PROBING THE IONOSPHERE WITH THE VERY LARGE ARRAY

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ABSTRACT

A phase stable radio interferometer is a sensitive instrument for measuring path length differences induced by the atmosphere on astronomical signals. At frequencies below $\sim$ 1 GHz, these path length differences are dominated by ionospheric effects, and can be measured with an accuracy better than 0.001 TECU. Data from the Very Large Array taken at 327 and 74 MHz can be used to construct a map of the TEC above the array, relative to a central ray. We show examples of the potential of these measurements.

IONOSPHERIC MODULATION OF EXTRA-TERRESTRIAL RADIO SIGNALS

Passage of an electromagnetic wave through the ionosphere notably modifies the polarization, direction of arrival, and in particular the phase of astronomical radiation for frequencies below $\sim$ 10 GHz. For a single antenna, this phase modulation is unimportant, but for a phase-stable interferometer, at low ($\nu < 1$ GHz) frequencies, the measured phase is dominated by ionospheric effects. Astronomers are interested in the source visibility phase, and have developed powerful algorithms which can separate this from the propagation path phases, permitting them to image the astronomical source as if the atmosphere were not present.

The propagation path phases which are determined by these algorithms are not the total phases, but is rather the *differences* in the phase perturbations between the various antennas (locations) and a reference antenna (generally taken near the center of the array). We can write this difference as: $\delta\phi = 2\pi(\delta L_1 - \delta)/\lambda$, where L_n is the phase-path change in length induced by the ionosphere over antenna n. In terms of the column density, this can be written:

$$\delta\phi = 8500 \frac{\delta N_{TECU}}{\nu_M} \qquad \text{radians,}$$

where δN_{TECU} is the difference in column density through the ionosphere between the two antennas in TEC units ($1\ \mathrm{TECU} = 10^{16} \mathrm{electrons/m^2}$), and ν_M is the observing frequency in MHz. For a frequency of 100 MHz, an interferometer phase perturbation of one electrical degree corresponds to a column density path difference of 2×10^{-4} TECU = 2×10^{12} electrons/m^2! Radio interferometers are routinely capable of measuring phase differences of this size. They thus have the potential of measuring ionospheric column density differentials of a tiny fraction of a TEC unit.

THE VERY LARGE ARRAY AS AN IONOSPHERIC RESEARCH TOOL

The Very Large Array, located in central New Mexico, comprises 27 antennas on three equiangular arms. Two of the arms (SE, SW) are 21 km in length, the third (N) is 18.9 km long. The data calibration process thus provides the propagation path differences beween a reference antenna (generally chosen to be near the middle of the array) and the other 26 antennas, as a function of time. An example of the results of this process are shown in Fig. 1, where we show the ionospherically-induced phases for a number of baselines on the north arm of the VLA. It is immediately clear that the phases (or, path length differences) increase approximately in proportion to baseline length, and hence represent large-scale travelling structures in the ionosphere.

We can conveniently represent the effects of the phase screen through imaging the background source. A linear gradient will simply offset the apparent source position. Higher order terms will cause distortions. An example of the evolution of the offset (linear) terms is shown in Fig. 2, for the powerful radio source Virgo A at 73.8 MHz. These data are from a ten hour observation on 19 January 2001, and show a wide range of interesting phenomena.

There are at least four distinct phenomena clearly represented in Fig 2: (a) Long periods of quiescence, notably between hour angles -1.75 to +1.75; (b) A period of scintillation, centered around HA=-2; (c) A large-scale refractive wedge, starting just before local dawn (HA = 1.5); and (d) large scale travelling waves, beginning near HA = 3, and extending until the end of the observing run. Their wavelengths are about 250 km, and they are travelling with a velocity of at least

