PROCEEDINGS OF SCIENCE

Enhanced VLBI Astrometric Capabilities for ASKAP and next-generation of "Multi-Beam" Instruments at Low Frequencies

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We revisit the *"Cluster-Cluster"* or multi-view VLBI technique from the perspective of its synergy with the multi-beam features inherent in the Australian Square Kilometer Array Pathfinder (ASKAP) and its potential to improve the outcomes of VLBI observations with ASKAP. The results of our previous *cluster-cluster* observations at 1.6 GHz demonstrated the advantages of this configuration to calibrate the ionospheric distortions responsible for the loss of positional accuracy at low frequencies, using multiple calibrators in a range between 1 to 6 degrees away from the target. Therefore, we conclude that joint observations of ASKAP with other multi-view sites using *cluster-cluster* techniques would improve the outcomes of the high spatial resolution component of ASKAP applied to astrometric projects, achieving higher precision for many more targets, and with lower detection thresholds. We include a list of candidate VLBI sites that already support or can be upgraded to support multi-view VLBI located in Australia and overseas, and which have common visibility with ASKAP. We present results from recent developments to implement "cluster-cluster" observations in VLBI observations with ASKAP, such as the demonstration of "multi-view" capability at Parkes.

ISKAF2010 Science Meeting - ISKAF2010
June 10-14, 2010
Assen, the Netherlands

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1. Phase calibration issues at low frequencies and "Cluster-Cluster" configuration

Conventional Very Long Baseline Interferometry (VLBI) phase-referencing techniques can achieve the highest precision relative astrometric measurements of a target source, using alternating observations of a nearby calibrator source, at frequencies between a few and tens of GHz. At lower frequencies, i.e., below 2 GHz, its application is constrained. The cause of this limitation is the unpredictability of both the temporal variations and the spatial irregularities in the plasma density in the ionosphere, which introduce differential path variations between the observations of the two sources, even for very fast switching times and small source separations. The temporal and spatial differential ionospheric fluctuations degrade the positional accuracy of the technique and, eventually, prevent the phase connection process and the use of conventional phase referencing. These fluctuations are larger at lower frequencies. In general, observations which involve more than one calibrator have demonstrated advantages for astrometric VLBI at low frequencies [3]. The exception is the ideal but unusual configuration when a target and a calibrator lie within the field-of-view (FoV) of the VLBI antennas (an "in-beam" calibrator), and thus can be observed simultaneously [2]. The results obtained with this approach are promising; however its widespread application is still limited by sensitivity. Also, it is extremely unlikely that such calibrators will be directly connected to the ICRF reference frame.

Cluster-Cluster or multi-view VLBI is a technique that replaces single-beam telescopes by sites with multiple-beam capabilities (a "*cluster*") [11]. The *cluster-cluster* concept offers the prospect of correcting for phase perturbations arising from the spatial and temporal structure in the troposphere and ionosphere, since such structure can be modelled using simultaneous observations of multiple reference sources. The improved calibration leads to high quality images and accurate positions of the targets with respect to the calibrators. The feasibility and advantages of this approach have been demonstrated with observations, for example, carried out in November 1999 with 3 interferometers, the VLA, WSRT and MERLIN, at 1.6 GHz, shown in Figure 1 ([5],[6],[7],[4]). Briefly, each interferometer observed four sources simultaneously, selected from the VLBA calibrator list such that one of them, the target, lay in the sky surrounded by the other three sources, the calibrators. The angular separations from the central target source were 1, 3 and 6 degrees. Despite these benefits its use has been limited by the shortage of observing sites, and the complexity in its implementation. We wish to revisit this technique now in the light of the next generation of instruments for low frequency observations that will become operational in the course of the next decade, for which the multi-beam capability is an "in-built" feature, such as ASKAP in the near future, and SKA in the long term.

2. ASKAP in the context of "Cluster-Cluster" VLBI

The Australian SKA Pathfinder (ASKAP) is a next generation mid-to-low-frequency radio interferometer and one of the SKA demonstration telescopes under construction in Western Australia. It comprises 36 12-m multi-beam antennas distributed over 6 km, with most of them lying within a circle 2 km in diameter. It incorporates novel receiver technology consisting of phased-array-feeds

