AMPLITUDE CORRECTION FACTORS OF KOREAN VLBI NETWORK OBSERVATIONS

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Abstract: We report results of investigation of amplitude calibration for very long baseline interferometry (VLBI) observations with Korean VLBI Network (KVN). Amplitude correction factors are estimated based on comparison of KVN observations at 22 GHz correlated by Daejeon hardware correlator and DiFX software correlator in Korea Astronomy and Space Science Institute (KASI) with Very Long Baseline Array (VLBA) observations at 22 GHz by DiFX software correlator in National Radio Astronomy Observatory (NRAO). We used the observations for compact radio sources, 3C 454.3, NRAO 512, OJ 287, BL Lac, 3C 279, 1633+382, and 1510−089, which are almost unresolved for baselines in a range of 350–477 km. Visibility data of the sources obtained with similar baselines at KVN and VLBA are selected, fringe-fitted, calibrated, and compared for their amplitudes. We found that visibility amplitudes of KVN observations should be corrected by factors of 1.10 and 1.35 when correlated by DiFX and Daejeon correlators, respectively. These correction factors are attributed to the combination of two steps of 2-bit quantization in KVN observing systems and characteristics of Daejeon correlator.

Key words: Techniques: interferometric — Instrumentation: interferometers — Radio continuum: galaxies

1. INTRODUCTION

The Korean VLBI Network (KVN) was built in Korea, as the first mm-dedicated Very Long Baseline Interferometry (VLBI) network, with its main goals for high resolution multi-frequency study of the formation and death of stars, the structure and dynamics of our Galaxy, and the nature of active galactic nuclei (AGNs) [Lee et al. 2011, 2014]. The KVN consists of three 21-m radio telescopes: KVN Yonsei Radio Telescope (KY), KVN Ulsan Radio Telescope (KU), and KVN Tanna Radio Telescope (KT), with baseline lengths of 305–477 km, operating at four frequency bands of 22 GHz, 43 GHz, 86 GHz, and 129 GHz. The maximum angular resolution at the 129 GHz band is $\sim 1$ milliarcsecond (mas).

Amplitude calibration of the KVN observations is performed according to a conventional VLBI calibration consisting of (a) calibration for amplitude variation due to atmospheric fluctuation, receiver noise fluctuation, elevation dependence of the antenna gains, etc, (b) amplitude correction for the atmospheric opacity on an antenna, and (c) re-normalization of the fringe amplitude for restoring amplitude distortion due to quantization [Lee et al. 2014]. In order to confirm the amplitude calibration of the KVN observations, the VLBI data correlated with DiFX correlator were compared with that of the Very Long Baseline Array (VLBA) observations conducted on the same source and in a similar time, assuming the amplitude calibration of the VLBA has been confirmed. Lee et al. (2014) compared the KVN 22 GHz observations conducted on 2010 October 1 with the VLBA observations on 2010 October 2. They selected the $uv$-data with the same $uv$-distances from both observations for extragalactic compact radio sources, and compared them each other, estimating the correction factors of $< 13\%$ for individual antenna. Petrov et al. (2012) found that the amplitude correction factors of KVN observations at 43 GHz are within 30% based on the similar comparison with VLBA observations. However, the authors for the previous works could not conclude to which these amplitude correction factors were specifically attributed and whether they should be applied to all KVN observations or not.

In this paper we report our understanding of the KVN systems related to the amplitude calibration, our findings for the KVN amplitude correction factors for the data correlated by DiFX and Daejeon correlators, respectively, and the reasonable suggestion of the application of the correction factors to the future KVN observations, based on observational tests of re-quantization losses in the KVN system. In Section 2, we overview general aspects of the KVN observing systems focusing on the two-step quantization loss. In Section 3, we summarize the observation data used and describe the data reduction procedure. In Section 4, we report...
the results of the amplitude correction factors. Finally, we make discussion and conclusion in Section 5.

