Measurement of core-shifts with astrometric multi-frequency calibration

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Abstract

VLBI is unique, among the space geodetic techniques, in its contribution to defining and maintaining the International Celestial Reference Frame, providing precise measurements of coordinates of extragalactic radiosources. The quest for increasing accuracy of VLBI geodetic products has lead to a deeper revision of all aspects that might introduce errors in the analysis. The departure of the observed sources from perfect, stable, compact and achromatic celestial targets falls within this category. This paper is concerned with the impact of unaccounted frequency-dependent position shifts of source cores in the analysis of dual-band S/X VLBI geodesy observations, and proposes a new method to measure them. The multi-frequency phase transfer technique developed and demonstrated by Middelberg et al. (2005) increases the high frequency coherence times of VLBI observations, using the observations at a lower frequency. Our proposed Source/frequency phase referencing method endows it with astrometric applications by adding a strategy to estimate the ionospheric contributions. Here we report on the first successful application to measure the core shift of the quasar 1038+528 A at S and X-bands, and validate the results by comparison with those from standard phase referencing techniques. In this particular case, and in general in the cm-wavelength regime, both methods are equivalent. Moreover the proposed method opens a new horizon with targets and fields suitable for high precision astrometric studies with VLBI, especially at high frequencies where severe limitations imposed by the rapid fluctuations in the troposphere prevent the use of standard phase referencing techniques.

1. Introduction

Geodetic VLBI observations with a network of antennas at the Earth are affected by the propagation medium, mainly the ionosphere and the troposphere. It is a basic practice in geodesy to calibrate the ionospheric contribution with simultaneous observations at S/X-bands (2.2GHz/8.4GHz, respectively). The ionospheric-free delay observables at X-band ($\tau^c_x$) are estimated from a combination of observed delays ($\tau_x, \tau_s$) at both bands:

$$\tau^c_x = \frac{\nu^2_x}{\nu^2_x-\nu^2_s} \cdot \tau_x - \frac{\nu^2_s}{\nu^2_x-\nu^2_s} \cdot \tau_s$$

and used to estimate the geodetic parameters. This approach works under the critical assumption that the brightness distributions for each source are identical and are co-located at both frequencies. In sources for which the VLBI core position is frequency dependent the exact expression must include a 24-hour sinusoidal extra term whose amplitude depends on the magnitude of the shift of the position of the source core (core shift):

$$+\frac{\nu^2_s}{\nu^2_x-\nu^2_s} \cdot \Delta \tau_{sx}^{geo} \sim 0.08 \cdot \Delta \tau_{sx}^{geo}$$
where $\Delta \tau_{sx}^{geo} = \frac{\vec{D} \cdot \vec{\theta}_{sx}}{c}$, and $\vec{\theta}_{sx}$ corresponds to the core shift between S and X-bands.

The non-inclusion of this extra term introduces errors in the estimated ionosphere-free observables, and hence on the astrometric/geodetic products from the analysis. For sources with non-varying (i.e. stable) core shift $\theta_{sx}$, the unaccounted extra term will propagate into an offset from the true X-band position, of magnitude $(\theta_{sx} \ast 0.08)$ in the direction away from the S-band position [8]. Instead, unstable core shifts can propagate also into uncertainties in the estimated Earth orientation parameters (Engelhardt, these proceedings) in the multi-epoch geodetic analysis. Section 2 is concerned with the origin, magnitude and geodetic impact of core shifts; Section 3 discusses the methods to measure them and Section 4 presents the results of our proposed method.

2. Core shifts do exist

Changes in the observed core positions at different frequencies have been measured in several sources, for example, 1038+528 A [4],[9], 4C39.25 [1], 3C395 [2] and 1823+568 [7]. We propose to classify the core shifts in two groups depending on their origin:

- “Astronomical core shifts” result from opacity effects in the jet. The unresolved “core” of a compact extragalactic radio source is believed to mark the location where the optical depth to synchrotron self absorption $\sim 1$. This position changes with observing frequency as $R_{core} \propto \nu^{-1/k_r}$, where $k_r$ depends on physical conditions in the jet. Core position shifts between S and X-bands of up to 1.5 milli-arcsecond (mas) are predicted in [3].

