THE POWER OF SIMULTANEOUS MULTIFREQUENCY OBSERVATIONS FOR mm-VLBI: ASTROMETRY UP TO 130 GHz WITH THE KVN

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ABSTRACT

Simultaneous observations at multiple frequency bands have the potential to overcome the fundamental limitation imposed by the atmospheric propagation in (sub)millimeter very long baseline interferometry (mm-VLBI) observations. The propagation effects place a severe limit on the sensitivity achievable in mm-VLBI, reducing the time over which the signals can be coherently combined, and preventing the use of phase referencing and astrometric measurements. We carried out simultaneous observations at 22, 43, 87, and 130 GHz of a group of five active galactic nuclei, the weakest of which is ~200 mJy at 130 GHz, with angular separations ranging from 3°6 to 11°, using the Korean VLBI Network. We analyzed these data using the frequency phase transfer (FPT) and the source frequency phase referencing (SFPR) techniques, which use the observations at a lower frequency to correct those at a higher frequency. The results of the analysis provide an empirical demonstration of the increase in the coherence times at 130 GHz from a few tens of seconds to about 20 minutes, with FPT, and up to many hours with SFPR. Moreover, the astrometric analysis provides high-precision relative position measurements between two frequencies, including, for the first time, astrometry at 130 GHz. Finally, we demonstrate a method for the generalized decomposition of the relative position measurements into absolute position shifts for bona fide astrometric registration of the maps of the individual sources at multiple frequencies, up to 130 GHz.

Key words: astrometry – galaxies: individual (1803+784, 1807+698, 1842+681, 1928+738, 2007+777) – radio continuum: galaxies – techniques: interferometric

1. INTRODUCTION

Astronomical study by means of very long baseline interferometry (VLBI) observations at centimeter wavelengths is a well established field, with advanced technological developments and analysis techniques that result in superb quality images, including those of very weak microjansky sources (e.g., Garrett 2005) and with microarcsecond (μas) astrometry measurements (e.g., Reid & Honma 2014), using phase-referencing techniques. This is applied to a wide variety of targets and fields of study.

VLBI at (sub)millimeter wavelengths (hereafter mm-VLBI) can result in the highest angular resolutions achieved in astronomy and has a unique access to emission regions that are inaccessible with any other approach or at longer wavelengths, because the compact areas of interest are often self-absorbed. Therefore, it holds the potential to improve our understanding of the physical processes in, e.g., active galactic nuclei (AGNs) and in the vicinity of supermassive black holes, and for studies of molecular transitions at high frequencies.

Nevertheless, the applications of mm-VLBI are much less widespread. The observations become progressively more challenging as the wavelength gets shorter because of the limited telescope surface accuracy and aperture efficiency, receiver system temperatures and sensitivity, and shorter atmospheric coherence times and because sources are intrinsically weaker in general. Moreover, phase-referencing techniques, which are routinely used in cm-VLBI, fail to work beyond 43 GHz (excluding a single case at 86 GHz with the Very Long Baseline Array, VLBA; Porcas & Rioja 2002).

Continuous development and technical improvements have led to a sustained increase of the high-frequency threshold for VLBI observations in the past two decades (see Krichbaum et al. 2014 for a review). Regular observations up to 86 GHz are being carried out with well-established networks such as the VLBA and the Global Millimeter VLBI Array, more recently up to 130 GHz with the Korean VLBI Network (KVN) and ad hoc observations at the highest frequencies up to 240 GHz (Doeleman et al. 2008). The field of mm-VLBI will greatly benefit from the arrival of the phased-up Atacama Large Millimeter Array (ALMA; Matthews & Crew 2015) for joint VLBI observations.

In this paper we will focus on two aspects that limit the potential of mm-VLBI observations: (1) achieving improved sensitivity through increased coherence times, to increase the number of targets; (2) achieving astrometry, and in particular for “bona fide” registration of images at multiple frequency bands, to reveal the physical processes in a number of fields of astronomy.

For example, for AGN studies, maps of the spectral index or rotation measure across the source, at millimeter wavelengths, provide crucial insights into the development of the magnetic field strength and particle densities as the jet exits the core region and extends down the outflow. However, astrometric map registration is crucial to make a reliable measurement and to form a meaningful interpretation. There are a number of methods in AGN studies that can be used to align images at multiple frequencies, as discussed in Hovatta et al. (2014). They argued that any results derived without accurate astrometric registration are questionable in the vicinity of the...
core, which is the most interesting region in mm-VLBI. Also, in studies of the maser emission from the molecular species that exist in circumstellar envelopes (CSEs) and star-forming regions, the comparison of the locations of the different species of maser emission can be inverted to reveal the physical conditions as a function of the distance from the central star pumping the masers (e.g., see discussion in Reid & Moran 1988). In both cases this would allow one to fully understand the flow of material and energy in stellar environments during the formation and evolution of stars. Traditionally, there has been no mechanism other than phase referencing to accurately astrometrically register the maps at the different bands.

