An Approach to Ionospheric Calibration

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Abstract. I am a low frequency radio astronomer, not an ionospheric physicist. Therefore, I struggle with the ionosphere and know about it only in the sense of "know thy enemy". Much of what I say in this note is probably naive from the standpoint of ionospheric physics. Nevertheless, I hope that some of my suggestions may prove to be useful.

1. Introduction

Since the early days of radio astronomy there have been many attempts to use ionospheric data to mitigate the effects of ionospheric refraction on radio astronomical observations (Hewish 1951),(Bolton et al 1953). These projects have met with only modest success, largely because the radio astronomical data are highly dependent on the extremely small variations in Total Electron Content that are not measured by standard ionospheric sounders and because mitigation of the effects requires ionospheric data on very small spatial scales that are not practical to measure using conventional sounding techniques. This was shown in a recent attempt to use GPS data for the correction of VLA data (Erickson et al 2001). The most successful correction methods have been developed by Cotton et al (2004) using the radio astronomical data themselves. These corrections have been developed for 74 MHz VLA data but are severely hampered by the low sensitivity of this system. With the sensitivity of the LWA it should be possible to alleviate many of these sensitivity problems but with the higher angular resolution of the LWA the problems will also become much more difficult. In any event, I believe that the primary source of calibration information must come from the radio astronomical data themselves, not from ionospheric sounding systems external to the LWA. To build a fully adequate sounding system for LWA calibration would require an effort comparable or greater than construction of the LWA itself.

2. Philosophy

First, we must recognize that ionospheric compensation is the most serious problem facing the LWA. If successful compensation techniques can be developed, the LWA should be a spectacularly successful instrument. If the compensation is less successful, the LWA will be proportionately less successful. In a sense, we should think of the LWA as an ionospheric measuring device that, if successful, will also be able to carry out good radio astronomical observations. Rather than spending too much effort developing plans for astronomical programs, the main development effort needs to be on ionospheric calibration.

The second bit of philosophy that I wish to expound is that the ionosphere is actually a rather benign plasma most of the time. Ionospheric motions are limited to ≤ 1 km/s and ionospheric dimensions are only hundreds of kilometers. Radio astronomers usually deal with plasmas traveling with speeds $\gg 1000$ km/s and with dimensions of many parsecs. We should not be frightened by the prospect of having to deal with the ionosphere.

Third, the algorithms developed so far deal, primarily, with the ionosphere in a reactive manner. Proactive algorithms may need to be developed. These algorithms would use an ionospheric model and data from an all-sky monitor to track disturbances across the sky and predict the refractive effects in any given observing direction.

Finally, we should accept that there will be times when the ionosphere is so disturbed that no model will be successful and all observations will probably be impossible. This will be particularly true for observations in the lower part of the frequency band whenever amplitude scintillations are occuring. Dynamic scheduling, adapted to ionospheric conditions, will be a necessity.

3. An Ocean Wave Analogy

I love sailing off the south coast of Tasmania in the prevailing westerlies of the "Roaring Forties" where the nearest land upwind is South America. Large swells build up in this band of southern latitudes. I spend a lot of time looking at the swells and the waves on top of them and thinking about their analogies with ionospheric waves. Perhaps I push these analogies too far but so be it, some of the concepts may still be useful.

If one looks at just one point on the ocean's surface by observing the motion of a single cork as it bobs up and down, from this complex motion it would be impossible determine pattern of the various waves traveling in different directions with different amplitudes and speed. Most of the ionospheric correction schemes to date are like this, and the wave patterns causing the motion cannot be discerned. If one spreads a score of corks out over a larger area, 10 or 20 meters across, one could begin to map the pattern. This is analogous to Bill Cotton's far more successful algorithm in which he maps the small region of the sky within the primary beamwidth of the 74 MHz VLA dishes. However, if one observes the ocean surface all the way to the horizon one sees many trains of waves in different directions. These were used by the ancient Polynesian navigators who could sense the existence of an island far beyond the horizon by sensing the wave pattern reflected from it. LWA correction algorithms may need to reach a similar level of sophistication.

