Ionospheric Disturbances Observed with the VLA Low-band Ionosphere and Transient Experiment (VLITE)

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1. Introduction

The Very Large Array (VLA) in western/central New Mexico is the world's preeminent radio interferometer. It is comprised of 27, 25-m dish antennas spanning nearly 40 km and operated by the National Radio Astronomy Observatory (NRAO). It has been upgraded with a new VHF/UHF receiving system by the Naval Research Laboratory (NRL) and NRAO as part of a partnership dating to the 1980s. This partnership has led to decades of cutting-edge astrophysics research at low radio frequencies (<1 GHz), yielding some of the highest quality astronomical images ever achieved within this frequency regime.

Imaging below 1 GHz requires a detailed knowledge of the Earth's ionosphere since even fine-scale (a few kilometers) fluctuations in total electron content (TEC) can cause distortions a these frequencies that preclude high-fidelity imaging. Thus, NRL has pioneered techniques for ionospheric calibration that have in turn spawned a new field of high-precision ionospheric remote sensing. When observing a bright cosmic source below 1 GHz, the VLA can be used to sense and characterize fluctuations in the horizontal TEC gradient to a precision as good as 10^{-4} TECU km^{-1} (1 TECU = 10^{16} e^{-} m^{-2}) on time scales as short as a few seconds (see Helmboldt et al. 2012a,b,c; Helmboldt and Intema 2012).

The success NRL has achieved within the fields of astrophysics and ionospheric physics with a veritable handful of limited, proposal-based observing campaigns has motivated an ambitious new undertaking, the VLA Low-band Ionosphere and Transient Experiment (VLITE). Funded by NRL and executed by a joint NRL/NRAO team, VLITE enables acquisition of the UHF band between 320 and 384 MHz *continuously* from 10 antennas, amounting to ~3,000 hours per year. VLITE has its own dedicated processing systems that include a real-time ionospheric analysis pipeline and an imaging system searching for new transient sources of cosmic low-frequency radio emission.

The nominal lifetime of VLITE is three years, commencing with science operations that started in November 2014. Within this time frame, the VLITE ionospheric data products will be used to provide a full climatological database of the spectrum of ionospheric fluctuations down to spatial and temporal scales of ~1 km and ~4 seconds, respectively. We plan to use these to develop empirical models of fine-scale, mid-latitude fluctuations that may be added to larger-scale ionospheric simulations (e.g., NRL's SAMI2/3 models; Huba et al. 2010) to provide more realistic estimates of noise/clutter levels. These will be valuable for, e.g., OTH geolocation calculations and estimates of the detectability ionospheric responses to ground and atmospheric perturbations. In addition, VLITE will be used to characterize the fine scale ionospheric response to specific events like earthquakes, surface explosions (local to NM), geomagnetic storms and substorms, solar flares, sudden stratospheric warmings, etc.

2. Ionospheric Analysis Pipeline

VLITE data is automatically processed in near real time to characterize ionospheric fluctuations toward the cosmic radio source(s) being observed by the VLA. As mentioned above, an interferometer like the VLA is essentially sensitive to the horizontal gradient in TEC, and thus is especially sensitive to fine-scale fluctuations. The interferometer produces correlations of signals from each unique pair of antennas, or "baselines" averaged over a chosen time interval. For VLITE, this is done with a dedicated software correlator, which nominally generates correlations or, "visibilities" every two seconds within 640 frequency channels, each 100 kHz wide. The visibilities are complex quantities, the phases of which vary in time due to a number of factors such as the structure of the cosmic source(s), telescope pointing errors, instrumental response, and ionospheric variations.

On relatively short time scales (minutes), the dominant cause of phase fluctuations below 1 GHz is the ionosphere. Specifically, the baseline phase at a given time is proportional to the difference in TEC between the two antennas' lines of sight, or δTEC. When observing a bright cosmic source at the low end of the UHF band (<400 MHz), such phase fluctuations within VLA data can be used to measure δTEC to a remarkable precision of as good as 2×10^{-4} TECU (Helmboldt et al. 2012a). These δTEC measurements can then be used to determine the full two-dimensional TEC gradient at each antenna. Due to the inverted "Y" shape of the VLA, Helmboldt et al. (2012a) showed that this is best done with a two-dimensional, second order polynomial fit (i.e., second order Taylor series) that generally captures all or nearly all of the δTEC temporal structure for each baseline. To fully characterize the observe field of fluctuations, the resulting TEC gradient time series can then be processed with a three-dimensional (one temporal, two spatial) spectral analysis, described in detail by Helmboldt and Intema (2014).