The KVN (Kim et al. 2004; Lee et al. 2014) is the first dedicated mm-VLBI array and addresses one of the fundamental limitations of the field, the atmospheric stability. It currently consists of three antennas operated by the Korea Astronomy and Space Science Institute, spread across South Korea, located in the campus of the Universities of Yonsei and Ulsan on the mainland and on Jeju Island. The observing frequencies are centered at 22, 43, 87, and 130 GHz. The baseline lengths between the antennas range from 300 to 500 km, which provide a spatial resolution of ~1 mas at the highest frequency band. The innovative multiband receiver (Han et al. 2008, 2013) of KVN is designed to mitigate the atmospheric propagation effects using simultaneous observations at multiple bands. The KVN, combined with the frequency phase transfer (FPT) and source frequency phase referencing (SFPR) data analysis techniques (Dodson & Rioja 2009; Rioja & Dodson 2011; Rioja et al. 2011, 2014; see also references therein), allows an effective increase of the coherence time, well beyond that imposed by tropospheric fluctuations, as well as high-precision astrometric measurements, even at the highest frequencies. We know of no demonstrated upper frequency limit, and the methods would be expected to work as long as the tropospheric propagation effects were nondispersive.

In this context, successful tests are ongoing with ALMA (Fomalont et al. 2014) at frequencies as high as 650 GHz (where this is known as the band-to-band (B2B) mode). In Rioja et al. (2014) we presented results of SFPR astrometric measurements with KVN at 22 and 43 GHz for continuum sources, along with a detailed comparative study using fast frequency switching observations with the VLBA. Dodson et al. (2014) presented the application of SFPR to spectral line studies for astrometric registration of the H$_2$O and SiO maser maps, at 22 and 43 GHz, respectively, in CSEs. In this paper we extend the astrometric measurements to all four frequency bands supported by the KVN, up to 130 GHz, and quantify the increase in coherence time. The paper layout is as follows: the simultaneous multifrequency observations at four bands are presented in Section 2; a description of the analysis carried out to obtain the maps, astrometric measurements, and “bona fide” astrometric registration of multifrequency images is in Section 3; the results are presented in Section 4; and a discussion of the results is given in Section 5.

2. OBSERVATIONS

In 2014 March 5, we carried out simultaneous observations at four frequencies, i.e., 22, 43, 87, and 130 GHz (also known as K, Q, W, and D bands, respectively), with the three antennas of the KVN, toward five AGN target sources, for a total duration of 9 hr.

3. METHODS

In this section we describe the various mapping and astrometric analyses carried out.

3.1. Hybrid Maps at the Four KVN Frequency Bands

We followed standard procedures for imaging VLBI data sets using AIPS (Diamond 1995). One of the major challenges of imaging KVN observations arises from the small number of antennas, which prevents the application of amplitude self-calibration techniques to derive amplitude gain corrections, as this requires a minimum of four antennas.

At the lower frequencies (K and Q bands), the system temperature measurements, along with regular sky dipping, have been shown to provide a good estimate of the system performance (Lee et al. 2014). However, at the higher frequencies the recording consisted of four consecutive 16 MHz intermediate-frequency (IF) subbands at each frequency. The lower edges of the first IFs at Q, W, and D bands were selected to be multiples of that at K band, those being 21.65, 43.30, 86.60, and 129.90 GHz. Having integer frequency ratios is important for the successful application of tropospheric compensation techniques using multifrequency observations. The correlation was done with the DiFX correlator (Deller et al. 2011) with 1 s averaging and a spectral resolution of 64 channels per IF.

The target sources were selected from the 86 GHz VLBI catalog (Lee et al. 2008) based on two criteria: to have strong detections at W band, and angular separations in the sky ranging from a few to many degrees. Figure 1 shows the distribution in the sky of the five selected sources (1803+784, 1807+698, 1842+681, 1928+738, and 2007+777) along with their angular separations, which range between ~3°6 and 11°. None of the sources had been observed previously with VLBI at 130 GHz. The observations consisted of ~3-minute-long scans alternating between the sources in each of the two triangles shown in Figure 1, and between the triangles approximately every hour and a half, at the four bands simultaneously. Alternating between multiple sources allowed us to develop a strategy to decompose the relative astrometric measurements into single-source position shifts that allow, for example, the registration of the images at different frequencies.