2. Overview of the KVN Observing Systems

The KVN observing system consists of three 21-m antennas, quasi-optical systems, receivers operating at four frequency bands – 22 GHz, 43 GHz, 86 GHz, and 129 GHz – and backend systems, as described in Lee et al. (2011). The backend systems include the KVN Data Acquisition System (DAS) which consists of four subsystems: digital samplers, optical transmission system (OTS), digital filter bank (DFB) and digital spectrometer (DSM), as shown in Figure 1. The digital samplers in antenna cabin digitize the observation data into 2-bit data streams with four quantization levels. The OTS transmits the digitized signals to the observing building through optical fibers. The digitized signals are fed into the digital filter bank (DFB), which process the signals to be 16 sub-bands of 16 MHz wide with a frequency interval of 16 MHz. The processed signals are recorded by the Mark 5B system at an aggregate recording rate of 1024 Mbps. For the observations at the aggregate recording rate of 2048 Mbps, the digitized signals from the digital samplers can be directly recorded into the Mark 5B+ system with a single band of 512 MHz bandwidth, without passing through the DFB. The recorded data are shipped to the Korea-Japan Correlation Center (KJCC) and correlated with the DiFX software correlator or the Daejeon hardware correlator. In this section, we focus on describing the digital sampler and the digital filter bank systems, which generate the quantization loss of the data, although detailed information for the KVN DAS is described in Oh et al. (2011), and on introducing the DiFX software correlator and Daejeon hardware correlator.

2.1. Digital Sampler and Digital Filter Bank

In VLBI systems, the digital sampler is more preferable to the analog sampler due to important practical advantages for compensating time delays and measuring cross-correlation of signals such as Thompson et al. (2001): (a) higher accuracy (∼10-100 psec) of the long delay can be easily obtained in digital signal processing, and (b) the digital signal is not distorted by the digital instrumentation except for the quantization whose effects can be estimated. The digital sampler performs sampling the voltages of the analog signals at periodic intervals and quantizing the sampled value of the voltages with a small number of bits (e.g., 1-bit or 2-bit). The low level (or small bit number) quantization result in a quantization noise, i.e., a loss of sensitivity in digitizing the analog signals. Therefore, the optimal number of quantization levels is important in the digital signal process, and the investigations of the optimal quantization levels can be found in the literature (Thompson et al. 2001, and references therein). The investigations result in the well-known efficiency factors, for Nyquist sampling, 0.637 for 2-level quantization, 0.810 for 3-level, and 0.881 for 4-level. It should be noted that the efficiency factors for 3-level and 4-level quantizations are the maximum values when the sampling threshold is properly set, and hence, in practice, lower efficiencies are expected if the sampling threshold is not properly adjusted.

The digital samplers used in KVN is based on ADS-1000 Giga-Bit-Sampler (GBS) developed by the National Institute of Information and Communications Technology (NiCT), Japan (Nakajima et al. 2000). The digital sampler quantizes an intermediate frequency analog signal, converted from the radio frequency signals by receivers, with a bandwidth of 512 MHz and in four quantization levels (or in two bits), in order to achieve a higher sensitivity in the quantization. Since the bandwidth of the sampled signals by the digital sampler is 512 MHz, it is necessary to process the signals fitted into a bandwidth of 256 MHz for the Mark 5B system. Moreover, it is also required to channelize the whole frequency band into sub-bands and pick up the desired sub-bands optimized for scientific interests. Therefore, the DFB is introduced in the KVN DAS for flexibly channelizing and extracting the desired frequency bands according to the scientific purposes. In fact, the DFB filters out the desired frequency bands in the digital waveforms generated by the digital samplers with four-level (2-bit) quantized sampling. Since the data processing rate is limited by the instrumental capability, it is required to re-quantize the signal after the digital filtering (Iguchi et al. 2005).

2.2. DiFX and Daejeon correlator

A software correlator based on DiFX (Distributed FX; Deller et al. 2007, 2011) has been installed and used mainly for correlating data from the KVN observations. The software version of DiFX has been upgraded and the current version is 2.3. Detailed information of the DiFX installed for the KVN is described in Lee et al. (2014). A new hardware correlator (Daejeon correlator) was developed in 2009 by Korea Astronomy and Space Science Institute (KASI) and National Astronomical Observatory of Japan (NAOJ). The Daejeon correlator is mainly used for the East Asian VLBI Network (EAVN) consisting of Korean VLBI Network (KVN), Japanese VLBI Network (JVN) including the VLBI Exploration of Radio Astrometry (VERA) in Japan, and the Chinese VLBI Network (CVN). More information of the Daejeon correlator is summarized in Lee et al. (2014).

