43 GHZ High-Precision Wide-Angle VLBI Astrometry of the Complete S5 Polar Cap Sample at the Technical Limit

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Minute motions of the cores of radio quasars and BL Lac objects and the chromatic dependence of the positions of those cores (the so-called core shift) can be studied by means of VLBI phase delay astrometry. We report on the results of 14.4/43.1GHz VLBA observations of the complete S5 polar cap sample carried out in 2010 compared to 15 GHz observations made in 2000. The successful 43 GHz observations in 2010, globally phase-delay connected for the first time, mark the state-of-the-art of the technique and probably its limit.

Keywords: VLBI, Astrometry.

1 Introduction

Over the last decades, we have carried out a set of Very Long Baseline Interferometry (VLBI) observations of the complete S5 polar cap sample. This sample consists of 13 radio-loud AGN (8 Quasi Stellar Objects and 5 BL-Lac Objects) that are located at high declinations ($\delta > 70^\circ$) and with high flux densities, all of them having well-defined ICRF positions [1]. The observations were taken with the Very Long Baseline Array (VLBA) at 8.4, 15, and 43 GHz [2], [3], [4].

The main goals of this campaign were the study of the frequency dependence and time stability of the jet structures (especially, the jet cores), as well as the characterization of the absolute kinematics of the optically-thin jet components of all sources. All observations were performed in phase-referencing mode, to enable us the use of differential phase delays in the astrometric analysis of the source positions. The differential phase delays are the most precise interferometric observables and encode robust information on the relative position of the sources (e. g., [6]).

Here we report on the new preliminary results from the latest observations of this campaign, which were taken in 2010 at 14.4 and 43.1 GHz, using, for the first time in this project, the fast frequency-switching (FFS) observing capabilities of the VLBA, which enable us to apply the source-frequency phase-referencing (SFPR) technique (e. g., [5]). A detailed analysis of the astrometric results at 14.4 GHz, as well as the relative astrometry between 14.4 and 43.1 GHz using the SFPR technique, has been already published ([7]; hereafter Paper I). In this work we present the first global phase connection at a frequency as high as 43.1 GHz and discuss about what it is likely the limit of application of this tecnique. We also compare these preliminary results with those obtained at the lower frequency (14.4 GHz) and with the results from a previous epoch (year 2000). This analysis enables us to determine the core shifts of most of the sources of the sample with a precision impossible to achieve by other methods.

2 Observations and data reduction

The VLBA observations were performed in 2010 December 18, and were arranged in duty cycles with a total duration of about 24 hours (see Paper I for further details). We used the NRAO Astronomical Image Processing System (AIPS) for the calibration of the visibilities. After a standard fringe-fitting procedure, we obtained the delay rates, group delays and phase delays of all the sources. We used DIFMAP to make the maps of the sources needed to correct for the phase delays associated with the structure of the sources.

3 Phase connection at 43.1 GHz

Phase connection is the process by which phase delays are converted into a non-ambiguous observable. We made use of the group delays and the delay rates at 43.1 GHz of all sources to derive good *a priori* models for the atmospheric non-dispersive delay and the drifts of the clocks of the stations. These models were then used to perform a preliminary connection of the phase delays. The remaining unmodelled phase cycles were derived using an automatic phase connection algorithm (see [4]. With the phase delay ambiguities properly corrected, we finally computed the differential phase delays (i. e., differences among delays for sources observed in the same duty cycle).

As an example of the quality of our fit, we show in Fig. 1 the residuals of the undifferenced and differenced phase delays corresponding to all the observed sources for baselines Hancock – Kitt Peak (3623 km) and Fort Davis – North Liberty (1654 km). Since the phase cycle at 43.1 GHz is just $\sim$23 ps, the phase connection procedure at such a high frequency becomes very difficult because we need to "follow" all possible changes in the phase delay at a very short timescale. We discuss further on the details in Sect. 6.

4 Comparison between 14.4 GHz and 43.1 GHz

We can compare our results at 43.1 GHz with the astrometric results obtained at 14.4 GHz in Paper I. In that publication we performed a Monte Carlo approach to estimate the final corrected positions in 2010 with respect to the final positions in

