Three dimensional tomography of the ionosphere using a radio telescope interferometer

Christopher Watts[1], Jeffery Karle[1], K.F. Dymond[2], the Long Wavelength Array Team

1. University of New Mexico, Albuquerque, NM; 2. Naval Research Labs, Washington, DC

Abstract: Space weather is now widely appreciated as having a critical influence on modern society, which relies heavily on communication and navigational systems that are strongly affected by the ionosphere. Precise GPS positioning and satellite communication can be disrupted if there are irregularities in the ionosphere. It is therefore becoming increasingly important to understand in detail the characteristics and behavior of the ionosphere on small spatial (<1km) and temporal (<1 min) scales. We present initial studies of a technique to resolve such structures using a radio telescope interferometer, the Very Large Array (VLA). Such interferometers are extremely sensitive to relative density changes, or total electron content (TEC), in the ionosphere. The reconstruction technique makes use of regularization functions, which incorporate the VLA TEC data as well as similar data from GPS receivers.

Frequencies below 300 MHz are among the most poorly explored regions of the electromagnetic spectrum in radio astronomy. This is largely because the detected signals are strongly distorted by Earth's ionosphere. Nonetheless, several long-wavelength radio telescopes are due to come online in the near future, with the goal of astronomical observations at the longest wavelengths possible from the ground.[1, 2] These arrays – the Long Wavelength Array (LWA), LOFAR, Murchison Widefield Array (MWA) - will have interferometric baselines up to several hundred kilometers, and a collecting area that approaches one square kilometer at the lowest frequencies. Because the frequency range of these telescopes is close to the plasma cutoff frequency of the ionosphere, ~10MHz, there are both significant phase delay and refractive effects as an electromagnetic wave travels through the ionosphere. At 50 MHz the phase delay is of order 1000 cycles. The spatial and temporal structure of the ionosphere leads to varying phase delays at different “stations” (equivalent to a single parabolic dish) of the telescope. This severely limits both the resolution and sensitivity of the instrument, as each station of the array sees a different distorted image.

The solution to these problems presents a major opportunity for ionospheric science. Ionospheric scientists have exploited the phase delay effect to measure the electron density of the ionosphere using trans-ionospheric radio sources. GPS is one convenient source, taking advantage of two frequency sources collocated on a single GPS satellite.[3, 4] Radio telescopes also have a history of probing the ionosphere using a complementary technique.[5, 6] By contrast to GPS, two receivers at different locations are used to measure the phase difference at a single frequency from a celestial source. Radio telescopes are still used today in the study of some large-scale ionospheric structures, including gravity waves and TIDs.[7] The new generation of radio telescopes can exploit this effect for detailed ionospheric measurements, gaining a factor of ten increase in sensitivity over GPS operating at frequencies near 1GHz.

Although the VLA is primarily an astronomy instrument, it has successfully been used for ionospheric studies.[8] In the two lowest frequency bands (P band, 300-340MHz; 4 band, 73-74MHz) the telescope is extremely sensitive to ionospheric irregularities. At 74MHz a 1° phase variation between two antennas (easily measureable) corresponds to ~0.003 TECU, or a 100 m structure with 1% deviation from the peak density of 10^{12} m^{-3}. Kassim , *et al*. report measurements where several prominent ionospheric features are identified, including sporadic E layers, the dawn wedge buildup and a traveling ionospheric disturbance (TID), during the course of one 12 hour observation period. [9]

Typically, astronomers "calibrate" the interferometer array to remove such unwanted ionospheric (and internal source) phase contamination effects. [9] Our goal is the inverse: to use this data in an attempt to reconstruct the ionospheric density profile over the VLA from the observed differential phases. Data from the VLA is supplemented, where possible, with independent measurements of the ionospheric density from other instruments: GPS, ionosondes. We are using both archive data from the 74MHz system, as well as data from a dedicated campaign described below. To do the reconstruction we are implementing a technique similar to that of Lee, *et al*., which has proven successful at 3D reconstructions of the ionosphere from GPS data.[10] In addition, we have developed a ray tracing code that is used to further refine the profile by including ray bending and refractive effects. We note that Intema, *et al*. have successfully used VLA data to reconstruct 2D TEC contour maps.[11]

Our primary data source is from a trial experiment undertaken in September, 2007. The goal of the Combined Radio Interferometer-COSMIC Experiment in Tomography (CRICkET) was to explore the possibility of using multiple TEC measurement techniques in combination to reconstruct the ionospheric density profile.[12] The campaign made use of the VLA at 74 MHz, an array of four beacon receivers (similar to GPS receivers) deployed at the ends of each of the VLA arms, nearby permanent GPS receivers, and the COSMIC satellite constellation. We took data in two different modes. During the first epoch the VLA operated in "self-calibration" mode, where the ionosphere was back illuminated by an unresolved, bright radio source. In the second epoch we operated in "field-calibration" mode, where multiple (dimmer) calibration sources were scattered over the viewing field.