- “Instrumental core shifts” result from convolving the source structure with different resolutions at different frequencies, causing core shifts of up to half the beam size at the lower frequency.

While the existence of source “core shifts” cannot be predicted, there are some clues which alert one to them. Larger “astronomical core shifts” are expected for flat spectrum sources, where the power index $k_r \sim 1$; “instrumental core shifts” can be expected if the source structure at the higher frequency falls within a small fraction of the beam size at the lower frequency. Regardless of its nature, both core shifts have an identical effect on the analysis of S/X geodesy data. Table 1 lists the propagation of plausible unaccounted stable core shifts into the analysis products.

| Observing frequencies | “Astronomical” core shift | “Instrumental” core shift | Source position error |
|-----------------------|---------------------------|---------------------------|-----------------------|
| 2.2/8.4 GHz            | 0 – 1 mas                 | 0 – 2 mas                 | 0 – 200 µas           |
| 8.4/30 GHz             | 0 – 0.25 mas              | 0 – 0.5 mas               | 0 – 50 µas            |

Table 1: Propagation of unaccounted non-varying core shifts into an offset from the true X and K-band position in the geodetic analysis of 2.2/8.4 GHz (S/X) and 8.4/30 GHz (X/K) observations, respectively.
Figure 1. Hybrid map of 1038+528 A at S-band (left), and at X-band (right). The S-band beam superimposed on the X-band map illustrates the case of structure blending effects from insufficient resolution at lower frequencies, and therefore “instrumental” core shifts.

3. Ways to measure frequency-dependent core shifts

Using closure phase relations in the image processing of VLBI data results in lack of absolute positional information in the hybrid maps. A rigorous alignment of maps at different frequencies, to measure frequency-dependent shifts of the core position, requires absolute astrometry observations, or standard phase-referencing to a nearby (achromatic) radio source. If astrometric observations are not feasible, a simpler but more imprecise procedure for extended sources is to use an optically thin component to align maps at different frequencies, and close epochs, and then estimate the change in the position of the core.

Recently, Middelberg et al. [5, 6] proposed a new astrometric method that uses fast frequency switching observations of the target source and relies on the transfer of calibration from the lower to the higher frequency, after scaling by the frequency ratio. Their implementation proved to be a successful strategy to calibrate the rapid fluctuations of the troposphere, and hence extended the coherence time, in VLBA observations at 86 GHz, using interleaved scans at 15 GHz. This allowed the detection of a very weak, 100 mJy source. It also served to unveil the non-integer frequency ratio problem in the application of this method. On the other hand, the unaccounted dispersive ionospheric contamination, which was non-negligible even at these high frequencies, prevented them from making a proper astrometric measurement of the core shift.

We present an extension of this method, a so-called “SOURCE/FREQUENCY PHASE REFERENCING” which complements the fast frequency switching observing strategy with source switching, in order to calibrate the remaining dispersive contaminating contributions to the observables. Section 4 describes the first successful astrometric measurement of a core shift with this method, and Appendix A contains a brief discussion of the basics of the method.
4. Source/frequency phase-referencing

Conventional VLBI at high frequencies is severely constrained by the short coherence times imposed by the rapid fluctuations in the troposphere. The non-dispersive nature of the tropospheric propagation 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 (i.e., coherence time) at the lower frequency. This is the basis of the multi-frequency phase transfer technique developed and demonstrated by Middelberg et al. [5, 6]. Our SOURCE/FREQUENCY PHASE REFERENCING method adds a source switching observing strategy, in addition to the fast frequency switching, to calibrate the dispersive contributions in the phase transfer strategy. The nodding between sources has to match the temporal and spatial structures of ionospheric propagation, and other non-dispersive terms, such as instrumental based contributions. A complete description of the method is given in Appendix A.

