The Effects of Variable Ionospheric and Plasmaspheric Faraday Rotation on Low Frequency Radio Arrays

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Abstract

Low frequency arrays such as the Murchison Widefield Array (MWA), which use fixed dipoles operating at meter wavelengths and longer, have very large fields of view and exhibit strong cross-polarization response due to geometric effects, as well as the characteristics of the electronics. The linearly polarized sky at these frequencies is bright and complex in structure, demanding accurate polarimetric calibration for high fidelity imaging. This calibration is made more challenging by high-amplitude time- and direction-dependent ionospheric and plasmaspheric Faraday rotation. In this contribution we describe the relevant ionospheric behaviors, and discuss approaches for dealing with the resulting effects.

1. Introduction

Several new dipole-based low-frequency arrays are under development or are entering service, including the Murchison Widefield Array (MWA), the Low Frequency Array (LOFAR), the Precision Array for Probing the Epoch of Reionization (PAPER) and the Long Wavelength Array (LWA). These arrays are characterized by very wide fields of view, over which the instrumental calibration cannot be assumed to be constant. Furthermore, at the low frequencies of operation, ionospheric phase delays are a strong and rapidly time-varying function of direction on the sky, and location on the ground. Powerful new direction-dependent calibration algorithms are being developed to meet these formidable challenges. In addition, because of a strong and complex linearly polarized brightness distribution across the sky, due to galactic synchrotron emission modulated by interstellar Faraday rotation, a precise instrumental polarimetric calibration is required for high fidelity imaging with such instruments. In this contribution we consider the effects of Faraday rotation due to the plasmasphere and ionosphere, which will vary both with time and with direction on the sky, and discuss the establishment and maintenance over time of the polarimetric calibration, with specific application to the MWA.

2. The Problem

Linearly polarized radiation from the distant universe must pass through heliospheric, magnetospheric, plasmaspheric and ionospheric magnetized plasmas before reaching the ground, and will undergo Faraday rotation as a result. Consideration of the typical physical parameters of these plasmas shows that in terms of generating challenges for instrumental calibration, the plasmasphere and ionosphere are by far the most problematic. This is due to the magnitude of the rotation, and the variability of that rotation both with time and with direction on the sky, with the ionosphere dominating these effects. Unless the Faraday rotation is monitored in space and time, and even if an accurate model of the unrotated polarized sky has been developed, the detailed appearance of that sky will be unknown at any given time and in any given direction. Since an accurate polarimetric calibration depends on comparing measurements with a known sky brightness distribution, this can prevent both the initial generation and subsequent tracking of the direction-dependent instrumental polarization calibration. Therefore, a method or methods must be devised to determine the ionospheric and plasmaspheric Faraday rotation as a function of both time and position, on timescales short compared with that for significant changes in the instrumental response.

3. Solutions

Several different approaches exist for using data from the array itself to deduce the Faraday rotation as a function of direction on the sky. These fall into two classes, namely direct measurements of sources with known intrinsic

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polarizations, and indirect deduction of the total electron content of the ionosphere via refractive effects, combined with an external model of the terrestrial magnetic field. Both these techniques have significant limitations.

Direct methods rely on relatively weak polarized sources and limited SNR, leading to a tradeoff between spatial density of sources and required integration time. Direct measurement of ionospheric Faraday rotation has already been demonstrated by the MWA project using the linearly polarized DMSP15 satellite, and the results will be presented. However, in general the SNR limitations associated with the astronomical polarized source population introduce the risk of serious undersampling in time and/or direction, with attendant large errors in the interpolated FR.

Indirect methods suffer from the fundamental nature of interferometric phase delay measurements, which are sensitive to differential TEC between lines of sight from different points on the ground, but which are insensitive to changes in total TEC affecting both ends of the baseline. This can be addressed in principle by finding a reference point at which TEC has been calibrated, and integrating the TEC gradients derived from refraction measurements to fill in the rest of the field of view. It is unclear how accurately such extrapolation can be done.

It is also possible to use external data to estimate the TEC, and given a model for the magnetic field, the Faraday rotation. The most promising such method is to use dual-frequency GPS measurements to estimate TEC, which unlike array-based methods, can be done with high time resolution. This approach has two important limitations. The first is the TEC measurement accuracy, currently of order 1.5 TEC units, although it may be possible to reduce this to ~0.5 TEC units. This latter figure corresponds to about 10 degrees of Faraday rotation at 150 MHz which while very useful, is still less precise than one might like. The second is sampling of sky directions, which at any given time is limited by the number and positions of visible GPS satellites. This limitation can be overcome by the deployment of multiple widely spaced GPS receivers with independent lines of sight to the satellites, perhaps combined with tomographic 3-D ionospheric modeling, although this is potentially costly, and represents considerable effort.

4. Conclusions

Time and direction dependent ionospheric and plasmaspheric Faraday rotation presents a serious potential risk to developing and maintaining an accurate instrumental polarimetric calibration for the new low-frequency dipole-based arrays. Multiple, somewhat complementary approaches for measuring and monitoring the rotation exist, but none are yet known to be capable of achieving the necessary precision, spatial coverage, and time resolution. Prudence thus dictates that all such methods be investigated, and perhaps used operationally, in parallel.