Initial analysis has sought simply to demonstrate semi-quantitative agreement among the various data sets. The VLA essentially measures the ionosphere over a cylinder about 35km in diameter. In ionospheres with horizontal gradients linear in TEC, the ionospherically induced phase differential is proportional to the VLA antenna separation. This was true for the TEC gradients on the West and North arms, implying structures larger than the array dimensions. Moreover, the phase progressions on the North and West arms indicate a wave traveling roughly in the North-to-South direction (Figure 1). However, the data on the East arm did not show clean phase progressions and baseline scaling. Taken together, this phase behavior indicates a large-scale wave traveling approximately perpendicular to the East arm. Data from

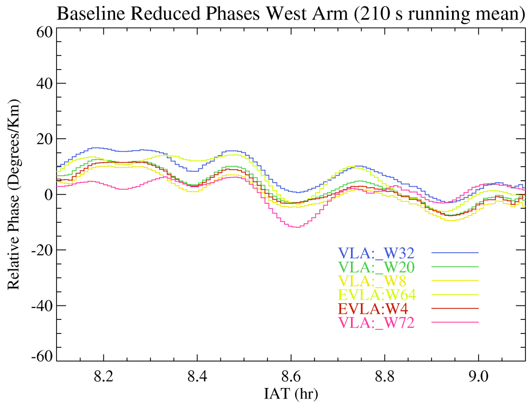

Figure 1: Relative phases of the VLA west arm.

the Tiny Ionospheric Photometer (TIP) on the COSMIC satellites, which measures UV radiance that is proportional to the F region electron density,[13] corroborates this interpretation. The TEC variation shows what appears to be a Gaussian envelope with two sinusoidal modulations. We also make use of GPS occultation, where a low Earth orbiting (LEO) satellite with a GPS receiver – in this case COSMIC – can measure TEC along a horizontal chord passing through the ionosphere.[14] Chords are typically sparse. However, one fairly close to the region of interest also shows a wavelike structure in the vertical ionosphere profile. We interpret these in combination as a mid-scale traveling ionospheric disturbance (MSTID). Data from the network of publically available GPS receivers has neither the spatial nor temporal resolution to indentify this feature. However, we can use the GPS data to provide boundary conditions for measurement of absolute TEC and density.

The next step in the reconstruction of the density profile will involve further development of a pseudo-tomographic technique, and work has only just begun on this. The reconstruction problem is formulated using a series expansion (weighted sum) of basis functions. The inverse problem using the raypath geometry is ill-posed, with the limited number of viewing angles of the measurement geometry being the fundamental difficulty in its solution. Typically, some form of *a priori* information is often necessary to improve the resolution of the reconstructed vertical profile.

Essentially, the algorithm makes use of regularization techniques. The sample volume is discretized, and the density profile is extracted that best matches the raypath data, but subject to a "cost" function. The general framework can be written as

$$J(x) = \| \mathbf{y} - \mathbf{Hx} \|^2 \ \mathbf{w} + \sum \gamma_i \mathbf{C}_i(\mathbf{x}) \tag{1}$$

Here, $\mathbf{y}$ are the measured GPS or VLA TEC values along the raypaths, $\mathbf{x}$ are the electron densities at each voxel and $\mathbf{H}$ is a observation weighting matrix. The first term is the familiar least squares minimization, with a weighting matrix $\mathbf{w}$. The second term is the cost or regularization functions, which controls how well the fit matches *a priori* knowledge of the solution. "Standard" ionospheric models (e.g. the IRI model) or smoothness criteria, or data from independent sources (e.g. ionosondes) can serve as regularization functions.

