the NRAO Mars emission model (Butler et al. 2001). To check the results, we compared these conversion factors with those obtained for planets (Lee et al. 2011), which have ~10% uncertainty, and found that they are consistent within 10% and 8% in the K and Q bands, respectively. Finally, the conversion factors obtained for 3C 286 were applied to estimate the source flux densities.

4. Results and Discussion

4.1. Flux Density Measurement

Of the 2043 sources, the flux densities of 1533 (75%) and 533 (27%) sources with 3σ noise levels of 66 (K band) and 108 (Q band) mJy were measured successfully. Their median flux densities were 397 and 588 mJy and the lowest flux densities were ~70 and ~120 mJy in the K and Q bands, respectively. Of these, the flux densities of 513 sources were simultaneously measured in the K and Q bands. The distribution of the measured flux densities are shown in Figure 2 and the measured flux densities are listed in Table 2.

The luminosity distribution of 1138 sources as a function of redshift ($z$) are plotted in Figure 3. Archival redshifts were taken from NASA/IPAC Extragalactic Database (NED) and the Sloan Digital Sky Survey (SDSS) DR13. Only 23 sources were given as the photometric redshifts, and their mean uncertainties are about 0.618. These luminosities are calculated with $H_0 = 73$ km s$^{-1}$ Mpc$^{-1}$ and $\Omega_m = 0.27$ at 21.7 GHz$^5$, according to the arbitrarily spectral indices ($\alpha = -1.0$ and 0.0, $S \sim \nu^\alpha$, where $S$ is the flux and $\nu$ is the observed frequency). We denote spectra as steep ($\alpha < -0.5$), flat ($-0.5 \leq \alpha \leq 0.5$), and inverted ($\alpha > 0.5$) in this study. This figure reflects that our data are those of flux-limited samples, and they show the distribution of high-power radio sources, which ranges from $10^{24}$ to $10^{29}$ W Hz$^{-1}$ at 21.7 GHz (the observing frequency). According to the number distribution with respect to $z$ in the bottom right panel in Figure 3, the peak is located at the $z \sim 1$.

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**Figure 6.** Top: flux–flux relationship of 232 common sources in K band between single-dish observations from the KVNCS and VLBI observations from (Charlot et al. 2010) according to the structure index (SI). The error bar of each source indicates the 1σ measurement error. Regions (1) and (2) are separated by the median flux densities (the first dotted line) of the KVNCS in K band. Regions (2) and (3) are separated by 1 Jy (the second dotted line) arbitrarily. Red (SI $< 3$) and blue (SI $\geq 3$) lines show the weighted linear fit results obtained using the data in (2) and those from all extended sources, respectively (black line: proportional case). Bottom: flux–flux relationship of 76 common sources in the Q band. The error bar of each source indicates the 1σ measurement error. The green line shows the weighted linear fit result obtained using the all data, regardless of the SI (black line: proportional case).

**Table 3**

Statistics of $\alpha$ for 1533 Sources in the K Band, 553 Sources in the Q Band, and 513 Sources Simultaneously Measured in the K and Q Bands

| Spectral index | 1533 (K) Sources | 553 (Q) Sources | 513 Sources |
|----------------|-----------------|----------------|-------------|
|                | Steep (%)       | Flat (%)       | Invert (%)  |
| $\alpha_{\text{KQ}}$ | 6.9             | 88.5           | 4.6         |
| $\alpha_{\text{KQ}}$ | 6.6             | 89.5           | 4.1         |
| $\alpha_{\text{KQ}}$ | 12.9            | 68.2           | 19.9        |
| $\alpha_{\text{Q}}$ | 5.8             | 62.6           | 31.6        |
| $\alpha_{\text{Q}}$ | 2.3             | 82.3           | 15.4        |
| $\alpha_{\text{Q}}$ | 2.7             | 84.2           | 13.0        |
| $\alpha_{\text{Q}}$ | 13.5            | 76.2           | 10.3        |

$$(T'_{a,\text{Az}})^{*} = T_{a,\text{Az}} \times \exp \left[ 4 \ln 2 \frac{x^2_{\text{Az}}}{\sigma^2_{\text{Az}}} \right]$$  \hspace{1cm} (2)$$

