Fundamental Accuracy Limits of Ionospheric Characterization by Radio Interferometers

Stefan J. Wijnholds
Netherlands Institute for Radio Astronomy (ASTRON)
Oude Hoogeveensedijk 4, 7991 PD Dwingeloo, The Netherlands

The ionosphere has a profound effect on the propagation of radio waves. This will blur radio astronomical images, in particular at low radio frequencies (< 300 MHz), if the ionospheric layer above an interferometric array is not properly characterized and its effects compensated during imaging. Radio interferometers are insensitive to common propagation delays but can determine differential delays very accurately using self-calibration. An astronomical imaging interferometer is therefore a very accurate probe for TEC differences in the ionosphere over distances defined by the extent of the array. In the self-calibration process, readily available astronomical sources are used for calibration and define the directions of ionosphere patches. Since we cannot control the strength of these sources while the ionosphere variability dictates the calibration update rate, the SNR and source configuration may limit our accuracy. In this presentation, I provide a quantitative discussion of these limitations and discuss the implications for ionospheric calibration for the Low Frequency Array (LOFAR) and the Low Frequency Aperture Array (LFAA) system for the Square Kilometre Array (SKA).

In my analysis, I describe ionospheric characterization as an estimation problem with a complex gain parameter per calibration source per receiving station of the array. Each source within the station beam defines a particular direction for which a patch is defined. This formulation allows deriving the Cramer-Rao Bound (CRB), which gives the lowest possible variance on the estimated parameters for an unbiased estimator. Since the source configuration and source fluxes depend on the observation, I use known source statistics to generate realistic sky models. In a Monte Carlo simulation, the CRB is calculated for 250 randomly generated sky models for a given station configuration. I use this approach to study the limits of radio interferometric calibration at different frequencies and with different numbers of sources for the LOFAR and for different numbers of stations for the LFAA.

A key result from this analysis is that the accuracy of the differential TEC values for different directions within a station beam mainly depends on the SNR of the calibration sources. A surprising result is that the number of source directions for which gain parameters are estimated hardly affects the calibration accuracy as long as the total number of parameters does not get close to the number of measurements. This is a counter-intuitive result, since the number of degrees of freedom grows with the number of sources while the number of available measurements scales with the square of the number of receiving elements in the array and is therefore independent of the number of sources. In my presentation, I explain this counter-intuitive result and discuss the implications for the ability of the LOFAR and the LFAA to track short-term (timescales of ~10 seconds) ionospheric variability.

Although not designed as ionosphere investigation tool, radio interferometers are capable of making very detailed local maps of the differential variations in the ionospheric TEC-layer above the array with accuracies in the milli-TEC-regime. In contrast, conventional methods, such as GPS measurements, provide global data on the absolute TEC-value of the ionospheric layer with an accuracy that is one to two orders of magnitude lower. Arrays like the LOFAR and the LFAA may thus provide data that complements standard ionospheric data very nicely.