Our extension to this work will be to use the VLA raypaths in addition to the GPS data. However, the addition is not necessarily straightforward, in that while GPS can measure absolute TEC along the raypaths, the VLA is only capable of measuring *relative* TEC. A critical component of the reconstruction is the incorporation of a true ray tracing algorithm, as opposed to using line-of-sight paths through the ionosphere. In our code the ionosphere is modeled as a cold plasma, and magnetic field effects, which modify the refraction and introduce Faraday rotation, are also included. One can appreciate the additional problems introduced by the very long wavelengths of the LWA from Figure 2. Not only are the signals phase-shifted by the ionosphere, but ray bending effects also become significant. Modeled is a laminar ionosphere with a superimposed TID. At 1 GHz the ray deviation is less than 10 m horizontally from a true ray path at 70° elevation angle. This becomes ~100 m at 300 MHz, which is of order the conjectured ionospheric structure scale size; at 74 MHz (the case depicted) the deviation is more than 1 km, with the pointing direction modified by several arc minutes. The right figure depicts the effect of a "dawn wedge", where the ionospheric density increases with the rising sun, for a collection of sources down to elevations of 30°. The contour plot illustrates the phase change due to the ionosphere at one minute intervals. Overhead the phase change is less than π, and hence can be compensated for. However, at elevations below ~50° refractive effects are severe enough to lead to changes greater than π every 10s, resulting in phase ambiguity and loss of calibration.

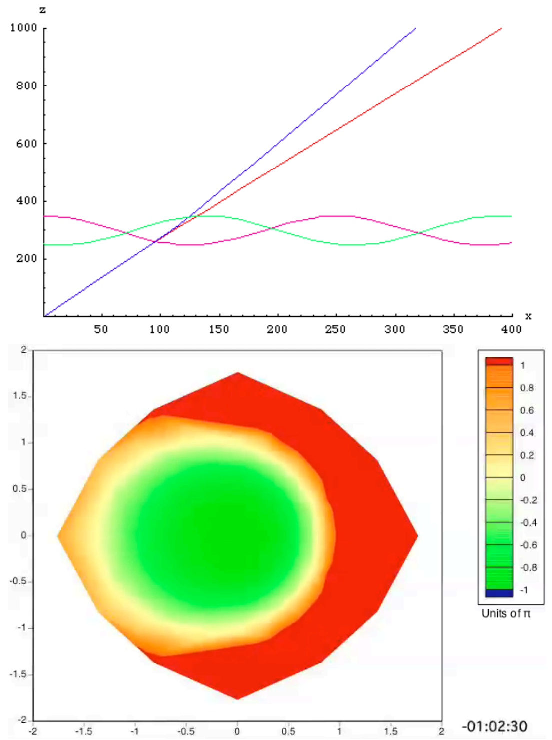

Figure 2: The refractive effects on radio signals as a TID propagates overhead. These can lead to ambiguity in the phase over the telescope array.

Further development of such techniques for radio telescope interferometers will provide a valuable tool for the study of ionospheric physics at the smallest scales.

1. H. R. Butcher, Proc. SPIE - Int. Soc. Opt. Eng., 2004, vol. 5489, 537.
2. N. Kassim, et al., From Clark Lake to the LWA, Bill Erickson's Radio Science (2005), Vol. 345.
3. J. R. Austen, et al., Radio Science 23 (3), 299-307 (1988).
4. J. A. Klobuchar, et al., AGARD Conf. Proc. No. 284 London, UK, 1980, 36.
5. A. Hewish, Royal Society -- Proceedings 124 (1119), 494-514 (1952).
6. R. S. Lawrence, et al., IEEE Proceedings 52 (1), 4-27 (1964).
7. C. Mercier and A. R. Jacobson, Annales Geophysicae 15 (4), 430-442 (1997).
8. A. R. Jacobson and W. C. Erickson, Planetary and Space Science 40 (4), 447-455 (1992).
9. N. E. Kassim, et al., Astrophysical Journal Supplement Series 172, 686 (2007).
10. J. K. Lee, et al., Radio Science 42 (4) (2007).
11. H. T. Intema, et al., Astronomy and Astrophysics 501, 1185-1205 (2009).
12. K. F. Dymond, Radio Science (2008)
13. P. C. Kalmanson, *et al.*, SPIE - Int. Soc. Opt. Eng., 2004, vol. 5660, 259
14. P. A. Bernhardt, *et al.*, Physics of Plasmas **5** (5), 2010-2021 (1998).