Figure 1. Sky distribution of the five AGN sources in this study. The source pairs in the SFPR analysis are connected with a line and have angular separations ranging from 3°6 to 11°. The triangles connect sources that were observed in a ~1.5 hr block, alternating between the two triangles.
frequencies (W and D bands) significant discrepancies can be expected. Hence, we have attempted to use the observations of the five target sources to estimate global (i.e., for all sources) amplitude gain correction factors that should rescale the nominal calibration information, at each band. We assumed a point-source model of arbitrary flux (for all sources) and calculated the normalized amplitude gain corrections, for each individual source and at each frequency band. The individual gain estimates for all sources at a given band showed a good agreement, as shown in Figure 2; this supports the validity of the assumption of point-source structure with KVN resolutions at all bands. At each band, the values for all sources were merged and smoothed together, thereby further suppressing any individual source structure contributions to the estimated gain amplitudes, except for one of the weakest sources, 2007$+777$, at the highest frequency, 130 GHz, which has noisy solutions. The resultant amplitude gain correction factors were applied to the corresponding data sets using AIPS. The hybrid maps, made with DIFMAP (Shepherd et al. 1994), are presented in Section 4.

3.2. SFPR Maps and Astrometric Analysis

We carried out SFPR astrometric analysis of the four-band multifrequency KVN data set using AIPS. The details of SFPR analysis are presented elsewhere (Dodson & Rioja 2009; Rioja Figure 2. Superimposed normalized amplitude gain correction factors to the nominal KVN calibration, vs. time, derived assuming point-source models for each source (small symbols: crosses, circles, squares, triangles, and diamonds for 1803$+784$, 1807$+698$, 1842$+681$, 1928$+738$, and 2007$+777$, respectively), at all bands: (a) 22 GHz, (b) 43 GHz, (c) 87 GHz, and (d) 130 GHz. At each band, the corrections from the individual sources were merged and smoothed to provide the final set of amplitude corrections, which were globally applied (large black crosses). At the lower frequencies (i.e., 22 and 43 GHz) the estimated corrections were close to unity. On the other hand, at the higher frequencies the corrections spanned a greater range both above and below the nominal value, with long periods where the gain corrections are less than unity. That implies significantly better than 100% efficiency, which is unlikely; therefore, these gains were adjusted so that the maximum efficiency correction was 100%. These occurred at the highest elevations where one would expect the least deviation from the nominal gain performance.
No matter how many combinations of sources one measures, there will always remain an ambiguity of the global (i.e., common for all sources) absolute correction. That is, for example, in the case that all the sources have identical position shifts it would leave no signature in the measurements. Therefore, once we have decomposed the measurements into the contributions from the individual sources, we still need to find the global absolute correction. We have additional information that allows us to do this in most cases, namely, that a frequency-dependent source position shift is expected to be aligned with the direction of the jet in the map of the source. This expectation applies for both types of position shifts described above, i.e., core shifts arising from opacity effects and/or centroid shifts arising from structure blending, regardless of its nature. This approach will fail for the cases when the position shifts and the jet axis do not coincide, which would be unexpected, or when all the sources have similar jet directions and therefore there is no clear best global correction to be determined. The group of sources in our observations shows a wide range of jet directions in the high-resolution VLBI MOJAVE maps (Lister & Homan 2005; Hovatta et al. 2014). Hence, by adding the constraint that the position-shift direction must align with the upstream jet direction, we can determine both the appropriate global correction and unambiguous individual source position shifts (also called absolute position shifts hereafter). The latter are also the shifts required for a bona fide astrometric registration of the images at the four observed frequencies, for all the sources.

4. RESULTS

4.1. Hybrid Maps at the Four KVN Frequency Bands

Figure 3 shows self-calibration images for the five AGN sources in the multifrequency KVN observations, including the first images of these sources at 130 GHz. The visibility data sets were model fitted and imaged and show little divergence from point-source core-dominated images; in some cases there appears to be some elongation aligned with the jet direction, as seen in higher-resolution maps from MOJAVE (Lister & Homan 2005; Hovatta et al. 2014).

Table 1 lists the total flux values as measured from the maps, at all frequency bands. It should be noted that the absolute flux values might suffer from the lack of absolute calibration, especially at the highest frequency band, 130 GHz (see Section 3.1 for a description of the amplitude calibration).

It is worth emphasizing that not all sources had direct detections, i.e., within the atmospheric coherence time, and for those that did not, we benefited from the extended coherence time resulting from a previous trans-frequency FPT analysis calibration. Note that remaining dispersive residuals prevent making a map after solely FPT calibration; nevertheless, the FPT analysis conditions the data set at $\nu_{\text{high}}$ and allows for a self-calibration analysis using much longer phase solution time intervals, hence enabling the detection of sources that would not be detected otherwise (i.e., within the atmospheric coherence time interval). The resulting maps are therefore self-calibration maps and have no astrometry information. This procedure enabled the imaging of 2007+777 and 1842+681 at 130 GHz, which were too weak for direct detections.
4.2. Increased Coherence Time for mm-VLBI