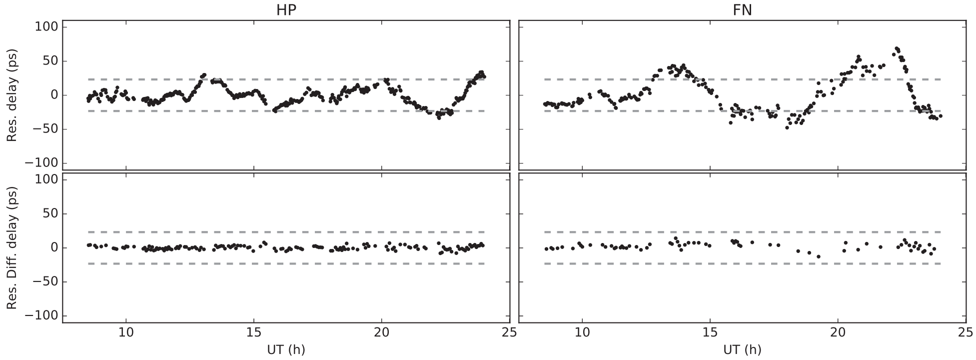

Fig. 1. Postfit residuals of the undifferenced (*above*) and differenced (*below*) phase delays of all the pairs of sources for baselines Hancock – Kitt Peak (*left*) and Fort Davis – North Liberty (*right*). The dashed lines represent the delays ~ 23 ps corresponding to $+1$ and -1 cycles of phase at 43.1 GHz

year 2000 [4] that were used as *a priori* positions in the new fit. We made a series of realizations allowing some variations in the tropospheric delays, ionospheric delays, and antenna-position shifts. In this work we have extended this analysis and, for each iteration in the fit, we have used the final corrected positions at 14.4 GHz in 2010 as the *a priori* positions for the 43.1 GHz fit. This is a reasonable approach since we expect the 43.1 GHz positions of the sources to be close to the 14.1 GHz positions. And this helps us to unambiguosly perform the fit at 43.1 GHz which otherwise could be affected for some effects like the fixing of the constant clock offsets of the antennas, due to the short phase cycle at this high frequency.

Once we have the final corrected positions at 43.1 GHz, we can calculate the difference in the angular separation between pairs of sources among the two frequencies. In Fig. 2 we show an example of the difference in the separation between source 0716+714 and source 0836+710 at 14.1 and 43.1 GHz for all the realizations of the fit.

5 Core shifts

Since we have the phase delays of the sources at 14.4 GHz and 43.1 GHz, we can determine the core shifts by just comparing the phase delays at both frequencies. For each source independently, we have used the position at 14.4 GHz at epoch 2010 as the reference position, and we have computed the differenced phase delays between the frequencies to obtain the corrections in right ascension and declination with respect to the reference position. This enables us to calculate the core shift of each source, which in this case is just the difference between the position at 14.4 and 43.1 GHz. As before, we have performed a Montecarlo analysis for a realistic estimate of the uncertainties.

Our main goal is to compare the core shifts obtained with this tecnique with the values reported in Paper I by means of SFPR calibration. In Fig. 3 we show an

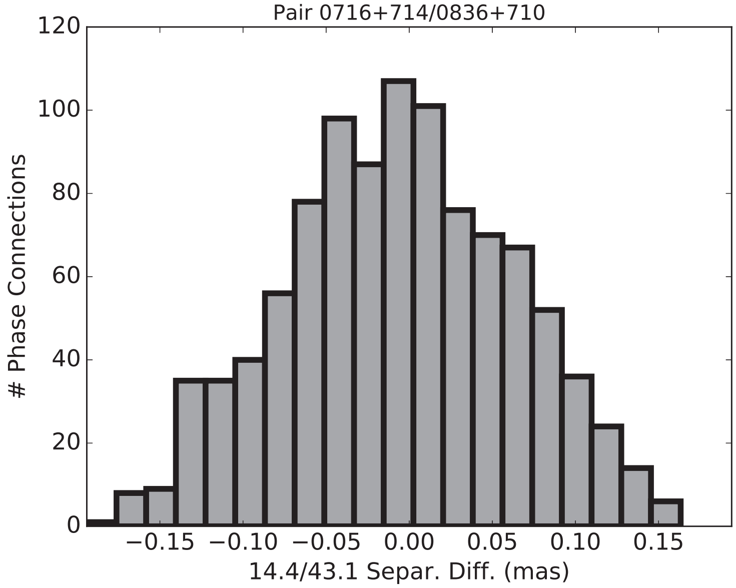

Fig. 2. Difference in the angular separation (mas) between the pair of sources 0716+714 and 0836+710 at 14.1 and 43.1 GHz for all the realizations of the fit

example of the offsets in right ascension, declination and core shift with respect to the mean values for the source 0716+714.