The VLITE pipeline automatically executes several signal processing steps using the visibilities from each VLA scan, a contiguous block of observations of a single pointing. Typically, even observations that are several hours long are broken into scans of 5-10 minutes in length. Due to considerations that are beyond the scope of this paper, the VLITE correlator works on each VLA scan separately, outputting a standalone FITS data file for each. Thus, the most convenient mode of operation for the ionospheric pipeline is to process each scan separately once it is written to disk (monitored using the inotify subsystem). The signal processing is designed to isolate the ionospheric signature within the visibility phases from other contributions per scan. The steps include:

a. *RFI mitigation*: Sigma-clipping is employed using the real and imaginary parts of the visibilities to identify and flag aberrant data points resulting from radio frequency interference (RFI). An algorithm is also employed to identify and subtract the unique signature of stationary sources of RFI, and an additional algorithm identifies and flags any unusual "jumps" in phase due to external and/or internal interference.

b. *De-trending*: After flagging is finished, baseline phase time series are computed within four frequency sub-bands and separately for each linear polarization (the low-band system uses crossed-dipole feeds). These are each unwrapped in time within contiguous chunks of un-flagged data, where the maximum allowed gap within such a chunk is 10 seconds. Each time series is then de-trended by subtracting a linear fit to un-flagged data within a sliding 128-second wide box (a single fit is subtracted for scans that are <128 seconds long).
c. *Ionospheric signature isolation*: After de-trending, the phases are converted to δTEC units and median combined among the four sub-bands, separately for each polarization. A process commonly referred to as baseline calibration is then used to identify and remove baseline-based errors to isolate the antenna-based ionospheric effects. These errors include contributions from the cosmic source(s), pointing errors for fields of view with multiple sources, and noise. Baseline calibration is applied separately to each polarization, and then the two are averaged. The difference between the results for the two polarizations is used to characterize the uncertainty in the final δTEC time series. A polynomial fit then converts these to antenna-based TEC gradients.

In addition to these steps, the output from the VLA's atmospheric phase interferometer API; Morris 2014) is obtained in real time and used to flag scans for which tropospheric fluctuations are large enough to possibly rival those due to the ionosphere at VLITE frequencies. The API uses a compact (baselines <300 meters) array of 1.5-meter dish antennas to observe a geostationary satellite at 11.7 GHz and measure the RMS baseline phase fluctuation within one-minute intervals to characterized tropospheric variability. This is used to aid in the dynamic scheduling of high-frequency (>10 GHz) VLA observations that require a relatively quiet troposphere. Test observations indicate that real-time API outputs provide an adequate method for flagging scans that are possibly contaminated by significant tropospheric fluctuations.

Following the signal processing steps detailed above, the pipeline performs the spectral analysis detailed by Helmboldt and Intema (2014). The temporal portion of the Fourier-based analysis uses an FFT with a sliding 128-second wide Hamming window, and thus this is only executed for scans that are longer than 128 seconds. The data products yielded by this analysis are (1) a mean baseline temporal spectrum using FFTs of the δTEC time series, normalized by baseline length, and (2) a power spectrum cube generated from the antenna-based TEC gradients. Each of these has an accompanying noise spectrum produced using the difference between the two polarizations. This is especially important along the temporal axis as the process of unwrapping phases can introduce structure within the noise, especially for low signal-to-noise ratio data (i.e., the noise spectrum is typically not flat). These fluctuation spectra, along with the δTEC and gradient time series and other relevant quantities, are stored in FITS files for future offline analysis.

Each of these steps has been tested and validated using observations of bright cosmic sources during the commissioning phase of VLITE. Specifically, the results have been compared to simultaneous observations with a prototype VLA system operating between 55 and 85 MHz. The δTEC time series produced by the pipeline match 72 MHz phase time series on the same baselines when appropriately scaled with frequency. Additionally, the baseline calibration process has been shown to reasonably reproduce the expected phase contributions from an extremely bright and somewhat complex cosmic source, Cygnus A. Pipeline-based spectral analysis of commissioning observations of Cygnus A also detected and characterized a traveling ionospheric disturbance (TID) that matched results from s similar spectral-based analysis of contemporaneous data from 20 continuously operating GPS stations within 200 km of the VLA.