In order to evaluate the performance of the new hardware correlator, Lee et al. (2015) carefully compared the correlation outputs of both the DiFX and Daejeon correlators, using the KVN observations conducted at 22 GHz on 2011 January 28-29. They found that the two correlators are comparable each other in the correlation outputs except for the visibility amplitudes of the hardware correlator being lower by a factor of <8% than those of the DiFX correlator. The amplitude difference is due to the characteristics of the hardware correlator: (a) the way of fringe phase tracking (causing
an amplitude loss of $\sim 5\%$ due to coarse phase tracking
and see Iguchi et al. (2000) and (b) an unusual pattern
of the amplitude of the correlation output (causing an
amplitude loss of $\sim 3\%$). Fortunately, it was announced
by the KJCC operation team that the latter characteristic
has been fixed for the data correlated after 2015 March.

It should be noted that Lee et al. (2015) did not apply
digital correction (by switching off the option DIGI-
COR of the task FITLD) in order to compare the raw
outputs from the two correlators. In fact, the option
is required for proper amplitude calibration in case of
DiFX data, usually, unless DiFX was configured to use
Ts0 files during correlation. However, for the case of
the hardware correlator, the option DIGICOR does not
properly work. It may be because the option DIGI-
COR works for the DiFX data even for non-VLBA
arrays whereas the Daejeon correlator generates FITS
data whose header information is not optimized for the
use of the option DIGICOR. Since the scaling differ-
ence between DIGICOR ON/OFF cases could be some
percent (e.g., 1/0.88 for 2-bit quantization), the actual
difference of the amplitudes between KJCC and DiFX
after applying the option DIGICOR is larger than 8%.
In order to investigate the difference, it is required to
compare the DIGICOR-ON-outputs of the KVN data
correlated by DiFX and Daejeon correlator with those
of the VLBA data correlated by DiFX.

3. OBSERVATIONAL DATA AND DATA REDUCTION

3.1. Observational data

We compared KVN data obtained at 22 GHz with
VLBA data at 22 GHz. We selected the VLBA data ob-
tained close to the KVN data in time within a month in order to reduce source variability effect. The observational data at 22 GHz are used since we expect relatively less uncertainty of the amplitude calibration at this frequency than at higher frequencies, due to the atmospheric effect, pointing offset, etc. We used two KVN experiments (r11027 and n14sl01h) on 2011 January 28 and 2014 April 22 together with four VLBA experiments (BF104A, BM272, TD074, and S6096A) on 2011 January 17, 2011 February 26, 2014 April 13 and 2014 April 26. All experiments were conducted at 22 GHz bands. The KVN and VLBA data for this paper are summarized in Table 1.

3.2. Data reduction

For all of the data sets selected, we performed the same post-correlation processing using the NRAO Astronomical Imaging Processing System (AIPS), following a standard processing procedure as described in Figure 2. The correlated output FITS data was uploaded by FITLD task. In using FITLD, we did apply digital correction (DIGICOR = 1) for all the data sets whether it works or not. This is the first task related with the amplitude calibration and one proper chance to correct any unwanted visibility amplitude offset, which we want to correct, can be corrected in conducting the AP- CAL. The specific APCAL options and parameters for the amplitude correction are (a) APARM(1) = B, a correction factor (e.g., 1.10), which is called B factor in AIPS, (b) OPCODE = ‘’, and (c) DOFIT > 1. The APCAL with this setup correct the amplitude of the visibility by multiplying the correction factor, B, with the original amplitude. It should be noted that since the APCAL corrects the amplitude of every visibility before the time and frequency averaging, the resultant scatter of the visibility amplitude may also increase by a factor of $< B$.

3.3. Amplitude correction

Any unwanted visibility amplitude offset, which we want to correct, can be corrected in conducting the APCAL. The specific APCAL options and parameters for the amplitude correction are (a) APARM(1) = B, a correction factor (e.g., 1.10), which is called B factor in AIPS, (b) OPCODE = ‘’, and (c) DOFIT > 1. The APCAL with this setup correct the amplitude of the visibility by multiplying the correction factor, $B$, with the original amplitude. It should be noted that since the APCAL corrects the amplitude of every visibility before the time and frequency averaging, the resultant scatter of the visibility amplitude may also increase by a factor of $< B$.

