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Astrometric “Core-shifts” at the Highest Frequencies

María Rioja [1], *Richard Dodson* [2]

[1] *ICRAR, University of Western Australia AND Observatorio Astronómico Nacional, Spain*
[2] *ICRAR*
Contact author: María Rioja, *e-mail:* `maria.rioja@icrar.org`

Abstract

We discuss the application of a new VLBI astrometric method named “Source/Frequency Phase Referencing” to measurements of “core-shifts” in radio sources used for geodetic observations. We detail the reasons that astrometrical observations of ‘core-shifts’ have become critical in the era of VLBI2010. We detail how this new method allows the problem to be addressed at the highest frequencies and outline its superior compensation of tropospheric errors.

1. Introduction

In the era of VLBI2010 all aspects of VLBI geodetic analysis need to be much more precise. The target positional accuracy of 1 mm converts to an angular precision of $\sim 30\,\mu$as. Therefore many effects, which have been considered secondary in the past, will now need to be accounted for. Among those is the changing observed position of celestial sources with observing frequency, known as “core-shifts”.

1.1. Effect of Core-shifts in VLBI Geodetic Studies

The standard theory for extragalactic radio sources predicts changes in their positions at different frequencies, although the black-hole “central engine” powering the typical core-jet structures is considered to be stationary [1]. Hence, the observed “apparent” celestial positions correspond to the location down the jet from the central engine at which the optical depth is equal to unity, which is known as the “core”. Prior to this location the emission is self-absorbed. Since the location at which the optical depth is unity is a function of frequency-dependent opacity effects, the “core” appears to move as the observing frequency changes. Such changes in position are termed “core-shifts”. Assuming a simple model for the jet, the distance of the first detectable emission is $\mathrm{r}_{core} \propto \nu^{-1/k_r}$, where ν is the observing frequency and the k_r is a power-law exponent which is commonly taken as unity.

Other than the intrinsic opacity-related effects, as mentioned above, the measured “core-shifts” may have another contribution related to insufficient resolution and structure blending effects at the lower frequencies. We term this contribution as “instrumental core shift”. Figure 1 is a sketch showing both contributions; typical values are listed in Table 1.

There is a wide observational evidence of existence of “core-shifts” revealed by VLBI astrometric techniques, e.g. [11, 3], and other approaches, e.g. [5]. Measurements of “core-shifts” are used in astronomy to probe the environments in the inner-jet regions and need to be accounted for in studies that involve the comparison of images at two or more frequencies to ensure a proper registration.

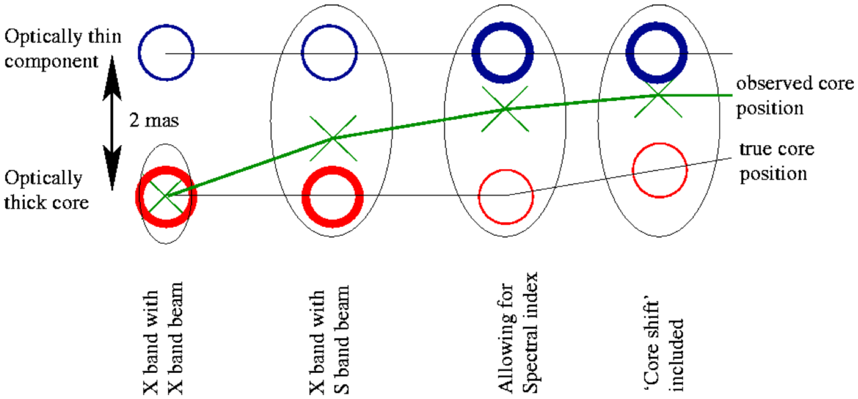

Figure 1. A sketch showing contributions to observed "core-shifts": *extrinsic*, due to structure blending at lower frequencies (first 3 starting from left), and *intrinsic* opacity (rightmost).

The influence of "core-shifts" in geodetic VLBI observations comes through the basic practice in geodesy of calibrating the ionospheric contribution with simultaneous observations at S/X-bands (2.2GHz/8.4GHz, respectively). This approach works under the critical assumption that the brightness distributions for each source are identical and are co-located at both frequencies. Otherwise, unaccounted "core-shifts" will introduce, in general, errors in the geodetic parameters. Nevertheless, for group-delay VLBI geodesy, as it has traditionally been performed, the effect of the intrinsic "core-shifts" is strongly attenuated in the analysis, and the estimated source positions correspond to those at zero wavelength (assuming k_r is unity) [9]. For phase-delay VLBI geodesy this is no longer the case, and the "core-shifts" will need to be corrected for across the observing frequency bands to avoid the propagation of errors into the estimated geodetic parameters; the same applies for the "instrumental core-shifts" in both phase and group-delay geodetic analysis.