The rapid changes in the observed interferometric phases introduced by the tropospheric propagation effects set a severe limit on the coherence time for integration of the signal in observations at high frequencies and therefore the sensitivity of those observations. A direct consequence of the effective tropospheric compensation achieved from simultaneous dual-frequency observations is an increased coherence time and therefore sensitivity. This can be visually appreciated in the FPTed and SFPRed phases shown in Figures 4 and 5, respectively. Figure 4 shows the FPTed calibrated visibility phases at $\nu_{\text{high}}$ for the five frequency pairs ($\nu_{\text{low}} \rightarrow \nu_{\text{high}}$) with $R$ integer, shown in separate plots, in our observations. Note that in all cases, the calibration applied has been derived from a different frequency band and scaled with the corresponding factor $R$. In all cases, the compensation of the fast tropospheric fluctuations results in a much higher degree of coherence, compared to the raw output of the correlator. Figure 5 shows the SFPRed visibility phases for a subset of frequency pairs and source pairs (using 1803+784 as reference) in these observations, which are representative of the final products of the observations.
SFPR analysis. It is immediately obvious that the remaining dispersive residual phase variation in the FPTed visibilities has been compensated for in the SFPR visibilities.

In order to quantify the increase in the coherence time, we have carried out a comparative study of the coherence times achieved with FPT and SFPR at 130 GHz. This is the highest frequency in our observations, where the propagation effects are most severe. To perform these tests, we use the AIPS task CALIB on FPTed and SFPRed calibrated data sets of 1842+681 at $\nu_{\text{low}} = 130$ GHz, with $\nu_{\text{low}}$ at 43 GHz and 1803+784 as the reference source, with a series of phase solution time intervals ranging from 0.5 to 480 minutes. In each case the phase solutions are applied and the calibrated visibility data Fourier-inverted to produce a map. We use the fractional peak recovered flux quantity, defined as the ratio of the peak flux in this map and that from self-calibrated maps, as a measure of remaining phase errors in the analysis. Figure 6 shows that the fractional peak recovered flux values in the maps decrease with increasing temporal solution intervals, as expected. The coherence time is defined as the solution interval at which the peak flux recovery is 60%, equivalent to the rms residual phase being equal to 1 rad. Our analysis shows that the coherence time at 130 GHz is $\sim 20$ minutes with FPT calibration. With SFPR calibration there is practically no limit in the coherence time; we could integrate up to 8 hr, the whole duration of the experiment, with a mere 20% loss of peak flux.

Note that the tropospheric coherence time at 130 GHz is some tens of seconds and that neither 1842+681 nor 2007+777 has direct detections at this frequency.

4.3. SFPR Maps and Astrometry at 22, 43, 87, and 130 GHz

The final outcome of the SFPR analysis is an SFPR map that conveys the astrometric information. Figure 5 shows a subset of the SFPRed maps obtained in the comprehensive analysis of KVN observations; they are the Fourier transform of the SFPR visibilities directly above in the same figure. The offset of the peak of brightness with respect to the center of the maps is a measurement of the relative position shift between the two frequency bands, for the two sources. The complete results...
which stand for $\nu_i = \nu_i^\text{high}$, respectively. The thermal noise term is the lowest, and the dynamic and static tropospheric errors are comparatively lower.

4.4. Decomposition of Relative Astrometric Measurements into Individual Source Position Shifts

Figure 7 shows polar plots of the pairwise astrometric measurements listed in Table 2, for the four source pairs involving 1803+784, and for the five frequency pairs. These are direct outcomes of the SFPR analysis. For each source pair, the measurements are the combined position shift contributions from both sources between the two frequencies, for each frequency pair, and therefore are expected to show little

from the SFPR astrometric analysis, comprising the five frequency pairs and six source pairs, are summarized in Table 2. Table 2 lists the R.A. and decl. offsets of the peak of brightness from the center of the SFPR maps, as measured with AIPS task MAXFIT; the DR of the map; the estimates of rms SFPR phase errors arising from the different contributions following formulae in Rioja & Dodson (2011), along with their quadratic sum; and the estimated astrometric errors as described in Section 4.5. Note that the dual-frequency calibration provides a perfect compensation for the nondispersive phase errors (i.e., $\phi_{\text{geom}}$, $\phi_{\text{dynam}}$, and $\phi_{\text{trop}}$) which stand for geometric, dynamic, and static tropospheric errors, respectively; that the thermal noise term ($\phi_{\text{thrm}}$) and the dynamic ionospheric errors ($\phi_{\text{ion}}$) are rarely significant; and that the phase errors are dominated by the contribution from the static ionosphere contribution ($\phi_{\text{ion}}^{\text{high}}$). The latter is largest for the frequency pairs with $\nu_{\text{low}} = 22$ GHz and increases with the angular separation between the sources.
### Table 2
Summary of the Measurements from the SFPR Astrometric Analysis Presented in This Paper, along with the Error Estimates, for the Five Frequency Pairs (Column 1) and for the Six Source Pairs (Separated by Horizontal Lines)