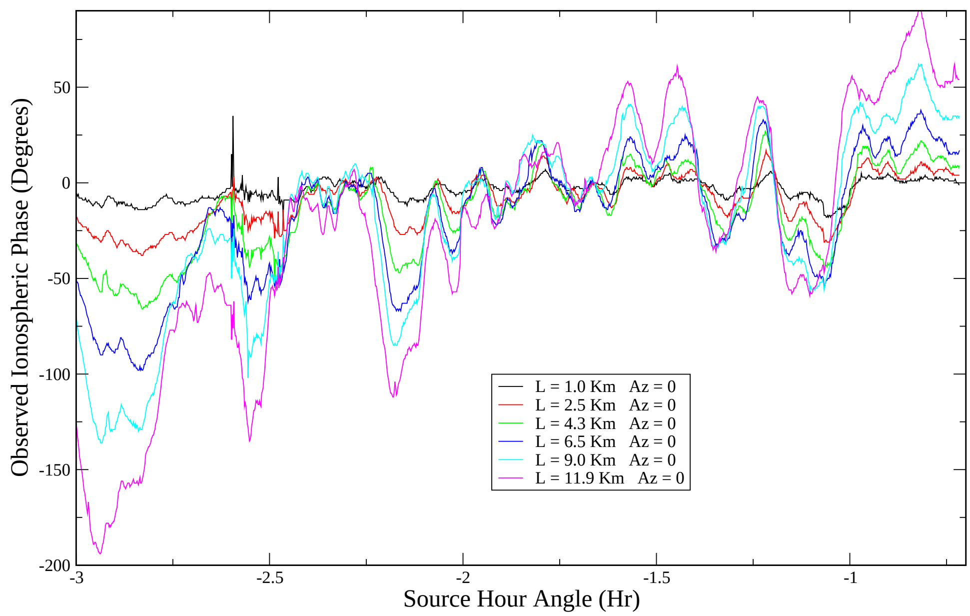

Figure 1: The observed phase at 327 MHz for various locations along the north arm. The amplitude of the large-scale waves grows roughly in proportion to the baseline length. Multiply by 7×10^{-4} to convert to TEC units

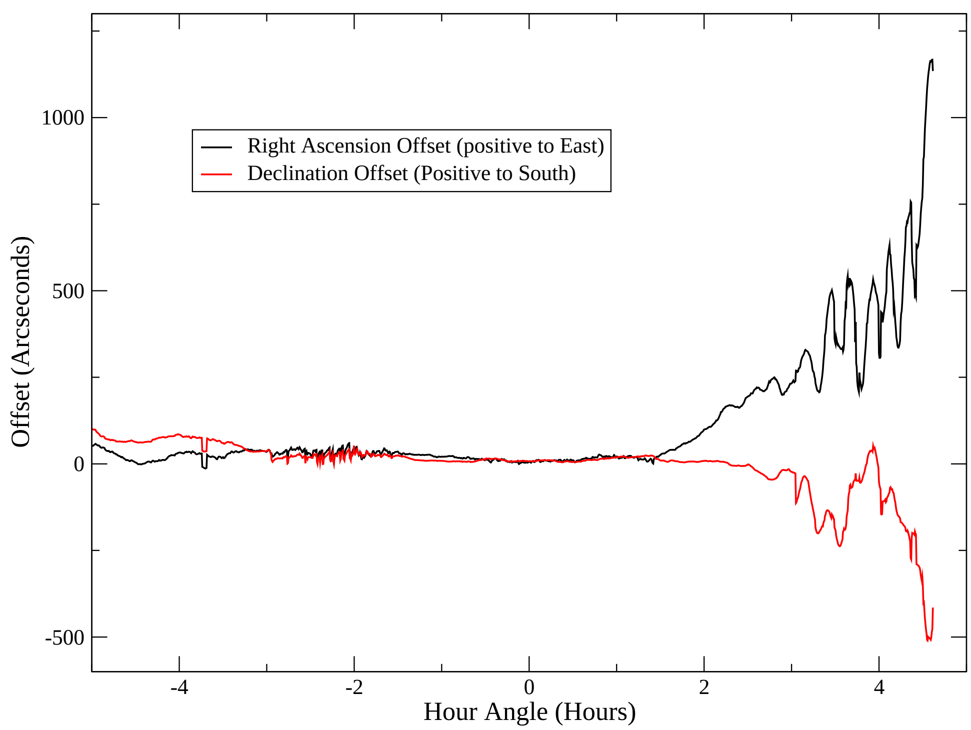

Figure 2: The apparent position offsets (refraction) of the powerful radio source Virgo A, as seen by the VLA at 73.8 MHz