4. RESULTS

After the amplitude calibration, we selected visibility data of 3C 454.3, NRAO 512, OJ 287, BL Lac, 3C 279, 1633+382, and 1510–089, obtained with similar baselines at KVN and VLBA. Since, at 22 GHz band, the KVN baseline lengths are in the range of 20–35 MA, we selected the VLBA data on the baselines, Fort Davis (FD) to Pie Town (PT), Kitt Peak (KP) to PT, Los Alamos (LA) to PT, FD to LA, FD to KP, or KP to Owens Valley (OV), whose baseline lengths are in the range of 17–35 MA. The visibility data were first averaged in time at an interval of 30 s. The amplitudes and antenna gains measured at each observational site are used for converting correlation coefficient to sky brightness and correcting for the amplitude errors. Depending on weather conditions and the accuracy of antenna gain measurements, we may expect the amplitude calibration errors as large as 10-30% for any VLBI array. The amplitude-calibrated data are further corrected for effect of bandpass filter on the spectrum shape using BPASS task. This is the fourth task related with the amplitude calibration. In this step, we only calibrated the amplitude with the BPASS task using the full bandwidth. For the multiple-source data, we split the data for individual source by SPLIT with chopping 10% of frequency channels at the band edge. This is the fifth step related to the amplitude calibration, since the excluded channels may be suffering from the amplitude loss due to the uncorrected effect of the bandpass filter.
Table 2
Mean visibility amplitude