| Freq. | SFPR Astrometry | rms SFPR Phase Errors | SFPR Errors |
|-------|-----------------|-----------------------|-------------|
| Pair  |                 |                       |             |
|       | ∆α, ∆δ          | ∆α, ∆δ                |             |
|       | (mas)           | (mas)                 |             |
|       |                  |                       |             |
|       |                  |                       |             |
|       |                  |                       |             |
| K → Q | 86              | 7                     | 1.6         |
|       | 390             | 390                   | 4.1         |
| K → W | 81              | 76                    | 1.9         |
|       | 320             | 320                   | 10.3        |
| K → D | 129             | 132                   | 27.1        |
|       | 23              | 23                    | 16.1        |
| Q → W | 192             | 110                   | 2.6         |
|       | 240             | 240                   | 2.2         |
| Q → D | 10              | 82                    | 4.5         |
|       | 138             | 138                   | 3.7         |

### Table 2 (continued)

| K → Q | −200           | 75                    | 1.7         |
|       | 360             | 360                   | 4.4         |
| K → W | −364           | 169                   | 3.1         |
|       | 200             | 200                   | 11.1        |
| K → D | −379           | 241                   | 15.6        |
|       | 40              | 40                    | 17.2        |
| Q → W | −192           | 110                   | 2.6         |
|       | 240             | 240                   | 2.1         |
| Q → D | −235           | 130                   | 10.9        |
|       | 57              | 57                    | 3.9         |

### Table 2 (continued)

| K → Q | −86            | 70                    | 0.8         |
|       | 830             | 830                   | 3.9         |
| K → W | −241           | 150                   | 1.6         |
|       | 380             | 380                   | 9.7         |
| K → D | −307           | 210                   | 6.2         |
|       | 100             | 100                   | 15.0        |
| Q → W | −156           | 64                    | 0.6         |
|       | 960             | 960                   | 1.9         |
| Q → D | −165           | 84                    | 4.2         |
|       | 150             | 150                   | 3.4         |

### Table 2 (continued)

| K → Q | −43            | 43                    | 1.6         |
|       | 390             | 390                   | 3.8         |
| K → W | 0              | 18                    | 8.9         |
|       | 70              | 70                    | 9.5         |
| K → D | −4             | 45                    | 9.0         |
|       | 69              | 69                    | 14.8        |
| Q → W | −41            | 15                    | 1.2         |
|       | 540             | 540                   | 1.9         |
| Q → D | −42            | 50                    | 7.3         |
|       | 85              | 85                    | 3.4         |

### Table 2 (continued)

| K → Q | −276           | 73                    | 1.7         |
|       | 376             | 376                   | 3.4         |
| K → W | −476           | 123                   | 2.7         |
|       | 227             | 227                   | 8.5         |
| K → D | −549           | 156                   | 9.3         |
|       | 67              | 67                    | 13.2        |
| Q → W | −185           | 47                    | 4.7         |
|       | 133             | 133                   | 1.7         |
| Q → D | −230           | 45                    | 4.4         |
|       | 143             | 143                   | 3.0         |

### Table 2 (continued)

| K → Q | 125            | −92                   | 1.9         |
|       | 193             | 193                   | 3.5         |
| K → W | 181            | −205                  | 2.2         |
|       | 162             | 162                   | 8.8         |
| K → D | 192            | −257                  | 4.2         |
|       | 85              | 85                    | 13.7        |
| Q → W | 69             | −76                   | 4.9         |
|       | 73              | 73                    | 1.8         |
| Q → D | 210            | −105                  | 5.1         |
|       | 70              | 70                    | 3.1         |

### Note
The relative astrometric offsets and the dynamic ranges (columns 2–3 and 4, respectively) are measured from the SFPR maps. A list of the estimated error contributions, per baseline, is provided: the thermal errors (column 5) are estimated from the dynamic range (see text); the geometric and propagation media contribution errors (columns 6–10) are estimated using the formulae in Rioja & Dodson (2011), for typical parameter uncertainties of the tropospheric zenith path delay and the TEC equal to 3 cm and 3 TECU, respectively, source angular separations as listed, simultaneous multiband observing (TECstrp = 0), and source switching cycle of Tstrp = 450 s. Column 11 is the quadratic sum of the forementioned errors. Columns 12 and 13 are the errors of the SFPR astrometric measurements, in R.A. and decl. directional coherence, except when one source has a dominant position shift (e.g., the plots involving 1842+681 or 1928+738). We have used SVD to decompose the pairwise position shifts into single-source frequency-dependent position shifts, albeit with degeneracies included. Those are shown in Figure 8, where one can appreciate an improved agreement between the directions of the position shifts for each source, although those are not well aligned with the jet direction in high-resolution maps. The jet directions in the high-resolution maps for the five AGN sources (Lister & Homan 2005; Hovatta et al. 2014) are also shown in Figure 8(f), and their values are listed in Table 3. We used the expectation of alignment to break the degeneracy, by finding the best global correction (i.e., common for all sources) through a grid search of a few hundred microseconds around the SVD solutions, for each frequency pair. Figure 9 shows the degree of alignment as a function of grid position for the K → Q data set. Table 4 lists the global corrections that were found to best align the SVD minimized single-source position shifts to the jet directions, for the five frequency pairs. Finally, Table 5 lists the resultant absolute single-source position shifts corresponding to the five
frequency pairs, for the five sources. Figure 10 shows polar plots of these single-source frequency-dependent absolute position shifts listed in Table 5, which display a tight agreement between the five frequency pairs and are well aligned with the jet directions for each source.