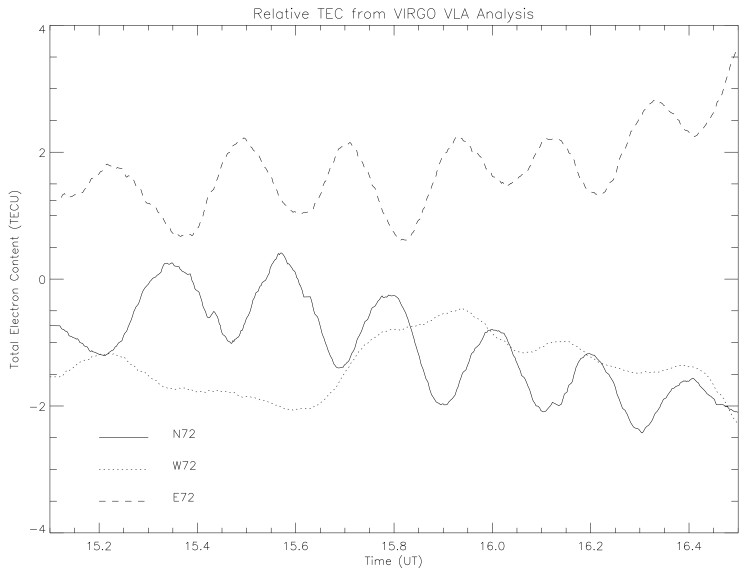

Figure 3: Fast travelling waves seen over the Very Large Array in the morning of Jan 18, 2001. The observed phases have been converted to TECU.

0.5 km/sec. In Fig. 3, we show the data for the three antennas located at the ends of the arms. Plotted is the column path differences in TECUs for an 80-minute period. The amplitude of these waves is largest on the north arm, and smallest (and nearly absent) on the west. The simplest interpretation is that the waves are travelling normal to the SW arm – from NW to SE.

Figure 4 shows how these data can be used to construct a map of the ionospheric wave structure above the array. Each panel shows the column density above the array at a different time.

DIFFERENTIAL (NON-LINEAR) EFFECTS

A phase screen of scale length 500 km subtends an angle of about 1 radian from the ground. The primary field-of-view of the VLA's antennas at 73.8 MHz is about 0.25 radian, so that significant differential imaging effects should be visible for background radio sources located at different parts of the field-of-view. In Fig. 5 we show the differential motions in one axis of the strongest five objects visible within the primary beam. The relative locations of these objects are included in the figure. Their motions relative to the central source Virgo A are poorly correlated, especially during the period of the TIDs. Note, however, that the large-scale refraction is absent, indicating the 'dawn' wedge is of a much larger angular scale than the antenna beam.

IONOSPHERIC TOMOGRAPHY?

The VLA extends over a distance of about 35 km. From the point of view of the ionosphere, the VLA subtends an angle of about 0.1 radian. The VLA's horizontal resolution at the height of the ionosphere is about 50 meters, so the vertical resolution will be ~ 500 meters. As the astronomical sky is filled with objects, there would appear to be the opportunity to utilize the interferometer phase data to make a 3-dimensional tomographic image of the ionosphere, with a potential resolution of 50 x 500 meters, along the azimuths of the three arms.

REFERENCES

[1] Lawrence, R.S., Little, C.G., and Chivers, H.J.A. A Survey of Ionospheric Effects Upon Earth-Space Radio Propagation. Proceedings of the IEEE, **52**, No. 1, 4 – 27, 1964.