| Source (1) | Telescope (2) | Correlator (3) | Epoch (4) | Baseline (5) | Length (MA) (6) | P.A. (°) (7) | Amplitude (Jy) (8) | Corrected amplitude (Jy) (9) |
|------------|--------------|----------------|-----------|--------------|-----------------|--------------|-------------------|-----------------------------|
| 3C 454.3   | KVN          | DiFX           | 2011 Jan 28 | KT-KY        | 34 ± 50         | 24.7 ± 0.7   | 27.1 ± 0.7        | -                          |
|            |              |                |           | KT-KU        | 24.7 ± 0.7      | 23.8 ± 0.7   | 28.1 ± 0.5         | -                          |
|            |              |                |           | KU-KY        | 24.7 ± 0.7      | 25.6 ± 0.4   | 27.3 ± 1.0         | -                          |
|            |              |                |           | KT-TY        | 24.7 ± 0.7      | 20.2 ± 0.7   | 27.3 ± 1.0         | -                          |
|            |              |                |           | KT-KU        | 24.7 ± 0.7      | 19.5 ± 0.7   | 26.4 ± 0.9         | -                          |
|            |              |                |           | KU-KY        | 24.7 ± 0.7      | 21.1 ± 0.6   | 28.4 ± 0.7         | -                          |
|            |              |                |           | VLBA         | DiFX           | 2011 Feb 26 |                   |                             |
|            |              |                |           | FD-Pt        | 24.7 ± 0.7      | 28.2 ± 0.4   | 28.2 ± 0.4         | -                          |
|            |              |                |           | KP-Pt        | 24.7 ± 0.7      | 26.8 ± 0.8   | 26.8 ± 0.8         | -                          |
|            |              |                |           | LA-Pt        | 24.7 ± 0.7      | 28.0 ± 0.4   | 28.0 ± 0.4         | -                          |
|            |              |                |           | KVN          | DiFX           | 2014 Apr 22 |                   |                             |
|            |              |                |           | KU-KY        | 24.7 ± 0.7      | 9.64 ± 0.06  | 10.6 ± 0.06        | -                          |
|            |              |                |           | KT-KY        | 24.7 ± 0.7      | 10.4 ± 0.08  | 11.4 ± 0.03        | -                          |
|            |              |                |           | VLBA         | DiFX           | 2014 Apr 13 |                   |                             |
|            |              |                |           | LA-Pt        | 24.7 ± 0.7      | 40.4 ± 0.08  | 40.4 ± 0.08        | -                          |
|            |              |                |           | LA-Pt        | 24.7 ± 0.7      | 51.7 ± 0.02  | 51.7 ± 0.02        | -                          |
|            |              |                |           | KP-Pt        | 24.7 ± 0.7      | 55.2 ± 0.05  | 55.2 ± 0.05        | -                          |
|            |              |                |           | NRAO 512     | KVN            | DiFX           | 2011 Jan 28 |                   |                             |
|            |              |                |           | KT-KY        | 24.7 ± 0.7      | 0.98 ± 0.05  | 1.08 ± 0.06        | -                          |
|            |              |                |           | KT-KU        | 24.7 ± 0.7      | 1.00 ± 0.05  | 1.10 ± 0.05        | -                          |
|            |              |                |           | KU-KY        | 24.7 ± 0.7      | 0.80 ± 0.05  | 1.08 ± 0.07        | -                          |
|            |              |                |           | VLBA         | DiFX           | 2014 Apr 26 |                   |                             |
|            |              |                |           | LA-Pt        | 24.7 ± 0.7      | 4.33 ± 0.01  | 4.40 ± 0.01        | -                          |
|            |              |                |           | KP-Pt        | 24.7 ± 0.7      | 4.22 ± 0.02  | 4.22 ± 0.02        | -                          |
|            |              |                |           | OJ 287       | KVN            | DiFX           | 2014 Apr 22 |                   |                             |
|            |              |                |           | KT-KY        | 24.7 ± 0.7      | 3.74 ± 0.01  | 4.08 ± 0.01        | -                          |
|            |              |                |           | VLBA         | DiFX           | 2014 Apr 26 |                   |                             |
|            |              |                |           | LA-Pt        | 24.7 ± 0.7      | 4.43 ± 0.01  | 4.43 ± 0.01        | -                          |
|            |              |                |           | KP-Pt        | 24.7 ± 0.7      | 4.22 ± 0.02  | 4.22 ± 0.02        | -                          |
|            |              |                |           | BL Lac       | KVN            | DiFX           | 2014 Apr 22 |                   |                             |
|            |              |                |           | KT-KY        | 24.7 ± 0.7      | 4.89 ± 0.01  | 5.48 ± 0.01        | -                          |
|            |              |                |           | KU-KY        | 24.7 ± 0.7      | 4.83 ± 0.03  | 5.32 ± 0.03        | -                          |
|            |              |                |           | VLBA         | DiFX           | 2014 Apr 26 |                   |                             |
|            |              |                |           | LA-Pt        | 24.7 ± 0.7      | 5.72 ± 0.01  | 5.72 ± 0.01        | -                          |
|            |              |                |           | KP-Pt        | 24.7 ± 0.7      | 5.27 ± 0.01  | 5.27 ± 0.01        | -                          |
|            |              |                |           | 3C 279       | KVN            | DiFX           | 2014 Apr 22 |                   |                             |
|            |              |                |           | KT-KU        | 24.7 ± 0.7      | 24.6 ± 0.07  | 27.1 ± 0.08        | -                          |
|            |              |                |           | KT-KY        | 24.7 ± 0.7      | 23.3 ± 0.03  | 25.6 ± 0.03        | -                          |
|            |              |                |           | VLBA         | DiFX           | 2014 Apr 26 |                   |                             |
|            |              |                |           | LA-Pt        | 24.7 ± 0.7      | 23.3 ± 0.03  | 25.6 ± 0.03        | -                          |
|            |              |                |           | KP-Pt        | 24.7 ± 0.7      | 26.0 ± 0.07  | 26.0 ± 0.07        | -                          |
|            |              |                |           | 1633+382     | KVN            | DiFX           | 2014 Apr 22 |                   |                             |
|            |              |                |           | KT-KY        | 24.7 ± 0.7      | 2.70 ± 0.01  | 2.98 ± 0.02        | -                          |
|            |              |                |           | VLBA         | DiFX           | 2014 Apr 26 |                   |                             |
|            |              |                |           | KP-La        | 24.7 ± 0.7      | 2.61 ± 0.02  | 2.88 ± 0.02        | -                          |
|            |              |                |           | 1510–089     | KVN            | DiFX           | 2014 Apr 22 |                   |                             |
|            |              |                |           | KT-Ky        | 24.7 ± 0.7      | 3.11 ± 0.01  | 3.42 ± 0.01        | -                          |
|            |              |                |           | VLBA         | DiFX           | 2014 Apr 26 |                   |                             |
|            |              |                |           | KP-ly        | 24.7 ± 0.7      | 3.33 ± 0.01  | 3.52 ± 0.02        | -                          |

of the visibility data for each baseline were averaged for all IF bands. The estimated mean visibility amplitudes for all baselines and sources are summarized in Table 2. The estimated mean amplitudes are compared between the KVN and VLBA baselines with similar baseline lengths and also compared between the KVN-DiFX and the KVN-Daejeon data. By taking into the comparison results, we determined the amplitude correction factors for the KVN observations correlated by DiFX and Daejeon correlators.