We have successfully applied this method to the astrometric analysis of dual-band S/X VLBA observations of the pair of quasars 1038+528 A and B, 33″ apart, and measured the core shift in the quasar 1038+528 A. The calibration transfer between frequencies involves multiplying the phases by the frequency ratio. The calibration transfer between sources is done as in standard phase referencing. The result is a SOURCE/FREQUENCY PHASE REFERENCED map, shown in figure 2, whose offset from the center is a direct measure of the combined core shifts in the two sources between the two frequencies. The interpretation in terms of individual contributions from each source, assuming that shifts in the core position in each source would occur along the jet axis directions, is simplified by the quasi-orthogonal structures in this pair. The close alignment of the core shift offset with the A quasar source axis suggests a dominant contribution arising from this quasar; moreover, the quantitative agreement between the magnitude of the offset and the separation between the core and second component in the map of quasar A at X-band suggests the “instrumental” dominant nature of the offset. The results from a previous standard phase referencing analysis [9] are in complete agreement with those presented here, validating this new approach.

5. Conclusions

Unaccounted core shifts in the analysis of dual frequency VLBI geodesy observations propagate into offsets from the true X-band positions for the ICRF. We estimate deviations up to 200 μas and 50 μas, respectively, for S/X and X/K observations, assuming temporally stable core shifts. Moreover, unstable core shifts can also corrupt the estimated Earth orientation parameters. We have successfully applied the SOURCE/FREQUENCY PHASE REFERENCING method to the analysis of dual band S/X VLBA observations of the pair of quasars 1038+528 A and B, and measured a core shift in quasar 1038+528 A of ca. 800 μas. Our result is equivalent to, within the errors, to those obtained using standard phase referencing techniques [9]. As far as we know this is the first case of successful astrometric application of this multi-frequency phase transfer method. In this case the simultaneous observations of both frequencies and sources allowed solutions despite the non-integer ratio of the observed frequencies. While this new strategy does not present any advantage with respect to traditional techniques in the cm-wavelength regime, it does hold a big potential at high frequencies, which are out of the range of conventional phase-referencing. In particular, we foresee a big impact when applied to observations of molecular line emission, where it
Figure 2. Left: SOURCE/FREQUENCY PHASE REFERENCED map of 1038+528 B from S/X VLBA observations; the \( \sim 800\mu\text{as} \) offset in NE direction is an estimate of the combined core shift of 1038+528 A and B quasars between S and X bands. Right: Same map, with the hybrid map of 1038+528 A quasar superimposed, to show the agreement between the offset and the separation between the 2 components in the hybrid map of A quasar. This is an argument in favor of “instrumental core shift”.

may provide bona fide astrometric alignment of emission arising from different transitions and help to elucidate the controversy between the proposed pumping mechanism for masers in evolved stars.

Appendix A. The basics of the new method

This section outlines the basics of this astrometric method SOURCE/FREQUENCY PHASE REFERENCING aimed to measure core shifts in radio sources. Its application involves observations of the target and a nearby source (in the formulae, A and B) at the two frequencies of interest (here \( x \) and \( s \)). At the post-processing, the amplitude calibration is done using traditional techniques, for all observations; a pure self-calibration analysis is used to solve for the phase, delay and rate of each low frequency (\( s \)) target source (A) observations. Following the standard nomenclature, the phase values \( \phi_A^s \) are shown as a compound of geometric, tropospheric, ionospheric and instrumental terms - assuming that structural contributions \( \phi_{A,\text{str}}^s \) have been computed using the hybrid maps, and removed:

\[
\phi_A^s = \phi_{A,\text{geo}}^s + \phi_{A,\text{tro}}^s + \phi_{A,\text{ion}}^s + \phi_{A,\text{inst}}^s + 2\pi n_A^s , \quad \text{with } n_A^s \text{ integer}
\]

These values are scaled by the frequency ratio, \( R \), and used to calibrate the high frequency observations. The resultant high frequency referenced phases to the low frequency are:

\[
\phi_A^s - R\phi_A^x = \phi_{A,\text{str}}^s + (\phi_{A,\text{geo}}^s - R\phi_{A,\text{geo}}^x) + (\phi_{A,\text{tro}}^s - R\phi_{A,\text{tro}}^x) + (\phi_{A,\text{ion}}^s - R\phi_{A,\text{ion}}^x) + (\phi_{A,\text{inst}}^s - R\phi_{A,\text{inst}}^x) + 2\pi(n_A^s - Rn_A^x) \tag{1}
\]