4.5. Astrometrical Error Analysis

We have carried out a comprehensive error analysis to estimate the propagation of random and systematic error contributions in the SFPR analysis, along with those from the SVD and global shift minimization analysis, into the frequency-dependent position shift astrometric measurements for each source.

For the SFPR error analysis, we have used the formulae in Rioja & Dodson (2011) to estimate the residual phase errors arising from typical parameter uncertainties in the “a priori” models for the propagation medium and the geometry contributions. The estimated values per baseline are listed in Table 2, for the geometry (σφ\text{geo}^\text{high}) and for the dynamic and static components of both the troposphere (σφ\text{dtrp}^\text{high} and σφ\text{strp}^\text{high}, respectively) and the ionosphere (σφ\text{dion}^\text{high} and σφ\text{sion}^\text{high}, respectively). It should be noted that the table entries corresponding to nondispersive errors are zero, as a result of the multifrequency calibration. Table 2 includes also the dynamic range (DR) values measured from the SFPR maps, which are used to estimate a per-baseline thermal phase error (σφ\text{thm}^\text{high}) using the expression 360°/DR/\sqrt{N_\text{ant}} , where N_\text{ant} is the number of antennas. This is derived using the relationship between positional error and DR (σ_\text{r,θ} ∼ θ_\text{beam}/DR) and the formulae in Thompson et al. (2007, A12.58). Note that the dominant error contribution in Table 2 is related to the static component of the ionospheric propagation, which reaches peak values for frequency pairs with ν_\text{low} = 22 GHz and larger values of R and source pair angular separations; this will be revisited in Section 5. The quadratic sum of the aforementioned errors (√(Σσ^2)) is converted to the final SFPR astrometric error (σ_\Delta\alpha \cos δ, σ_\Deltaδ), for the KVN baselines lengths of ~400 km.

Finally, we convert the SFPR astrometric errors to frequency-dependent position shift errors for each source by (1) passing those through the same SVD transformation used for the decomposition of the measurements and (2) combining the outcome with the errors in the global shift minimization analysis, i.e., the errors in the jet position angles measured from the maps, as listed in Table 3. The final astrometric accuracies are listed in Table 5, in μas, as σ_\Delta\alpha \cos δ and σ_\Delta δ.

These correspond to the errors in the measurements of the position shifts that enable the bona fide astrometric registration.
of the maps across frequencies, for each of the five observed sources.

5. DISCUSSIONS

5.1. Demonstration of Multifrequency Calibration and Astrometry up to 130 GHz

Simultaneous multifrequency observations offer an effective path to achieve increased sensitivity and precision astrometry in mm-VLBI, beyond the domain of standard techniques, such as phase referencing. The compensation of the fast phase changes imposed by the rapid tropospheric fluctuations in mm-VLBI, using observations at a lower frequency of the same source, results in an increased coherence time of up to 20 minutes at 130 GHz using FPT analysis, which results in a significant increase of sensitivity. Moreover, when combined with the observations of another source, a bona fide astrometric measurement of the relative frequency-dependent position shift between the two frequencies can be estimated using the SFPR technique. This in turn results in an unlimited extension of the coherence time.

The work presented in this paper corresponds to a first demonstration of SFPR at 130 GHz, the highest frequency of the KVN. The application of SFPR techniques has allowed the detection of weak sources that were not directly detected within the atmospheric coherence time (i.e., with self-calibration), and we have measured frequency-dependent position shifts in a range of frequencies from 22 up to 130 GHz with high-precision, for each of the observed AGNs. Previous attempts to carry out astrometry at such frequencies, with the VLBA up to 87 GHz, were very limited: once with conventional phase referencing using very fast source switching and a very close source pair with \( \sim 14' \) separation (Porcas & Rioja 2002), and once with fast frequency switching using SFPR (Rioja & Dodson 2011). Moreover, the fast frequency switching observing mode of the VLBA leads to residuals in the tropospheric compensation, which ultimately limit the accuracy and quality of the analysis. The simultaneous multifrequency observing capability simplifies and widens the application to even higher frequencies and to many targets. Therefore, we have demonstrated the benefits of simultaneous multifrequency observations for mm-VLBI, to achieve sensitivity and astrometry at frequencies up to 130 GHz, the maximum frequency.
similar procedure was carried out for each frequency pair; the results of the complete analysis are listed in Table 4.