$T_{a,\text{Az}}$ and $T_{a,\text{El}}$ are the measured antenna temperature corrected for atmospheric attenuation along the Az and El axes in the cs-
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The peak of bright quasars is known to be around $z \sim 1$ (White et al. 2000). In addition, these distributions in four-$z$ bins are shown in Figure 4. Gray filled and black hatched bars indicate each distribution according to $\alpha = -1.0$ and 0.0, respectively. The distributions according to $\alpha$ are similar in the low-$z$ region ($z < 0.5$), whereas they differ in the high-$z$ region ($z \geq 0.5$).

4.2. Comparison with the VLBI Flux Densities in the S, X, K, and Q Bands

We compared the VCS flux densities in the S and X bands with those of the KVNCS in the K and Q bands because a large difference, if any, between the observed flux densities in the K and Q bands and the extrapolated flux densities in the S and X bands would signify a VLBI missing flux problem, high source variability, or source evolution (e.g., opacity changes). Their correlations with the weighted linear fit lines are shown in Figure 5. The linear correlation coefficients are 0.77 ($S-K$), 0.87 ($X-K$), 0.81 ($S-Q$), and 0.85 ($X-Q$). The linear fit lines are obtained using the data with a $K$-band flux density greater than 397 mJy (median flux) and lower than 1 Jy (arbitrarily) and a $Q$-band flux density greater than 587 mJy (median flux), because the data contain faint sources that were not detected at high frequency (e.g., the K or $Q$ bands) but were detected at low frequency (e.g., the $S$ or X bands). This causes a selection effect for non-detected sources (the red and black arrows), which are faint sources with a flux density lower than $3\sigma$. Thus, sources with a flux lower than the median flux density were excepted from fitting. In addition, the bright sources (>1 Jy) in the $K$ band excluded for fitting because they can always be detected, although they are highly variable. The slopes of the weighted linear fit lines are $1.04 \pm 0.024$ and $0.79 \pm 0.005$ for the $S-K$ and $S-Q$ bands, respectively, whereas they are $0.63 \pm 0.024$.
(X–K) and 0.59 ± 0.005 (X–Q). The differences between the slopes in the S and X bands imply that there are missing flux densities in the X band. The flux densities measured from the VCS were calculated from the CLEAN components from VLBI observations, and the flux densities for some sources were obtained within 7 (S band) and 25 (X band) Mλ in projected u-distance (Petrov et al. 2006; Kovalev et al. 2007). Therefore, there is missing flux density in the X bands, depending on the structure of each source.

We also compared the flux densities of 232 (K band) and 76 (Q band) common sources from the KVNCS and VLBI imaging survey for the International CRF at 24 and 43 GHz (Charlot et al. 2010). Figure 6 shows their flux–flux relationships in the K and Q bands. On the basis of the structure index (SI) from Charlot et al. 2010, 195 (84%) and 63 (83%) sources were identified as SI < 3 (compact sources), and the remaining 37 (16%) and 13 (17%) sources showed SI ≥ 3 (sources with marginally compact or extended structure) in the K and Q bands, respectively. To obtain the weighted linear fit results, the data were selected in the same way as those in Figure 5. The linear fit at SI < 3 was performed for source flux densities greater than 397 mJy and lower than 1 Jy. However, some compact sources show great differences of flux density between VLBI and single-dish observations. For instance, a source with ~4 Jy in VLBI and ~1 Jy in single-dish flux densities has been known as a variable, J0238+1636, which had strong flux variations of around 5 Jy from 2007 to 2010. In addition, a source with ~0.3 Jy (VLBI) and ~3 Jy (single dish) is J1849 +6705. This has also been known as a variable and shows year-scale variations (see footnote 8). Therefore, these variables were not considered for the fit in K band. At SI ≥ 3, on the other hand, the linear fit results were calculated with all sources because the number of sources was small to fit. The slope for the compact sources is 1.07 ± 0.065, while that of extended sources is 0.66 ± 0.006 in K band. We infer that most of the radiation from the compact sources (SI < 3) comes from the compact core region, whereas the extended sources (SI ≥ 3) have missing flux. In the Q band, because there are few common sources, the weighted linear fit was applied to all 76 sources. We expect that most of the radiation (~80%) comes from the compact component, although about 20% of the flux density in the Q band is missing.