In the KVN baselines (or resolutions), the source compactness (defined as the ratio of the correlated flux
Table 3

Comparison of the visibility amplitude

| Source   | Epoch       | Baseline | S_{VLBA} | S_{KVN,DiFX} | S_{KVN,DaeJ} | S_{KVN,DaeJ} |
|----------|-------------|----------|----------|--------------|--------------|--------------|
| 3C 454.3 | 2011 Jan 28 | KT-KY    | 1.14     | 1.40         | 1.22         |              |
|          |             | KU-KY    | 1.13     | 1.37         | 1.22         |              |
|          |             | KT-KU    | 1.09     | 1.33         | 1.21         |              |
|          | 2014 Apr 22 | KT-KY    | 1.08     | -            | -            |              |
|          |             | KU-KY    | 1.09     | -            | -            |              |
| NRAO 512 | 2011 Jan 28 | KT-KY    | 1.08     | 1.34         | 1.24         |              |
|          |             | KU-KY    | -        | -            | 1.23         |              |
|          |             | KT-KU    | 1.07     | 1.34         | 1.25         |              |
| OJ 287   | 2014 Apr 22 | KT-KY    | 1.06     | -            | -            |              |
|          |             | KU-KY    | 1.19     | -            | -            |              |
| BL Lac   | 2014 Apr 22 | KT-KY    | 1.04     | -            | -            |              |
|          |             | KU-KY    | 1.12     | -            | -            |              |
| 3C 279   | 2014 Apr 22 | KT-KY    | 1.05     | -            | -            |              |
|          |             | KU-KY    | 1.06     | -            | -            |              |
|          |             | KT-KU    | 1.13     | -            | -            |              |
| 1633+382 | 2014 Apr 22 | KT-KY    | 1.14     | -            | -            |              |
|          |             | KU-KY    | 1.11     | -            | -            |              |
| 1510−089 | 2014 Apr 22 | KT-KY    | 1.09     | -            | -            |              |
|          |             | KU-KY    | 1.08     | -            | -            |              |

Mean 1.10 1.35 1.23

Table 4

Amplitude correction factors

| Telescope | Correlator | Frequency band | Correction Factor | Remarks          |
|-----------|------------|----------------|-------------------|------------------|
| KVN       | DiFX       | 22 GHz         | 1.10              |                  |
|           |            | 43-129 GHz     | 1.10              |                  |
| Daejeon   |            | 22 GHz         | 1.35              | before 2015 March|
|           |            | 22 GHz         | 1.30              | after 2015 March |
|           |            | 43-129 GHz     | 1.35              | before 2015 March|
|           |            | 43-129 GHz     | 1.30              | after 2015 March |
| VERA      | DiFX       | 22-43 GHz      | 1.10              |                  |
|           | Daejeon    | 22-43 GHz      | 1.35              | before 2015 March|
|           |            | 22-43 GHz      | 1.30              | after 2015 March |

The correction factors should be applied only to the KVN observations at a recording rate of 1024 Mbps. The correction factors in italic are the suggested values.

density on the longest baseline to that on the shortest baseline) is close to unity, implying that the source is very compact or unresolved. Since some of the VLBA baselines selected are not aligned with the KVN baselines in the position angle (P.A.) of the baseline, we may expect that a source structure resolved in the KVN baselines may result in different correlated flux density depending on the position angle of the baselines. However, we expect that the source structure effects are very small due to the compact structure of the sources. We found that, on average, the visibility amplitudes of VLBA data are higher than those of KVN-DiFX data by 10% and much higher than those of KVN-Daejeon data by 35%, as shown in Table 3. This is because the visibility amplitudes of the KVN-DiFX data are higher than those of the KVN-Daejeon by 23%.

By the amplitude correction factors determined, we corrected the amplitude of the KVN observations according to Section 3.3. As shown in Table 2 (Column 8), the mean visibility amplitudes for the KVN data are corrected to be consistent to those of the VLBA data. The scatter of the visibility amplitude get larger by the applied factors as expected.