Table 4
Global Astrometric Correction Vectors That Result in the Best Alignment of the Jet Directions (Listed in Table 3) and the Individual Source Frequency-dependent Position Shifts, for the Five Frequency Pairs

| Freq. Pairs | Global Correction (μas) | Errors (μas) |
|-------------|--------------------------|-------------|
| K → Q       | −42, −36                 | ±14, ±4     |
| K → W       | −82, −76                 | ±29, ±10    |
| K → D       | −88, −100                | ±39, ±13    |
| Q → W       | −48, −326                | ±10, ±6     |
| Q → D       | −82, −34                 | ±14, ±9     |

The corrections (column 2) are in μas on the sky of R. A. and decl.; the same applies for the errors (column 3).

Note. The corrections (column 2) in μas on the sky of R. A. and decl.; the same applies for the errors (column 3).

available with KVN. We believe that these benefits would continue to apply beyond this frequency.

5.2. Interpretation of the Measured Position Shifts

The outcome of the astrometric analysis presented in this paper is a measurement of the frequency-dependent absolute position shift of the brightest features, or reference points, in the maps at the four KVN frequency bands, for each of the five AGNs. In general, the reference points in the KVN maps do not correspond to the position of the “core” component, owing to structure blending effects resulting from the relatively short ~400 km baselines. Therefore, in general, our measurements correspond to the position shifts or angular separations between the centroids of the brightness distributions at the four frequencies; in the case of a point source, this would be the same as the “core shift.”

Higher-resolution observations with longer baselines would make it possible to isolate the “core” component as the reference point in the astrometric analysis and to achieve an increase in the astrometric precision directly proportional to the enlarged baseline. For example, an 8000 km baseline would result in a 20-fold decrease of the astrometric errors listed in Tables 2 and 5, which would be suitable to measure the small magnitude of the opacity “core-shift” effect between the four KVN frequency bands predicted in the standard model for extragalactic radio sources (Jung et al. 2015). Regardless of the baseline length, the SFPR measurements provide a bona fide astrometric registration of the maps, which is at the base for reliable spectral index maps and in general spectral distribution studies. Applying the absolute single-source position shifts in Table 5 to the hybrid maps in Figure 3 provides the required astrometric image registration for such analysis.

In this paper, despite having the measurements of the shifts for the “bona fide” astrometric registration of the maps, the poor amplitude calibration in our observations prevented us from obtaining meaningful spectral index maps. In a second epoch of observations we have included an improved amplitude calibration strategy to overcome this issue.

The canonical SFPR astrometric errors range from a few tens to a few hundreds of μas depending on the frequency pairs and are completely dominated by the systematic static ionospheric terms (σφsi). If this were actually the case, we would expect to find (i) very similar SFPR astrometric offsets in all source pairs with similar separations, for a given frequency pair (i.e., 1928 +738 and 2007+777 to 1803+784) and (ii) predictable ratios between the astrometric offsets, e.g., the ratio of the astrometric offsets for K → W and Q → W should be equal to 5 if the ionospheric uncertainties were dominant. As we see no indication of these signatures in our results, we believe that the ionospheric contributions are acting coherently across the sources and that the canonical errors are therefore
Table 5
List of Absolute Single-source Position Shifts between Two Frequencies, for the Five Frequency Pairs and for the Five AGNs in This Study, as Plotted in Figure 10

| Freq. Pair | Δα cosδ (μas) | Δδ (μas) | PA (deg) | σΔα cosδ (μas) | σΔδ (μas) |
|------------|---------------|---------|----------|----------------|-----------|
| K → Q      | -92           | -4      | 92       | 31             | 41        |
| K → W      | -200          | 0       | 89       | 43             | 51        |
| K → D      | -225          | 19      | 84       | 50             | 54        |
| Q → W      | -132          | 18      | 82       | 11             | 12        |
| Q → D      | -173          | 30      | 80       | 15             | 15        |

1803 + 784

| K → Q      | -164          | -3      | 91       | 24             | 29        |
| K → W      | -272          | -72     | 104      | 36             | 37        |
| K → D      | -324          | -93     | 106      | 43             | 39        |
| Q → W      | -116          | -36     | 115      | 10             | 9         |
| Q → D      | -167          | -59     | 109      | 14             | 12        |

1807 + 698

| K → Q      | 109           | -78     | -125     | 66             | 93        |
| K → W      | 183           | -182    | -134     | 85             | 117       |
| K → D      | 188           | -235    | -141     | 91             | 122       |
| Q → W      | 64            | -97     | -146     | 17             | 23        |
| Q → D      | 61            | -102    | -148     | 24             | 30        |