### 4.3. Spectral Index Distributions

Table 3 shows the statistics of α for 1533 sources in K band and 553 sources in the Q band, and 513 sources simultaneously detected in the K and Q bands. As expected, many of our sources have flat spectra in both the S and X and the K and Q bands. The distributions of the spectral indices of the S and X (αSX), X and K (αXK), X and Q (αXQ), and the K and Q (αKQ) bands are shown in Figure 7. The top panel shows the distributions of αSX and αXK for 1533 sources and αXQ for 553 sources. The distribution of αXK becomes broader than that of αSX, but ~88% of the αSX values and ~70% of the αXK values belong to the flat-spectrum ranges. In addition, the distribution of αXQ is similar, and we expect that these are relatively bright sources. In the bottom panel, the distribution of αXK is broader than the other distributions and shifts toward the inverted spectrum region because these sources are corrupted by flux density variability. There is an observational epoch gap between the VCS and KVNCS. However, αXQ shows a distribution similar to that of αSX. These sources are sufficiently bright. In addition, that of αXQ is steeper (~14%) than those of αSX (~6%), αXK (~6%), and αKQ (~3%). We infer that the sources become relatively optically thin in the K

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Footnote 8: F-GAMMA project: http://www3.mpifr-bonn.mpg.de/div/vlbi/fgamma/fgamma.html.
and $Q$ bands. Nevertheless, 76% of the sources show flat spectra in the $K$ and $Q$ bands.

4.4. Sky Coverage

Figure 8 clearly shows that our sample is fairly evenly distributed on the sky (this figure is the same as Figure 1 in Lee et al. 2012). Assuming a spatial coherence scale of 5°, which is the separation angle between a target and the calibrators, 99% of the sky is covered by these sources above −32°.5 in decl. (Figure 9). The sky coverage is improved by more than 20% compared to that of the existing calibrators shown in Figure 1. In the same way, if the spatial coherence scales are assumed as 2°.2 and 3°, the sky coverages are improved by about 28% and 38%, respectively. 2°.2 means a maximum separation of VERA dual-beam8, which is able to observe a target and a calibrator simultaneously, and 3° is a typical coherence scale in $K$ band. Hence it is expected that we have the possibility of improving the sky coverage of the $K$-band calibrators with a uniform distribution, compared to the existing one (Figure 1).

5. Summary

We conducted an extensive single-dish survey (the KVNCS) of 2043 extragalactic radio sources in the $K$ and $Q$ bands using the KVN and successfully detected 1533 (75%) of the sources in the $K$ band and 553 (27%) in the $Q$ band. In addition, the flux densities of 513 sources were simultaneously measured in the $K$ and $Q$ bands. This catalog is an important database for high-frequency VLBI observations with the KVN and other available radio telescopes worldwide. In addition, these sources become VLBI calibration candidates. The sky density distribution of the 1533 sources covered about 99% of the sky observable by the VLBI fringe and imaging surveys should be performed. These VLBI follow-ups are ongoing with the KVN and KaVA (KVN and VERA Array) in $K$ band. In addition, a simultaneous multiwavelength AGNs survey is in progress.

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