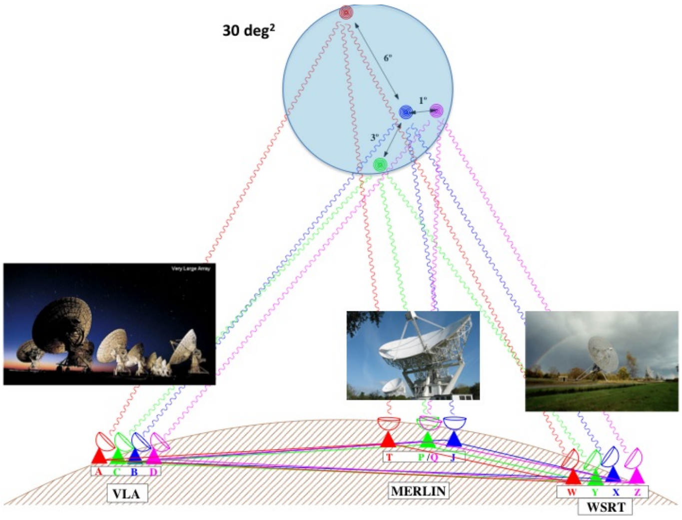

Figure 1: Sketch showing the *cluster-cluster* configuration in our observations using VLA, WSRT and MERLIN at 1.6 GHz. The angular separations from the central target source were 1, 3 and 6 degrees. For comparison, the blue circle corresponds to the ASKAP FoV. Our multi-calibrator analysis produced superior ionospheric compensation than using the single nearest source.

(PAF) and beam forming modules, which will result in an extremely wide FoV of about 30 square degrees in the observing frequency band from 0.7 to 1.8 GHz, using up to 36 beams per antenna.

2.1 ASKAP in VLBI

ASKAP will participate in VLBI observations as a tied-array, and will retain the unique multi-beam feature. The number of planned tied-array beams will be at least equal to that of antenna beams, and fully steerable within the wide antenna FoV. In other words, ASKAP operating in VLBI mode will be equivalent to having about 30 single-beam antennas, each with a collecting area equivalent to a 64-m dish, and independent pointing within the wide ASKAP FoV of about 30 square degrees. Hence, joint VLBI observations with a network of conventional single-beam antennas, with typical FoVs of about 0.5 to 1 degree, would only make use of a small fraction of the capabilities of ASKAP.

2.2 VLBI "Cluster-Cluster" observations with ASKAP

ASKAP meets the criteria to be a *cluster*, with the steerable multiple tied-array beams taking the place of the steerable single-beam antennas. Figure 2 shows candidate VLBI sites that already support or can be upgraded to support multi-view VLBI located in Australia and overseas. Such a network would provide the necessary counterpart to exploit the full capabilities of ASKAP, and improve the outcomes, in the VLBI domain. In particular, for astrometric projects, it would achieve higher precision for many more targets, and with lower detection thresholds.

2.3 First steps towards a "multi-view" network

We have started taking the first steps towards a "multi-view" network for joint VLBI observations with ASKAP. We have demonstrated the "multi-view" capabilities at Parkes, and identified

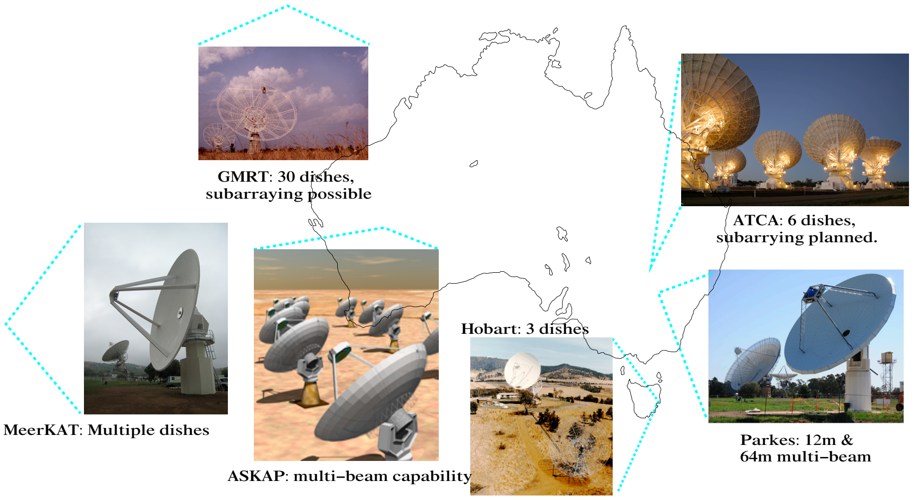

Figure 2: Candidate VLBI sites that already support, or can be upgraded to support multi-view operations and have common visibility with ASKAP.

the phase calibration requirements for ASKAP *cluster-cluster* operations. The outcomes are described in detail in [9], [10] within the framework of the ASKAP VLBI Survey Science Project (SSP). We include a brief description below.