1928 + 738

| K → Q      | 17            | -77     | -167     | 32             | 43        |
| K → W      | 46            | -145    | -162     | 45             | 54        |
| K → D      | 85            | -204    | -157     | 52             | 57        |
| Q → W      | 16            | -42     | -158     | 12             | 12        |
| Q → D      | 27            | -54     | -153     | 15             | 16        |

2007 + 777

| K → Q      | -78           | -16     | 101      | 18             | 20        |
| K → W      | -167          | 20      | 82       | 31             | 26        |
| K → D      | -163          | 13      | 85       | 39             | 28        |
| Q → W      | -71           | 18      | 75       | 10             | 9         |
| Q → D      | -157          | 15      | 84       | 13             | 10        |

Note. They have been derived from the SFPR pairwise measurements, using SVD plus the alignment constraint between the jet and the position shift directions, to decompose into single-source contributions and to break the degeneracy. Column 1 gives the frequency pairs; columns 2 and 3 are the R.A. and decl. of the position shifts, respectively, with the corresponding position shift direction (PA) in column 4. The errors (columns 5 and 6) include all random and systematic contributions. The position shift direction (PA) should be compared with the jet position angles given in Table 3.

providing a complete picture of the underlying physical mechanisms of jet formation across a very wide frequency range.

5.3. Comparison of SFPR to Other Methods

There exist a variety of methods used to register the images of AGNs and/or maser species at different frequencies; here we discuss those, in comparison to SFPR, for mm-VLBI. Hovatta et al. (2014) provide a thorough review of the alternative methods for registration of the images of AGNs at multiple frequencies. These broadly consist of using optically thin bright jet components (Fromm et al. 2013), 2D cross-correlation algorithms (Croke & Gabuzda 2008), or a combination of both. However, these methods are predicated on the assumption that there is a clearly identifiable optically thin bright jet component, which can act as a reference point for all frequencies, or an ensemble of less bright optically thin jet components, which can provide an average registration. Hovatta et al. carried out an error analysis of the propagation of incorrect alignments on spectral index and rotation measure maps. They concluded that the alignment errors are dominant around the core region (up to a distance of ~3 mas) and therefore the conclusions on the spectral index distribution for the innermost jet regions should be treated with caution. The application of these methods for compact sources and for sources with faint or smooth jets is clearly an issue. Therefore, these methods can be unreliable or impossible to use in mm-VLBI, where in many cases only the compact core can be detected.

In a similar fashion, some maser species can be assumed to form in a ring, and the center of the ring can therefore act as a reference point (Desmars et al. 2000), or one can identify a single component that appears similar in velocity and orientation with respect to the main body of emission and use that as the reference point across frequencies (Croke & Gabuzda 2008). It is not hard to see the shortfalls in such approaches, and these different methods tend to produce incompatible conclusions. Phase referencing would provide a clear solution for such challenges, but, as pointed out previously, phase referencing is not an option above 43 GHz, in general.

Therefore, SFPR stands alone as a method that will allow for the unambiguous registration across wide frequency spans for mm-VLBI images, for both continuum and spectral line studies, because it provides a complete compensation of atmospheric propagation and instrumental effects. SFPR is widely applicable for many sources, since the calibrator source can be at a significant angular separation and slow source switching does not undermine the result. The method will work even at very high frequencies, making it particularly suitable for mm-VLBI observations. We note that systematic effects do need to be carefully taken into account, particularly when using a lower frequency of 22 GHz.

6. CONCLUSIONS

We have demonstrated that the KVN multiband system is capable of delivering increased coherence times by calibrating the highest frequencies with the scaled-up phase solutions from the lower frequencies, using the FPT method. At 130 GHz the coherence times were extended from a few tens of seconds to 20 minutes, and to many hours by interleaving observations of
a second source. This provides improved sensitivity through allowing longer integrations on weak sources.

We have demonstrated that the KVN multiband system is capable of delivering astrometric results at the highest frequencies, using the SFPR technique. We have measured accurate relative position shifts between frequencies in the range of 22–130 GHz, using observations of six pairs of sources with angular separations between 3°.6 and 11°.

We have shown how to decompose these relative measurements into absolute single-source frequency-dependent position shifts. These decomposed position shift measurements are all that is required to form high-fidelity spectral index maps between the four frequency bands, which we will present in a subsequent paper.

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Figure 10. (a)–(e) Polar plots of the decomposed absolute single-source position shifts between two frequencies, for the five frequency pairs and the five AGNs. These are shown in different colors (as in Figure 7): K → Q (red), K → W (blue), K → D (black), Q → W (green), and Q → D (cyan). They have been derived from the SFPR pairwise measurements, using SVD plus the alignment constraint between the jet and the position shift directions, to break the degeneracy. The axes of the polar plots are as in Figure 7. (f) Polar plot of the jet directions as for Figure 8, showing the good alignment between the jet directions and that of the decomposed frequency-dependent position shifts, for each source. Thus, we have obtained absolute position shifts for the individual sources from the original pairwise measurements.
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