Table 1. Typical sizes of the *intrinsic* opacity and the *extrinsic* instrumental core-shift contributions, along with typical measured "core-shift" values.

	Opacity core shift	*Instrumental* core shift	Measured core shift
2.2/8.4 GHz	0–1 mas	0 – 2 mas	0 – 1400 μas
8.4/30 GHz	0–0.25 mas	0 – 0.5 mas	0 – 30 μas

2. The Basis of the Source/Frequency Phase Referencing Method

The phase referencing astrometric technique is well established and has produced many significant insights. However, the fast telescope switching cycles imposed by the rapid tropospheric fluctuations at higher frequencies has prevented the application of conventional phase referencing techniques beyond 43 GHz, except for a single case at 86 GHz [8]. This is particularly significant for "core-shift" measurements as it is in the mm-wavelengths that we see the 'naked' core, free of the confusing emission structure from the synchrotron jets.

We have proposed an advanced tropospheric calibration method which would allow phase referencing and astrometry under a wider variety of conditions at mm-wavelengths [2]. In previous work, "fast-frequency switching" has been shown to increase the coherence time at mm-wavelengths, but without achieving astrometry [7, 4]. The non-dispersive nature of the troposphere makes it possible to use lower frequency observations to calibrate higher, providing the switching interval between frequencies matches the temporal structure of the tropospheric fluctuations at the lower frequency.

Our SOURCE/FREQUENCY PHASE REFERENCING (SFPR) method adds a source switching to the observing strategy, in addition to the fast frequency switching, to calibrate the residual dispersive contributions remaining in the phase transfer between frequencies. The new method is an enhancement which allows "*bona fide*" astrometric measurements of "core-shifts" in radio sources. The nodding between sources has to match the temporal and spatial structures of ionospheric perturbations (with typical scales of several minutes, and several degrees), and other non-dispersive terms such as instrumental contributions (with typical timescales of many minutes). A complete description of the method is presented in [10], [2], and [12]. We include here a brief outline of the basics:

A pure self-calibration analysis is used for the low *reference* frequency (r) target source (A) observations. Following the standard nomenclature, the residual phase values (ϕ^r_A) are shown as a compound of geometric, tropospheric, ionospheric, and instrumental terms (excluding source structure and phase ambiguity terms, for simplicity):

$$\phi^r_A = \phi^r_{A,geo} + \phi^r_{A,tro} + \phi^r_{A,ion} + \phi^r_{A,inst}$$

The calibration transfer between frequencies involves multiplying the phases by the frequency ratio R. This results in the perfect cancellation of the non-dispersive errors, i.e., tropospheric and geometric (source and antenna coordinates), but not for the dispersive ones, which remain. The *target* frequency (t)-referenced phases are:

$$\phi^t_A - R.\phi^r_A = \phi^t_{A,str} + 2\pi\nu^t/c * (\bar{B}.\bar{\theta}_{A,shift}) + ION + INST$$

where $\bar{\theta}_{A,shift}$ is the "core-shift" in A between both bands; ION/INST are the residual dispersive long time-scale terms which have prevented direct imaging and hence astrometry in previous attempts of frequency-referenced maps.

SFPR enables astrometry by using interleaving observations on a calibrator source (C), with the same observational strategy and analysis as explained above for source A. The results of C are used to correct the A dataset. The calibration transfer between sources is done as in conventional phase referencing. The SFPR-ed phases are:

$$(\phi^t_A - R.\phi^r_A) - (\phi^t_C - R.\phi^r_C) = \phi^t_{A,str} + 2\pi\nu^t/c * (\bar{B}.\bar{\theta}_{A,shift} - \bar{B}.\bar{\theta}_{C,shift})$$

which can be inverted to yield a synthesis image of A at the *target* frequency where the offset from the center is the combined "core-shifts" in A and C, between both frequencies. Figure 2 shows the SFPR map result from our observational demonstration using the VLBA, at 43/86 GHz [2].