On February 26, 2010, we carried out interferometric observations between the 64-m and 12-m antennas in Parkes, at 1.4 GHz, of a bright calibrator source (0407-658) and a close pair of sources (2323-407 and 2322-411) with a separation of $29.8'$. The pair of sources was selected to allow simultaneous observations with the multi-beam receiver installed at the 64-m, using two beams, Beam 1 and Beam 3. The schedule consisted in alternated scans on the calibrator source with Beam 1 and Beam 3, followed with simultaneous observations of the close pair of sources, with the 64-m Also, both sources were observed simultaneously with the 12-m antenna, pointing towards the midpoint. The recording of the data from the two antennas was done using two LBA DAS units, with the four analog inputs available. Each recorded 2 inputs x 2 16MHz bands (Nyquist sampled) x 2bits for a total of 512Mb/s. The correlation was done using the DiFX software correlator [1] and multiple passes for the period of time when the close pair was observed, selecting a single source coordinates in each pass. The analysis was done using AIPS. We used the observations on 0407-658 for initial instrumental calibration and then performed a full phase referenced analysis of the source pair observations, that is using the self calibration analysis of observations with beam 1 from the 64 m, to calibrate beam 3, in baselines to the 12m antenna. The crossed-beam referenced calibrated visibility of source 2323-407 is shown in Figure 3, with the phase residuals very close to zero degrees. The small -6^o offset could arise from a number places, such as the projected baseline not being correct or the phase rotation not being perfect. With a single scan of a single pair of sources it is not possible to distinguish between the different possible causes. Nevertheless it demonstrates the *cluster-cluster* or multi-view capability at Parkes, using the Parkes multi-beam and the ASKAP test-bed antennae.

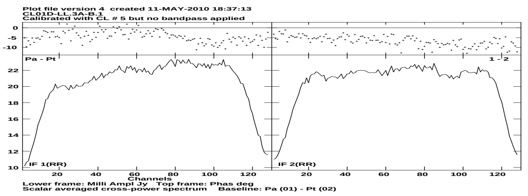

Figure 3: Spectrum of crossed-beam referenced visibility of source 2323-407, using observations with beams 1 and 3 from the multi-beam receiver at Parkes 64-m, in baselines to Parkes 12-m antennae, as displayed by AIPS task POSSM.

The precise calibration of the instrumental phases between individual tied-array beams and transmission systems is a crucial aspect for multi-view operations of ASKAP in VLBI observations. The degree to which we wish to calibrate those delay (and gain) errors is intimately related to the astrometric accuracy that can be achieved (assuming the instrumental contribution is the dominant source of astrometric errors). For example, a residual instrumental error of 2.4 cm (80 picoseconds) between two beams would lead to an astrometric error of $\sim$1 mas with a 5000 km baseline. In the same way, to achieve high precision astrometric measurements, with positional errors of $\sim 50\,\mu$as, the instrumental delay differences between the multiple tied-array beams need to be calibrated within errors of $\sim$0.1 cm (3 picoseconds). Also, for high precision astrometric measurements with positional errors $\sim 50\,\mu$as, the uncertainties in the VLBI station coordinates should be under 1 cm. With that high accuracy, and assuming other contributions to astrometric errors have been calibrated, distances D (kpc) can be measured (e.g. using maser observations and trigonometric parallax) to an accuracy of 5$\times$D%. Precise calibration strategies for ASKAP are still under discussion however some of the elements are clear. Small radiators on the surface of each dish will be used to inject low-level noise vectors into the PAF receiver. The signal paths for this noise injection will be phase stabilised and will remove, to high order, instrumental drifts of phase and amplitude. Array-phasing will be accomplished by processing the normal array visibility data (or some subset thereof) in parallel with the VLBI observation and using one or more strong calibrators within the FoV to measure and correct the complex gain errors of each antenna in near-real-time. The VLBI calibrator sources themselves could be used for this, though the 30 square degree FoV of ASKAP will typically contain several additional potential calibrators. Calibrating the phase, amplitude and delay errors between the tied-array beams pointed in different directions presents a more difficult piece of the problem but can in principle be addressed by steering the individual ASKAP antennas to place a strong calibrator on each tied-array beam in turn, whilst maintaining the direction of the formed beams fixed with respect the the antenna (i.e. holding beam-former weights fixed). The required re-calibration interval and precise strategy will likely be optimised during commissioning tests.

3. Summary and Future Plans

The spatial structure of the dominant ionospheric disturbance in observations at low frequencies imposes a limit to the application of conventional phase calibration techniques, used in the cmwavelength regime for astrometry and detection of weak sources. The use of multiple calibrators and spatial interpolation has several advantages. The *cluster-cluster* or multi-view configuration offers simultaneous observations of multiple sources and its benefits have been demonstrated in the past using observations with interferometers at 1.6 GHz. Similar benefits apply to observations with the new generation of low-frequency instruments, with multi-beam capabilities. We have started taking the first steps towards a multi-view network in Australia for joint VLBI observations with ASKAP, the Australian SKA demonstration telescope. We have identified the requirements for ASKAP multi-view operations, and demonstrated the multi-view capability at Parkes using cross-beam phase referencing analysis of observations between the 12-m test bed antenna and the 64-m multi-beam system. The outcomes have been presented as reports for the ASKAP VLBI Survey Science Project, and briefly summarised here. Next, we plan to continue with the testing of the multi-view capabilities in the other candidate sites as shown in Figure 2. We have also started using comparative simulation studies to characterize the limitations and benefits of *cluster-cluster* techniques at low frequencies. The improved ionospheric calibration will lead towards higher astrometric precision and improved sensitivity for detection of weaker sources in VLBI observations with ASKAP, and other "multi-beam" instruments.

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