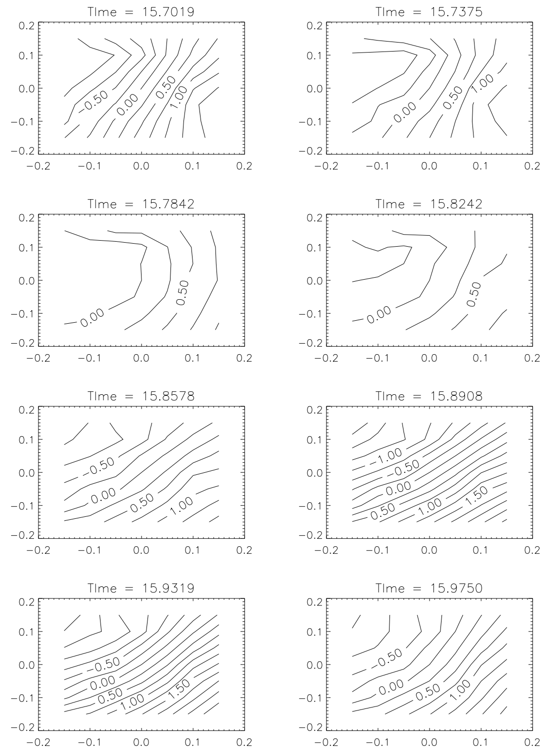

Figure 4: The ionospheric column path above the array on the morning of Jan 19, 2001, when a train of high-speed waves passed overhead.

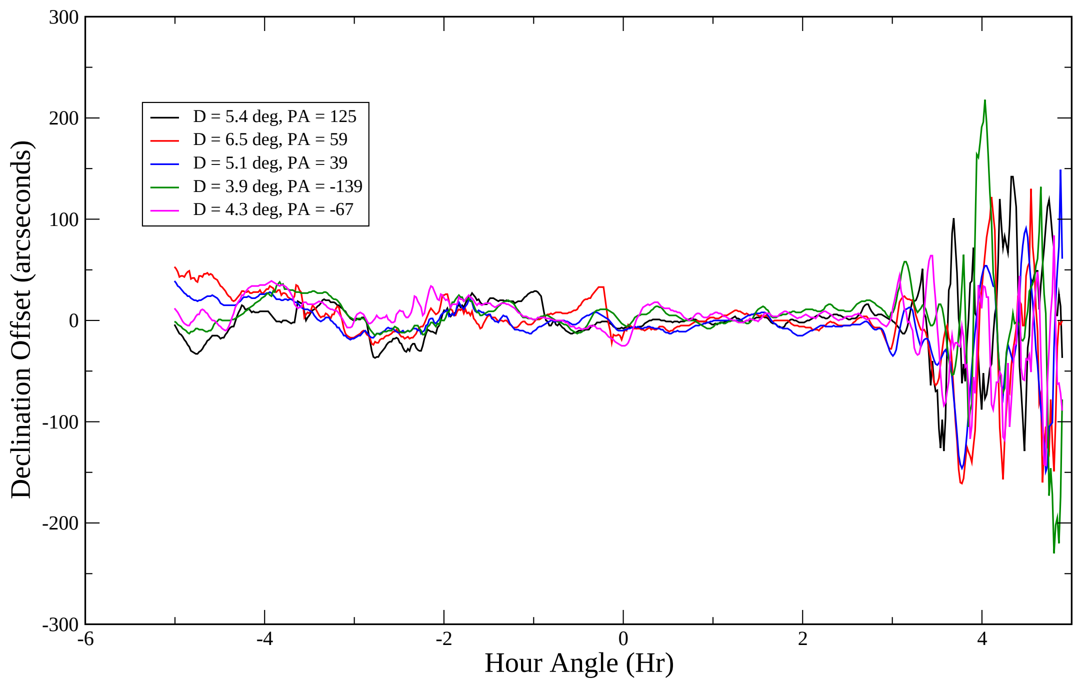

Figure 5: The apparent positions of 5 nearby objects with respect to the reference source Virgo A, as seen by the VLA at 73.8 MHz. Shown are the offsets in declination.