I'll make one more analogy to explain what I mean by a proactive algorithm rather than a reactive one. My boat gains speed as it surfs down the back of a wave into the trough, then it gets hit by the next wave. Anticipating this, a small motion of the tiller keeps the boat going straight and fast up and over the face of the next wave. However, my boat is heavy and if, when the wave hits it, one allows it to start turning leeward a large amount of angular momentum about its vertical axis quickly builds up. A large motion of the tiller is then required to stop the rotation; the boat wallows and slows way down. The waves are usually half or more of the height of the mast and they blanket the sails when the boat is in the troughs. As the boat rises over a crest the sails fill and the boat tries to turn windward as it builds up speed and surfs down the wave's back. Again, if this is anticipated only a small tiller motion is required to keep the boat moving straight and fast. It is great fun, I can do it right most of the time but unexpected waves often pop up and surprise me. The skill of an excellent ocean racing helmsman is to do it right all of the time (even at night when one cannot see the waves but only sense them by sound and the feel of the boat). This is proactive steering.

On the other hand, my autopilot is only reactive. It was top of the line when I purchased it a decade ago but it is really DUMB. It cannot see the waves and anticipate them and it never learns that the sails will fill at the crest of a wave. It can only sense direction so it waits until the boat has swung well off course before it begins to make a correction. It steers the boat safely enough but it makes me very uncomfortable as the boat wallows and swerves. This is reactive steering.

Analogously, I believe that we may need to develop ionospheric correction schemes for the LWA that will observe and model the whole visible ionosphere, observe ionospheric waves as they propagate across the sky, and correct for their effects proactively based upon a detailed, dynamic ionospheric model.

4. A Preliminary Proposal

As a first step towards ionospheric corrections for the LWA Bill Cotton's algorithm should be developed as far as possible. If it proves to be inadequate a different type of algorithm may be necessary. Here is a suggestion for one possibility.

Years ago Abe Jacobson and I used the VLA to study ionospheric waves (Jacobson & Erickson 1992a), (Jacobson & Erickson 1992b). We found that a significant fraction of radio source displacements, usually about half of them, could be characterized by a simple thin-screen model involving only single waves. This sort of concept needs to be greatly expanded using a thick screen model of the whole ionosphere. To obtain the necessary data an all-sky monitor would be needed, probably by simultaneously correlating all of the dipoles in the LWA core, although time sharing observations of the whole sky might provide sufficient sensitivity. I would first try modeling the whole ionosphere using an Earth-centered coordinate system. I would use a coordinate system tied to the diurnal motion of the Sun because the ionosphere is, to some extent, stationary in solar-based coordinates while the Earth rotates under it. In some ways the modeling scheme that I propose is similar to that employed in heliosiesmology. In the solar case, the propagation of seismic waves through the interior of the Sun are modeled; in our case the propagation of radio waves through the ionosphere are to be modeled. Spherical harmonics appear to provide the most natural system of orthogonal functions for such a model.

Real-time, world-wide ionospheric models exist. Such a model should be used as a first approximation to obtain the low order components of ionospheric density in angle and radius. Then much higher order components would be required to fit the results of ray tracing through the $\sim$ 4000 km portion of the ionosphere visible from any one point on Earth. Frankly, I don't know just how one would go about this, presumably one would start by fitting Acoustic Gravity Waves to the model because their properties (speeds and altitudes) are reasonably well known. Then one would try various MHD waves so see to what extent their inclusion would lower the residuals of the fit. With a number of waves at different altitudes and amplitudes and with different propagation vectors, a substantial number of parameters would be involved. On the other hand, the LWA core should be able to observe the positions of many thousands of radio sources; the number of data should greatly exceed the number of parameters in any model. It seems to me that the process should be convergent.

Once one has a good model for the ionosphere over the core, it should be possible to predict ionospheric refraction in any direction and even over the outlying LWA stations. For any given observation direction, as seen from the core, the outlying station's ionospheric peirce points are less than about 30° away from the core's peirce point. Presumably, a valid all-sky model for the ionosphere over the core would encompass the peirce points of the outlying stations. This prediction will not be easy; ionospheric waves are highly dispersive and their characteristics rapidly change as they propagate. It is unclear to me for what range of angles a prediction can be made but, with thousands of observable sources, I think that is should be possible to make a valid prediction for the refraction in any given direction.

5. Summary

I'm certain that this proposal is incredibly naive and that its implementation would involve a host of unanticipated problems. However, it seems to me that it is a possible line of attack on the central problem face by the LWA and that it merits at least preliminary consideration. The systems needed for solving the ionospheric refraction problems may have significant impacts upon the design of the LWA so they need to be considered at an early date.

If my proposed modeling scheme were to be successful, I would expect it to produce invaluable data for ionospheric physics. However, to quote Tom Lehrer, "That's not my department".

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