This calibration strategy results in perfect cancellation of non-dispersive tropospheric terms:

\( (\phi_{A,\text{tro}}^s - R\phi_{A,\text{tro}}^x) = 0 \), but not for the dispersive ionosphere:

\( (\phi_{A,\text{ion}}^s - R\phi_{A,\text{ion}}^x) = (R - \frac{1}{R})\phi_{A,\text{ion}}^x \)
Taking this into account in Equation (1) above results in:

\[
\phi_A^x - R \phi_A^s = \phi_{A,\text{str}}^x + 2\pi \frac{\bar{D}}{c} (\bar{\theta}_{A,x} - \bar{\theta}_{A,sx}) + (R - \frac{1}{R}) (\phi_{A,\text{ion}}^x - R \phi_{A,\text{inst}}^x) + 2\pi (n_A^x - R n_A^s)
\]  

(2)

where \(2\pi \frac{\bar{D}}{c} (\bar{\theta}_{A,x} - \bar{\theta}_{A,sx}) = (\phi_{A,\text{geo}}^x - R \phi_{A,\text{geo}}^s)\), and \(\bar{\theta}_{A,sx}\) is the core shift in A between \(s\) and \(x\).

Similarly, the analysis of the observations of a nearby calibrator, \(B\), after removing structural terms, \(\phi_{B,\text{str}}^x\) and \(\phi_{B,\text{str}}^s\), at both frequencies, results in:

\[
\phi_B^x - R \phi_B^s = 2\pi \frac{\bar{D}}{c} (\bar{\theta}_{B,x} - \bar{\theta}_{B,sx}) + (R - \frac{1}{R}) (\phi_{B,\text{ion}}^x - R \phi_{B,\text{inst}}^x) + 2\pi (n_B^x - R n_B^s)
\]  

(3)

which are transferred for further calibration of A source observations. The resultant source/frequency referenced phases, combining (2) and (3), are:

\[
(\phi_A^x - R \phi_A^s) - (\phi_B^x - R \phi_B^s) = \phi_{A,\text{str}}^x + 2\pi \frac{\bar{D}}{c} (\bar{\theta}_{A,x} - \bar{\theta}_{B,sx}) + (R - \frac{1}{R}) (\phi_{A,\text{ion}}^x - R \phi_{A,\text{inst}}^x) + (\phi_{A,\text{inst}}^x - R \phi_{A,\text{inst}}^s) - (\phi_{B,\text{inst}}^x - R \phi_{B,\text{inst}}^s) + 2\pi [(n_A^x - R n_A^s) - (n_B^x - R n_B^s)]
\]

A careful planning of the observations, namely switching between sufficiently nearby sources with a duty cycle which matches the ionospheric/instrumental time-scale variations, would result in negligible differential ionospheric error and instrumental corruption, that is:

\[
\begin{align*}
(R - \frac{1}{R}) (\phi_{A,\text{ion}}^x - R \phi_{A,\text{ion}}^s) & \sim 0 \\
(\phi_{A,\text{inst}}^x - R \phi_{A,\text{inst}}^s) - (\phi_{B,\text{inst}}^x - R \phi_{B,\text{inst}}^s) & \sim 0
\end{align*}
\]

which results in an expression for the source/frequency referenced phases for the target source free of ionospheric/instrumental corruption:

\[
(\phi_A^x - R \phi_A^s) - (\phi_B^x - R \phi_B^s) = \phi_{A,\text{str}}^x + 2\pi \frac{\bar{D}}{c} (\bar{\theta}_{A,x} - \bar{\theta}_{B,sx}) + 2\pi n'' , \text{ with } n'' \text{ integer if } R \text{ integer (or } n_A^s = n_B^s)
\]

And finally, the calibrated complex visibilities from the target observations are inverted to yield a synthesis image of A at x-band, where the offset from the center is an estimate of the combined core shifts in A and B between \(s\) and \(x\)-bands.

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