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Ionospheric limitations for SKA and LOFAR

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Low-frequency radio astronomy is a virtually unexplored field. A major problem in achieving high quality observations at low frequencies is the phase distortions caused by the Earth's ionosphere. For the future large, low-frequency arrays classical self-calibration will not work properly. We report here on an ongoing effort to study the calibratability of future radio telescopes. Combining simulations with new calibration techniques we intend to provide detailed information on how well an array can be calibrated in the presence of ionospheric distortions.

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1. Basic ionospheric effects

The ionosphere consists of the charged upper layer of the Earth's atmosphere, from 100 km altitude upwards. The integrated electron density along the line of sight is expressed in TEC (Total Electron Content). The electron density peaks typically between 200 and 400 km altitude. The free electrons rotate the phase of incoming rays of light. This rotation increases linearly with decreasing frequency and increasing TEC. Traveling acoustic waves and turbulence cause the phase rotation to be variable in time and space. The coherency timescale of these processes is of order tens of seconds to a minute, except during ionospheric scintillation, when time coherency is less than seconds.

When observing a source through the ionosphere, an ionospheric phase gradient translates into a change in source position. Observations with VLA towards Virgo A and the VLSS nicely illustrate this effect [1]. Curvature in the ionosphere causes sources to be deformed. In extreme cases a source breaks up into multiple components and eventually coherency is lost.

High-frequency radio telescopes have a small field of view (FOV), and in each integration every station sees a constant phase offset due to the ionosphere. Although the offset can differ between stations, even for very long baseline arrays the self-calibration technique will correct for this. The existing low-frequency arrays have larger FOV for each station, inside which the phase distortions show a gradient or even curvature. For the more compact layouts ($<$20 km baselines) they can still be corrected using the field-based calibration technique developed by Cotton et al. [2], since two separate stations observe the sources through almost identical ionospheric turbulence. Future large arrays observing at low frequencies, such as LOFAR and SKA, will no longer fall into this regime. Two separate stations will 'see' entirely different regions of the ionosphere, which show no spatial coherence.

2. Simulation and calibration of ionospheric effects: LIONS

To assess the full impact of the ionosphere on low frequency radio observations we have started a simulation effort using the MeqTree software developed at ASTRON [3]. The Lofar IONospheric Simulations (LIONS) have as a goal to determine under which conditions and with which techniques we can calibrate the ionospheric phases to reach the thermal noise level. We first simulate observations through an ionosphere and subsequently study the effect of different calibration techniques. These techniques will first be tested on LOFAR, which serves as an SKA pathfinder. Once succesful, it will be a small step to expand the methods for SKA and other arrays.

The simulations require as input an AIPS++ Measurement Set (MS) which includes the basic observational parameters, such as station locations and phase center, but no sources. The MS also specifies the time and frequency domain. In addition we need a Local Sky Model (LSM). In the sky model the source flux, position and geometry can be specified. We currently use sky models generated for SKADS by Wilman & Jarvis [4]. Last but not least we need the ionospheric model, and a set of basis functions to attempt a fit to the simulated phase screen.

2.1 Ionospheric models

We know from WSRT observations that the ionosphere over the Netherlands has a time coherency of order a minute. Within a day the ionospheric weather ranges from relatively smooth and long wavelength waves, which are easy to simulate and calibrate, to scintillation in which coherency is entirely lost, and the array is not calibratable. This implies that for our simulations we need to vary the ionospheric parameters to adequately represent all ionospheric conditions.

Currently we are exploring three main models. The simplest is the inclusion of Travelling Ionospheric Disturbances (TIDs) which are traveling waves, thought to occur in the lower regions of the ionosphere. In the near future we will also include Kolmogorov turbulence and actual observations from GPS stations for our ionospheric input model. Eventually we can even explore a combination of two models.

The TIDs are implemented using two orthogoal sinus functions, and assuming the ionosphere is a thin layer at a fixed altitude. Each line of sight from station to source cuts through this layer at a certain location and the function returns the TEC value at that piercing point and time-step. This is converted into a Z-Jones matrix, which is then fed into MeqTree. We will calibrate this model using VLSS observations.

2.2 Calibration

To properly solve for the ionospheric distortions, the biggest problem is trying to *calibrate* low frequency radio observations, either real or simulated. Since the ionosphere changes rapidly, a correction needs to be applied for each integration. For this we need sources bright enough to be visible within one integration. For these ionospheric calibrators we can measure ionospherice phase distortions. If we assume the ionosphere is a thin layer, the calibrators provide a collection of points projected on the ionosphere plane. We subsequently fit a 2D phase-screen to these points, and use this screen to correct the phases for all sources in the field. Iterating this method several times allows us to use more and more sources for fitting the screen, and thus improve the final results.

For the first iteration there is a delicate balance between the timescale of rapid ionospheric phase rotations and the time needed to reach adequate signal to noise for enough calibrators to achieve a good fit. The optimum solution interval is currently about 1 minute. We are investigating if the use of GPS observations of the TEC can improve the technique. The GPS will provide additional points to which we can fit a phase-screen.

Fitting the phase screen is done using a set of orthogonal basis functions, such as polynomials. The field-based calibration technique uses Zernike polynomials, which tend to go towards infinity when extrapolating. Improvement has been made by using the Karhunen-Loève transformation to derive basis functions and using a least-squares minimization technique combined with a Maximum A Posteriori estimator (see [5]).

3. The future

We know that the ionosphere has coherency in both space and time. Spatial coherency is currently being implemented, but time coherency is difficult to implement in MeqTree because we intrinsically fit the phase-screen independently for each timestep. We are currently investigating methods to include time coherency, which is expected to improve the results significantly. Another major issue we still have to include is the fact that the ionosphere is not a thin layer, but rather a thick 3D structure. In the near future we will assess this by simulating a multi-layer ionosphere. Finally, we have to be aware of specific issues that arise for very large arrays (baselines of order 500 km or more), such as ionospheric refraction and the Earth's curvature. Understanding the effects and calibratability of LOFAR is therefore indispensible for future very large arrays such as SKA.

Acknowledgements

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References

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