5. Discussion

The difference of the calibrated visibility amplitudes between KVN-DiFX, KVN-Daejeon, and VLBA-DiFX data are attributed to several aspects. We will consider here the factors which are important in causing the amplitude difference, and determine the correction factors for the KVN amplitude calibration.
5.1. Quantization loss

The quantization loss in digitizing analog signals has been theoretically analyzed (e.g., Thompson et al. 2001), and the digital loss in re-quantizing the digitized signals has been numerically investigated by Iguchi et al. (2003). The quantization loss is known to be 0.88 for the four-level (2-bit) quantization and the accumulated digital loss was shown to be 0.81 (= 0.88 × 0.92) in four-level re-quantization of the four-level quantized signals. Thus the additional digital loss due only to the four-level re-quantization is 0.92 in the case of the input signals of four-level quantization.

KVN observations experience a four-level quantization in the digital samplers and an additional four-level re-quantization in the DFB. As described in Section 2.2.1, the digital sampling and filtering are based on the four-level (2-bit) quantization, resulting in an accumulated digital loss factor of 0.81. In a standard calibration procedure, for example as described in Section 2.3, a quantization loss factor of 0.88 is corrected by switching on the option DIGICOR of the FITLD task. Thus, the quantization loss by the digital samplers can be corrected with the standard calibration procedure, whereas the re-quantization loss by the DFB is not, in general procedure. Consequently, the remaining amplitude loss factor for the properly calibrated visibility of the DiFX correlator is about 0.92, and the correction factor is 1.09, which is similar to the amplitude correction factor \( \frac{S_{\text{VLBA}}}{S_{\text{KVN, DiFX}}} = 1.10 \). The difference between the two correction factors, 1.09 and 1.10, may come from the difference of the amplitude correction uncertainties of KVN and VLBA (see below).

5.2. Characteristics of Daejeon correlator

As reported by Lee et al. (2013), the calibrated visibility of the Daejeon correlator suffers from two amplitude loss factors: (a) 0.95 (5%) due to the scheme of fringe tracking and (b) 0.97 (3%) due to the double-layer pattern problem. The fringe tracking scheme is the characteristics of the VLBI Correlation System (VCS) of the hardware correlator, which should be a constant loss factor as long as the hardware correlator uses the same fringe tracking scheme in the VCS. The double-layer pattern problem turns out to happen in serializing the data and mapping the memory in the VCS, and disappears in correlations after 2015 March (S. J. Oh, priv. communication).

In addition to these loss factors, the calibrated visibility of the Daejeon correlator may experience additional amplitude loss after the proper amplitude calibration since the quantization and re-quantization loss from the KVN observations is not properly corrected using a standard VLBI data reduction procedure, as described in Section 2.2. This characteristic results in an amplitude loss factor of 0.81. Therefore, the total amplitude loss factor for the properly calibrated visibility of the Daejeon correlator is about 0.75 (= 0.81 × 0.95 × 0.97), and the correction factor is 1.34, which is similar to the amplitude correction factor \( \frac{S_{\text{VLBA}}}{S_{\text{KVN, Daej}}} = 1.35 \). The difference between the two correction factors, 1.34 and 1.35, may come from the difference of the amplitude calibration uncertainties of KVN and VLBA (see below). Moreover, the amplitude ratio \( \frac{S_{\text{KVN, Daej}}}{S_{\text{DiFX}}} = 1.23 \) can be explained since the total amplitude loss factor of the Daejeon correlator compared to the DiFX is about 0.81 (= 0.88 × 0.92) and hence the correction factor is 1.23.

5.3. Calibration uncertainty and source variability

In addition to the two factors, the amplitude difference may also be attributed to the amplitude calibration uncertainties of KVN and VLBA and to the time-variability of the source brightness and structure. The difference of the amplitude calibration uncertainties may depend on the observing frequency band and the weather condition. And the source variability effect may be reduced by using the contemporaneous data from KVN and VLBA. Therefore, these two factors contribute very less to the difference of the visibility amplitude between KVN and VLBA data than the factors described above. Caution should be taken here, as the weather conditions are totally different in KVN and VLBA, and thus any systematics which could be caused by the weather may not be negligible.

5.4. Amplitude correction factors

Since the differences of the calibrated visibility amplitudes between KVN and VLBA data are attributed mainly to the digital characteristics of the KVN VLBI system and the hardware and software characteristics of Daejeon correlator, we may expect that the nature of the difference should remain constant in time and frequency bands. Therefore, one may apply the amplitude correction factors to the future KVN observations at 22 GHz, 43 GHz, 86 GHz and 129 GHz bands. The time and frequency dependence of the amplitude correction factors will be extensively investigated by using the KVN data of a KVN key science program, iMOGABA (Interferometric Monitoring of Gamma-ray Bright AGNs) (Wajima et al. 2015; Algaba et al. 2015; Lee et al. prep.), and the results will be reported elsewhere.