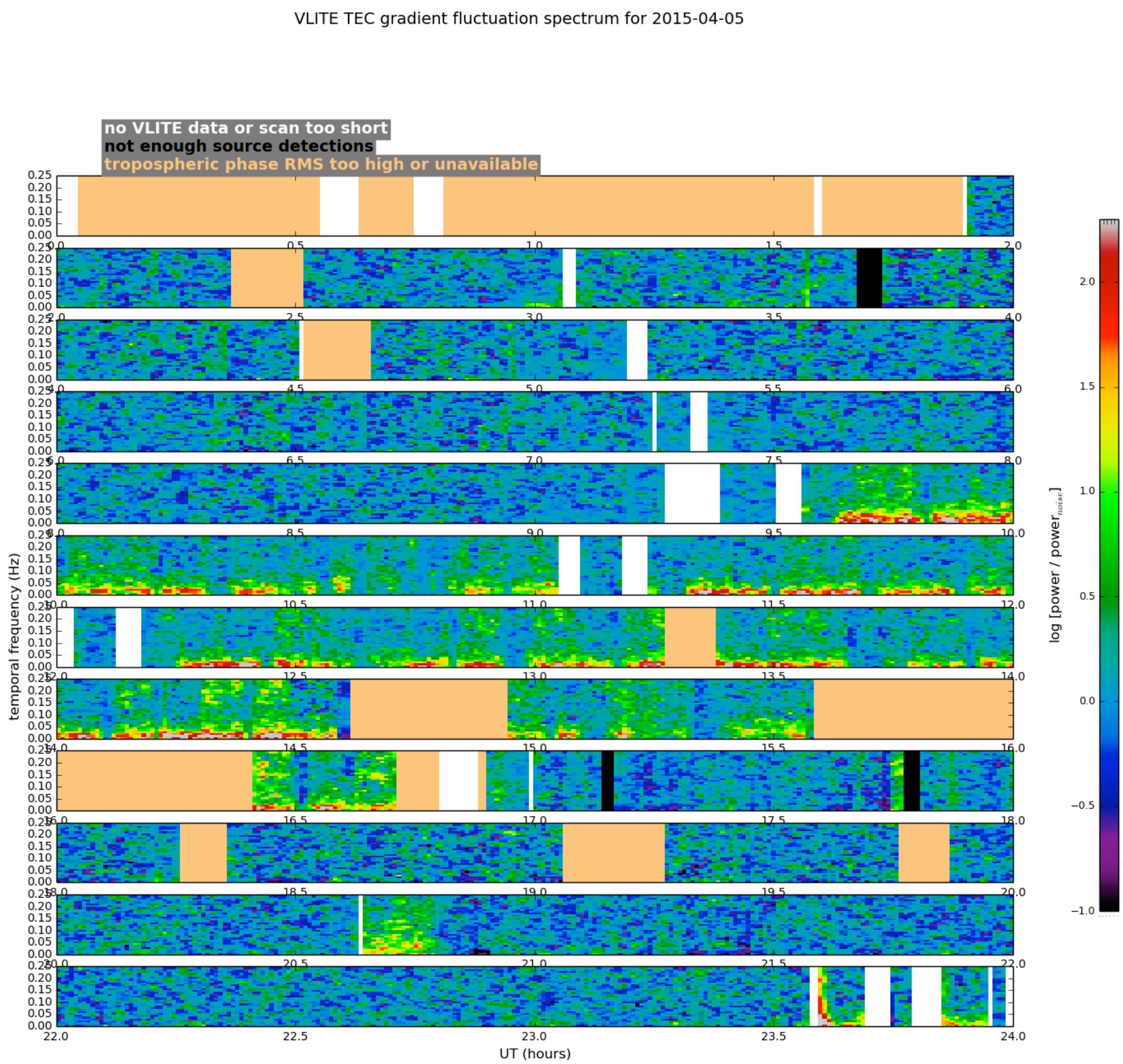

Figure 1 -- A 24-hour spectrogram of ionospheric fluctuations for 2015-04-05. These are automatically produced daily as part of VLITE operations. The spectra are normalized by the noise spectra (see Section 2) to highlight significant features.

Finally, as part of daily VLITE operations, the results from 24 hours of data are concatenated into one δTEC time series per baseline, from which a full 24-hour spectrogram is computed. This often includes the combination of several short (<128 seconds) scans of bright sources routinely observed for calibration purposes (i.e., calibrators) within a single FFT window, each of which effectively uses a different de-trending window. Thus, these spectrograms are only useful for diagnostic purposes, facilitating a "quick look" capability to identify obvious data issues or interesting phenomenon that warrant further scrutiny. An example generated for April 5, 2015 is shown in Fig. 1. The displayed spectrogram is divided by the accompanying noise spectra to highlight significant detections of disturbances. In this instance, one can see a prolonged period of activity between roughly 09:30 and 17:00 UT (about 02:30 and 10:00 local time).

3. Summary

While VLITE has been within full science operations mode since November 2014, we have barely begun to scratch the surface of the ionospheric information contained within the data. In addition to the larger statistical/climatological study that will be conducted, we have already begun to analyze data during specific events for which we would almost certainly not have had low-band data without VLITE. These include solar flares in the run-up to the March 2015 geomagnetic storm as well as several seismic events, detected/characterized using data from the seismic station in relatively nearby Albuquerque. We have also developed a complementary data processing pipeline to produce TEC fluctuation power spectrum cubes using 20 nearby GPS stations to characterize fluctuations on larger spatial and temporal scales than are accessible through VLITE data to explore possible coupling processes between large and small-scale disturbances. Thus, not only will VLITE produce a unique data set for the study of fine-scale ionospheric dynamics, but there are also many exciting potential synergies between its data products and those of other ionospheric remote sensing platforms.

References

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