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MultiView High Precision VLBI Astrometry at Low Frequencies

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Abstract. Observations at low frequencies ($< 8GHz$) are dominated by distinct direction dependent ionospheric propagation errors, which place a very tight limit on the angular separation of a suitable phase referencing calibrator and astrometry. To increase the capability for high precision astrometric measurements an effective calibration strategy of the systematic ionospheric propagation effects that is widely applicable is required. The MultiView technique holds the key to the compensation of atmospheric spatial-structure errors, by using observations of multiple calibrators and two dimensional interpolation. In this paper we present the first demonstration of the power of MultiView using three calibrators, several degrees from the target, along with a comparative study of the astrometric accuracy between MultiView and phase-referencing techniques. MultiView calibration provides an order of magnitude improvement in astrometry with respect to conventional phase referencing, achieving $\sim$ 100micro-arcseconds astrometry errors in a single epoch of observations, effectively reaching the thermal noise limit.

Keywords. astrometry - techniques: high angular resolution - techniques: interferometric

1. Introduction

Very Long Baseline Interferometry observations hold the potential to achieve the highest astrometric accuracy in astronomy. The development of advanced phase referencing (PR) techniques to compensate for the tropospheric propagation errors have led to routinely achieving micro-arcsecond (μas) astrometry at frequencies between $\sim$ 10 and a few tens of GHz using alternating observations of the target and a nearby calibrator (Reid & Brunthaler 2004; Honma *et al.* 2008). More recently, the development of phase calibration techniques using (nearly) simultaneous observations at multiple mm-wavelengths, that is Source Frequency Phase Referencing (SFPR) (Rioja & Dodson 2011) and Multi Frequency Phase Referencing (MFPR) (Dodson *et al.* 2017), have extended the capability to measure μas astrometry up to mm-wavelengths. This capability has resulted in a wide scientific applicability (Reid & Honma 2014, and references therein). Nevertheless the application of these advanced PR techniques to relatively low frequencies $\leqslant$ 8 GHz are hindered by the ionospheric propagation effects, increasingly dominant at lower frequencies. Therefore, a new strategy is required to overcome the limitations imposed by the ionospheric propagation medium. In this paper we present results from the MultiView (MV) technique which, by deriving 2-D phase screens from observations of three or more calibrators, achieves a superior mitigation of atmospheric errors that results in increased precision astrometry, along with wide applicability. For a complete review of MV and application to maser astrometry see Rioja *et al.* (2017) and Orosz *et al.* (2017).

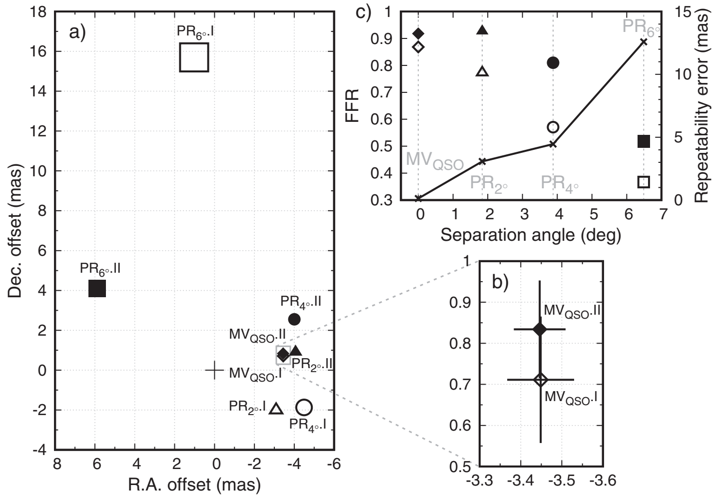

Figure 1. Sky distribution of the sources observed with the VLBA at 1.6 GHz. Dashed lines and arrows mark the source switching order during the observations with 5-min duty cycles. Star and solid symbols mark the simultaneously observed OH–C4 pair, with the VLBA antennas pointed halfway between the two. The two concentric circles represent the half-power beamwidth and full beamwidth of the antennas. Both OH and C4 are targets in the astrometric analyses, and C2, C1 and C3 are the calibrators $\sim 2^o, 4^o$ and 6^o away, respectively.

2. Observations

We conducted two epochs of observations with the Very Long Baseline Array (VLBA) separated by one month, on 2015 June 8 and July 7 at 1.6 GHz (obs. ID: BO047A7, BO047A4). Both epochs used identical setups with a duration of ∼4 hours.

The observations consisted of alternated scans switching between the sources shown in Fig. 1 with a duty cycle of ∼5 minutes. The two sources in the centre of the distribution, the OH maser and the quasar C4, were observed simultaneously since they lie within the primary beam of the antennas. They are the targets of the analyses presented in this paper, allowing the MultiView calibration to be tested for both a maser line and quasar continuum observations simultaneously. The other three sources act as calibrators.