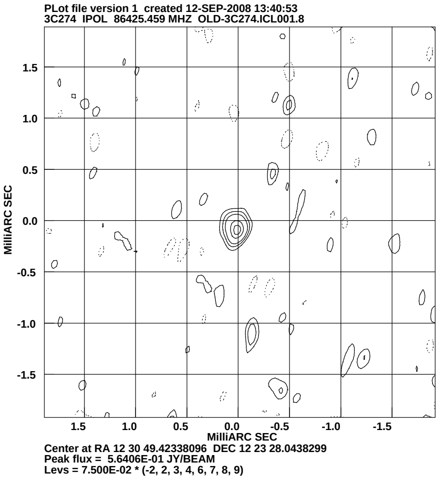

Figure 2. 86-GHz Source Frequency Phase-Referenced image of 3C274, calibrated against 43-GHz and 3C273. We believe that the core-shift seen is real as it matches the predicted values [6]. Typical errors appear to be of the order of 20 μas.

3. Tropospheric Compensation with the SFPR Method

Of particular interest to astrometric studies is that the SFPR method, by providing a superior tropospheric compensation, achieves high precision estimates at the highest frequencies. There are two major contributions to the tropospheric errors in VLBI observations: the “dynamic component”, due to uncertainties in the water vapor content in the troposphere (i.e., the ‘wet’ part) introduces random temporal variations, and the “static component”, due to slowly varying errors in the tropospheric zenith delay estimates at each station, which propagate into different errors along different line of sights as it is multiplied by the mapping function.

Because SFPR calibrates the high frequency target data using observations along the same line of sight, at a lower frequency, the residuals from the “static component” are naturally zeroed. When SFPR is used in frequency-switching mode (as for example with the VLBA) residual terms arising from “dynamic” random fluctuations in the time span between consecutive same-frequency scans are expected to remain in the high frequency target dataset. However, when simultaneous frequency-band observations are carried out, it eliminates the need for frequency switching and the “dynamic component” is also perfectly compensated for. Arrays like the KVN, and telescopes like Yebes and Haystack allow simultaneous multi-frequency observations, in the high frequency regime, and therefore would result in an exact adaptive tropospheric correction. Figure 3 shows a comparison of tropospheric compensation achieved with different astrometric techniques, for the “dynamic” and “static” contributions.

4. Conclusions

The phenomena of “core-shifts” in radio sources should be accounted for to achieve the VLBI2010 goals. We have presented an astrometric method, SFPR, which allows high precision measurements of “core-shifts” up to highest frequencies, beyond the current threshold for any other technique. The “core-shifts” measurements at high frequencies are expected to be free of “instrumental” effects, and hence could serve to disentangle the nature of the “core-shifts” at the frequencies of interest for the VLBI2010 program.

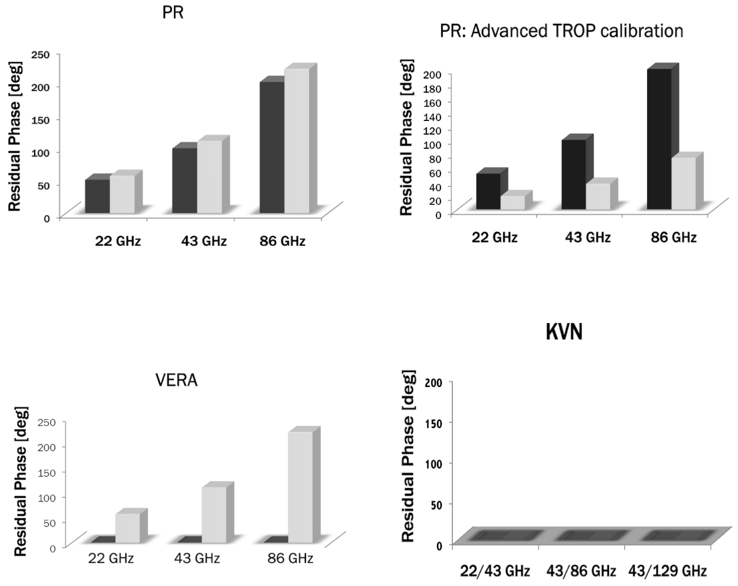

Figure 3. Residual tropospheric errors arising from the *dynamic* (dark) and *static* (light) components, vs. frequency, using **a)** conventional phase referencing techniques: using two sources 2^o away and telescope switching 1 minute (PR), plus geodetic setup to estimate tropospheric zenith delay (PR:Advanced), using simultaneous observations of the two sources (VERA); **b)** using SFPR technique, with two frequencies/sources (KVN).

Moreover, the SFPR method enables astrometric studies at the highest frequencies, with a very high precision resulting from the superior tropospheric compensation.

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