Our investigations are based on the KVN observations. However, the results may be applied to the VERA observations, since the backend system (in particular, digital sampler and DFB) of the VERA is similar to that of the KVN. Thus, we suggest that the amplitude correction factors determined in this paper can be applied to the VERA or KVN-VERA observations. Again, the amplitude correction factors for the KVN-VERA data will be confirmed and reported elsewhere (Oh. et al. in prep.).

Finally, we suggest to use the amplitude correction factors of 1.30 (= 0.81 × 1.35) for the VLBI data correlated by the Daejeon correlator since 2015 March, because the double-layer pattern problem is announced to be resolved for the recent correlations. All the determined and suggested correction factors are summarized.
in Table 4. The correction factors should be applied only to the KVN observations at a recording rate of 1024 Mbps.

6. Conclusion

The basic assumption that the VLBA amplitude calibration is robust enables to evaluate the amplitude calibration of KVN observations based on the rigorous comparison between the KVN and VLBA data obtained contemporaneously for extragalactic compact radio sources. We found that the VLBA data have higher amplitude than the KVN data by factors of 1.10 and 1.35 for the cases of DiFX and Daejeon correlators. Among several aspects contributing to the amplitude difference, we found that the quantization losses by the digital samplers and the DFB, and the characteristics of the Daejeon correlator are the main contributors. We expect that the nature of the amplitude losses is constant in time and frequency band. Therefore, we should apply the amplitude correction factors of 1.10 and 1.35 to the future KVN observations correlated by DiFX and Daejeon correlators, respectively. It is also suggested to apply these correction factors to observations using the KVN and VERA combined array.

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References

Algaba, J. C., Zhao, G. Y., Lee, S.-S., et al. 2015, IMOGABA II, JKAS, the KVN special issue, xxx
Deller, A. T., Tingay, S. J., Bailes, M., et al. 2017, DiFX: A Software Correlator for Very Long Baseline Interferometry Using Multiprocessor Computing Environments, PASP, 119, 318
Deller, A. T., Brisken, W. F., Phillips, C. J., et al. 2011, DiFX-2: A More Flexible, Efficient, Robust, and Powerful Software Correlator, PASP, 123, 275
Iguchi, S., Kawaguchi, N., Murata, Y., et al. 2000, Development and Performance of the Real-Time VLBI Correlator (RVC), IEICE Trans. Commun., E83-B, 2527
Iguchi, S., Kurayama, T., Kawaguchi, N., & Kawakami, K. 2005, Gigabit Digital Filter Bank: Digital Backend Subsystem in the VERA Data-Acquisition System PASJ, 57, 259
Lee, S.-S., Byun, D.-Y., Oh, C. S., et al. 2011, Single-Dish Performance of KVN 21 m Radio Telescopes: Simultaneous Observations at 22 and 43 GHz, PASP, 123, 1398
Lee, S.-S., Petrov, L., Byun, D.-Y., et al. 2014, Early Science with the Korean VLBI Network: Evaluation of System Performance, AJ, 147, 77
Lee, S.-S., Oh, C. S., Roh, D.-G., et al. 2015, A New Hardware Correlator in Korea: Performance Evaluation Using KVN Observations, JKAS, 48, 125
Nakajima, J., Sekido, M., & Suzuyama, T. 2000, Another giga-bit sampler prototype, Nearly completion: ADS-1000 development status, IVS CRL-TDC News, 17, 18
Oh, S.-J., Roh, D.-G., Wajima, K., et al. 2011, Design and Development of a High-Speed Data-Acquisition System for the Korean VLBI Network, PASJ, 63, 1229
Petrov, L., Lee, S. S., Kim, J., et al. 2012, Early Science with the Korean VLBI Network: The QCAL-1 43 GHz Calibrator Survey, AJ, 144, 150
Thompson, A. R., Moran, J. M., & Swenson, G. W., Jr. 2001, Interferometry and Synthesis in Radio Astronomy, 2nd Edition, (New York: John Wiley & Sons), 260
Wajima, K., Lee, S.-S., Algaba, J. C., et al. 2015, IMOGABA I, JKAS, the KVN special issue, xxx