3. Basis of Astrometric Technique: MultiView

The MV calibration strategy corrects for the direction dependent nature of the ionospheric phase errors by using simultaneous or near-simultaneous observations of multiple calibrators around the target. Then we use a two dimensional (2-D) interpolation of the antenna phases, estimated along the directions of all calibrators, to provide corrections along the line of sight of the target observations. This is realized by a weighted average of the complex antenna gains, representing the relative source distribution in the sky, as shown in Fig. 1 for the case of interest to this paper. This is equivalent to the treatment of the propagation medium as a wedge-like spatial structure, up to several degrees in size, above each antenna (Fomalont & Kopeikin 2002; Rioja *et al.* 2002). The temporal structure of the propagation medium effects is best calibrated using simultaneous observations of the calibrators and the target sources in MV observations. However when this observing configuration is not possible one can use alternating observations of the sources, as long as the duty cycle is less than the atmospheric coherence time. Our implementation of the MV direction dependent calibration strategy is more complicated

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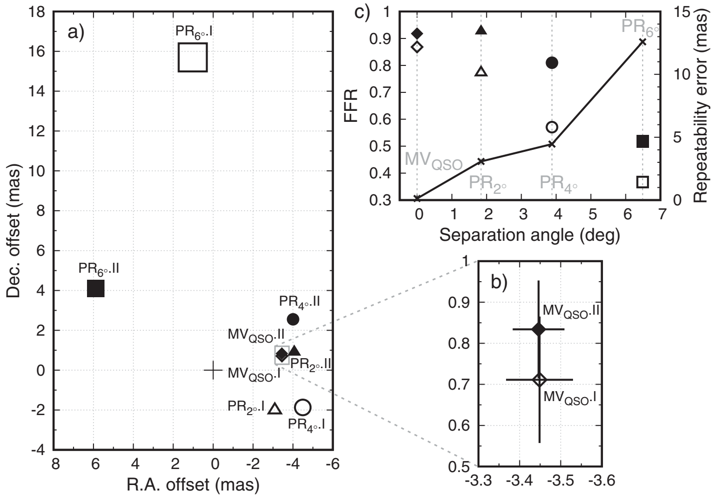

Figure 2. *a)* Astrometric offsets in the angular separations measured with MV (with three calibrators), and with PR_{2^o}, PR_{4^o} and PR_{6^o} analyses (with C2, C1, and C3 as calibrator, respectively), from the observations of quasars at the two epochs (I and II). The size of the plotted symbol corresponds to the estimated thermal noise error in each case. The labels describe the analysis id. and epoch of observations. *b)* Zoom for MV astrometric solutions. The error bars are the thermal noise errors. Both epochs agree within the error bars. *c)* Solid line shows the corresponding repeatability astrometric errors versus the angular separation between target and calibrator for PR analysis, and for an effective 0^o separation for MV. Filled and empty symbols show the Flux Fractional Recovery (FFR) quantity versus angular separation for MV (diamond), PR_{2^o} (triangle), PR_{4^o} (circle), and PR_{6^o} (square) analyses, for epochs I (empty) and II (filled).

than a basic bilinear interpolation. It includes a correction for untracked 2π-ambiguities inherent in the measured calibrator phases, which, if present, would lead to errors in the interpolated phases. We have carried out a comparative study between MV and PR astrometric analysis, the latter using one calibrator at a time. We have used the repeatability of the measured positions between the two epochs of observations, which provide independent measurements of the relative source position, as an empirical estimate of the precision of the calibration method. Note that while there is a limited sample of two epochs the different analyses are carried out on the same observations, enabling a direct comparison of the compensation efficiency of the systematic errors under the same weather conditions.

4. Results and Discussion

Fig. 2a shows the astrometric measurements of the target quasar C4 using PR (analysis id. PR_{2^o}, PR_{4^o}, PR_{6^o}) and MV (analysis id.: MV_{QSO}) at the two epochs of observations. Fig. 2b shows an expansion of the area around the MV measurements at the two epochs. The astrometric uncertainties in the plot are 1-σ thermal noise error bars. For stationary sources, as it is the case for quasars, no or negligible position changes are expected between the two epochs. Therefore one can estimate the astrometric error (σ_{rep}) using the repeatability between the two epochs. It is immediately obvious that σ_{rep} are much larger for PR, compared to those for MV. Also, that σ_{rep} are larger than the thermal noise errors for PR; instead they are within the 1σ thermal noise error bars for MV. Fig. 2c displays σ_{rep} as a function of source pair angular separations, for PR analysis. This linear trend is as expected from PR analysis, as closer angular separations provide a better

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atmospheric compensation. The MV σ_{rep} values are the smallest, more than one order of magnitude smaller than those for the closest pair with PR, and are equivalent to those from a very close pair of sources (i.e. close to zero angular separation) in PR analysis. Also in this figure are shown the coherence losses (i.e. FFR) in the images undergone in each analysis, for both epochs. It is worth highlighting that MV and PR_{2^o} images are of similar quality and have similar FFR values. This underlines the insensitivity of the PRed images to large systematic errors. Also, underlines the superior quality of the calibration of atmospheric errors using multiple calibrators, compared to that achieved with a single calibrator with the same range of angular separations, and that MV analysis leads to higher precision astrometry. This is in agreement with the findings from our previous simulation studies, where we concluded that using multiple calibrator sources with MV resulted in one order of magnitude improvement compared to PR with a single calibrator (Jimenez-Monferrer *et al.* 2010; Dodson *et al.* 2013).

5. Conclusion

We have presented a demonstration of the capability of the MultiView technique to achieve a superior mitigation of atmospheric errors that results in increased precision astrometry, along with wide applicability by relaxing the constraints on the angular separation up to few degrees, and does not require alignment of sources. The scope of application is for the low frequency regime where the perfomance of PR is degraded due to the spatial structure of the ionospheric dominant errors. We believe that the implementation of MultiView techniques will enhance the performance of VLBI observations, by providing higher precision astrometric measurements of many targets at low frequencies, in particular for methanol and OH maser astrometry.

MultiView will achieve its full potential with the enhanced sensitivity and multibeam capabilities of SKA and the pathfinders, which will enable simultaneous observations of the target and calibrators. Our demonstration indicates that the 10 micro-arcseconds goal of astrometry at $\sim$ 1.6GHz using VLBI with SKA is feasible using the MultiView technique.

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