URSI GASS 2023, Sapporo, Japan, 19 – 26 August 2023

Extending MWA-scale Ionospheric Calibration for SKA-Low

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Variability of the Earth's ionosphere poses significant challenges for low-frequency radio interferometry. Dispersive ionospheric delays can be highly variable with time, frequency, look direction and antenna location, leading to variable refraction, decoherence and depolarization in any or all of these dimensions. This impacts all areas of low-frequency radio astronomy, however will be a particular challenge for Epoch of Reionisation (EoR) imaging, where foreground galactic and extragalactic emission needs to be accurately suppressed or avoided, and systematics – particularly those varying in frequency and direction – need to be understood with high precision.

Lonsdale [1] considers four observing regimes with distinct ionospheric calibration needs. In the first, both the array and the field of view are small relative to any ionospheric irregularities of concern, while in the second regime the array is larger than the irregularities and antennas may look through different ionospheric patches. In both cases the field of view is small enough that any effect can be considered constant across an image, and can be corrected using antenna-based phase calibration. Due to the dispersive nature of the ionosphere, the phase measurements may need to be made in a number of spectral sub-bands. In regime three the field of view is larger and the delays vary across it, however the array is small enough that for a given direction the phase shifts across the array vary in a linear fashion. This results in apparent angular displacements of radio sources across an image, which can be corrected by re-gridding image pixels to their proper positions. The phase shifts change with both time and frequency, so this requires snapshot imaging in sub-bands. The final calibration regime is the general case of a large array with a large field of view.

SKA-Low falls in the final ionospheric calibration regime, as do a number of other large, low-frequency arrays. A common approach in such situations is to divide the field of view into facets, and apply antenna-based phase calibration to each facet. The phases can be applied directly in facet-based imaging, or used to estimate delays and form 2D or 3D models of the effect across the field of view. This works well for general imaging, however with the limited sensitivity of the individual phase measurements on short time and frequency intervals, it is possible that such an approach will not be adequate for EoR imaging. To extract more information, one can imagine constraining the model using the interferometric measurements directly, with knowledge of the expected response of each antenna to perhaps thousands of radio sources across the field of view. However, this can become an extremely large problem. SKA-Low will generate data at a rate close to a terabyte per second, and EoR datasets will run for hundreds of hours with ionospheric variation on 10 second time scales. But there are other intermediate data products that could be used alongside antenna-based delays to constrain the models. In particular, rather than dividing the sky into facets to follow regime two, can the array be split into clusters and follow regime three?

The Murchison Widefield Array **(**MWA) has the majority of its antennas within a few square kilometers, and when ionospheric conditions are benign a regime three calibration strategy can be employed. The MWA Real-Time System (RTS) was developed with this in mind [2], but rather than measuring pixel offsets in the image domain, phase gradients across the array are measured using the visibility data. While such gradients increase with the observing wavelength, this can be included in the calibration model and all baseline and frequency data can be combined into a single bivariate solution per direction. While this parameterization may probe ionospheric delays across the array with lower spatial resolution than antenna-based phase shifts, the large increase in data points per model parameter means that fainter radio sources can be used as calibrators, increasing the sampling across the field of view. The RTS approach may not seem suitable for geographically large arrays like SKA-Low, however many of the SKA-Low antennas are grouped in the inner kilometer of the array, and the other antennas are grouped in clusters. In this work we show how the RTS approach can be extended to include higher order variations for the inner array while simultaneously constraining additional low-order variations across the remaining antenna clusters.

References

[1] C. J. Lonsdale, "Configuration Considerations for Low Frequency Arrays," *ASP Conference Series*, **345**, 2005.
[2] D. A. Mitchell, et al., "Real-Time Calibration of the Murchison Widefield Array," *IEEE JSTSP*, **2** 5, 2008.