6 Conclusions and future work

We have performed a high-precision wide-angle astrometric analysis of a complete radio sample, and for the first time, we have globally connected the phase delays at a frequency as high as 43 GHz. This frequency is probably the observational limit for this astrometric technique, mainly due to the fast atmospheric variations and the long slewing time of the antennas. A similar work at higher frequencies (e. g., 86 GHz with a phase cycle of ~ 12 ps), where the atmospheric conditions vary faster than at lower frequencies, would require to account for all the possible ambiguities over the complete duration of the experiment. This will be very difficult (if not impossible) to achieve with the current instrumentation.

Our results are still in progress. We intend to compare our core shifts values with other methods (e. g., [8]. Currently we are working on the correct determination of the uncertainties in the analysis, which in any case will be more accurate and precise than many previous astrometric works. Also a deeper source-by-source analysis will be carried out, since we have found some sources with intriguing features (e. g., see discussion about source 0615+820 in Paper I).

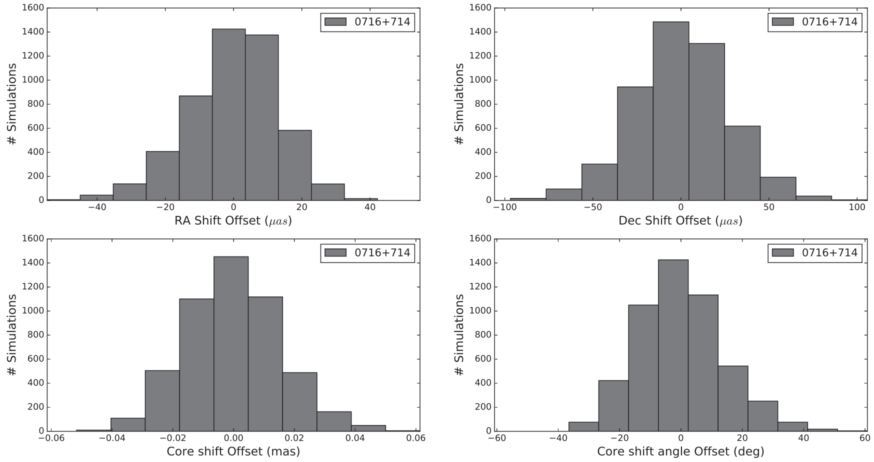

Fig. 3. Offsets in right ascension (*top left*), declination (*top right*), core shift value (*bottom left*) and core shift angle (*bottom right*) with respect to the mean values for the source 0716+714

Acknowledgments

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References

1. *Eckart A., Witzel A., Biermann P., et al.* Investigation of a complete sample of flat spectrum radio sources from the S5 survey // Astron. & Astrophys. — 1986. — Vol. 168. — P. 17–24.
2. *Ros E., Marcaide J. M., Guirado J. C., Pérez-Torres M. A.* Absolute kinematics of radio source components in the complete S5 polar cap sample. I. First and second epoch maps at 8.4 GHz // Astron. and Astrophys. — 2001. — Vol. 376. — P. 1090–1105.
3. *Pérez-Torres M. A., Marcaide J. M., Guirado J. C., Ros E.* Absolute kinematics of radio source components in the complete S5 polar cap sample. II. First and second epoch maps at 15 GHz // Astron. and Astrophys. — 2004. — Vol. 428. — P. 847–866.
4. *Martí-Vidal I., Marcaide J. M., Guirado J. C., Pérez-Torres M. A., Ros E.* Absolute kinematics of radio source components in the complete S5 polar cap sample. III. First wide-field high-precision astrometry at 15.4 GHz // Astron. and Astrophys. — 2008. — Vol. 478. — P. 267–275.

5. *Rioja M., Dodson R.* High-precision Astrometric Millimeter Very Long Baseline Interferometry Using a New Method for Atmospheric Calibration // Astron. J. — 2011. — Vol. 141. — P. 114, 15 pp.
6. *Marcaide J. M., Shapiro I. I.* High precision astrometry via very-long-baseline radio interferometry: Estimate of the angular separation between the quasars 1038+528A and B // Astron. J. — 1983. — Vol. 88. — P. 1133–1137.
7. *Martí-Vidal I., Abellán F. J., Marcaide J. M., et al.* Absolute kinematics of radio source components in the complete S5 polar cap sample. IV. Proper motions of the radio cores over a decade and spectral properties // Astron. and Astrophys. — 2016. — In press (arXiv: 1607.05089).
8. *Kovalev Y. Y., Lobanov A. P., Pushkarev A. B., Zensus J. A.* Opacity in compact extragalactic radio sources and its effect on astrophysical and astrometric studies // Astron. and Astrophys. — 2008. — Vol. 483. — P. 759–768.