# Ionospheric Modeling for Current and Future Radio Telescopes

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## Abstract

Correcting for ionospheric distortions is arguably the most difficult calibration challenge facing low-frequency radio telescopes such as LOFAR, the LWA, and the SKA. LOFAR must model the ionosphere to 0.001 TECU on small spatial scales over much of the Europe. Polarization measurements require modeling the electron density and magnetic field to within 0.1 percent of the nominal ionospheric Faraday rotation value. Using data from existing telescopes and GPS networks we are developing algorithms (for example, MIM, the minimum ionosphere model) and packages to model the three dimensional ionosphere for upcoming wide-field, multi-beam instruments.

## 1. Astronomical Overview

Low-frequency radio astronomy is experiencing a revitalization, with forthcoming and prospective instruments expanding the observational capabilities of radio astronomy. The Low Frequency Array (LOFAR) in Europe and the Long Wavelength Array (LWA) in the United States both have operational test stations, with large-scale construction efforts underway. The Square Kilometer Array (SKA), a major international project for radio astronomy, is currently being designed to operate down to at least 100 MHz, and numerous prototype instruments are in development or already operating. These new facilities will operate with simultaneously large fields of view and high resolution. For example, the European Low Frequency Array (E-LOFAR, and extension of LOFAR across Europe) will operate with up to eight digitally controlled beams on the sky, each of which is about 10 degrees across. With planned stations spread across Europe giving baselines longer than 1000 km, E-LOFAR will provide angular resolutions of about one arcsecond or better for the nominal frequency range of 30 to 240 MHz.

## 2. Ionospheric Background

The ionosphere is a major calibration challenges for these instruments. The variable signal delay through the ionosphere causes the positions of astronomical sources to wander, and the intensity of the received emission to fluctuate as the signals are decorrelated by the ionosphere. In order to adequately eliminate these effects, the ionosphere must be calibrated to better than 0.001 TECU for LOFAR. (One TECU is $10^{16}$ electrons per square meter, and corresponds to about 40/3 turns of phase at 100 MHz.) Astronomers have routinely reached this calibration level with existing instruments such as the 74 MHz system at the Very Large Array. Thus, the current challenge is to expand the angular region of calibration to cover a large fraction of the entire sky, and to expand the ground coverage from stations spread over a few kilometers to stations covering a continent. Furthermore, new instruments foresee polarization measurements playing a key role in the science drivers, such as the cosmic magnetism key-science projects for LOFAR and the SKA. At 30 MHz, the Faraday rotation caused by the interaction of the magnetic field and free electrons in the ionosphere is about 1000 times larger than the calibration precision required by LOFAR.

## 3. LIONS

The LOFAR Ionospheric Simulations (LIONS) group is working to overcome this calibration challenge, combining efforts from astronomers, ionospheric scientists, and software developers. LIONS is currently developing and implementing calibration algorithms to test calibration for existing astronomical instruments. In parallel we are developing software to utilize ionospheric information from dense GPS networks in combination with astronomical observations from future instruments such as LOFAR and the SKA. Our current efforts center around variations of a Minimum Ionosphere Model (MIM), which seeks to empirically fit ionospheric models. However, the resulting model fits as well as the raw measured electron contents toward many astronomical sources every few seconds will also be a valuable resource for scientists studying the physics of the ionosphere.