

Analysis of Low-Frequency Radio Array Mapping of D-Region Electron Densities and HF Absorption

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Abstract—We present results from an array of low-frequency (500 Hz - 500 kHz) radio receivers, passively recording VLF (3-30 kHz) emissions from natural lightning and navy VLF transmitters. A series of signal processing, machine learning, and tomographic techniques amalgamates this dataset to reconstruct the 3D D-region (60-90 km) ionospheric electron density profiles over the Gulf of Mexico and Southeastern USA. We present profiles over a selected 13-day period in August 2017 during which time there was a solar eclipse and multiple major solar flares. The VLF electron density profiles are also used to infer HF absorption as a function of location and time, a technique described in this paper. We use this to validate our D-region inferences by comparing against a ground-based ionosonde instrument.

Index Terms—VLF Array, Ionosonde, D-Region, Ionosphere

I. INTRODUCTION

The lowest and most dynamic region of the ionosphere is the D-region (60 - 90 km) which is too high for balloons, too low for satellites, and too sparsely charged for radars [1]. Nonetheless, this ionosphere layer impacts trans-ionospheric and over-the-horizon navigation and communication signals [2]. The D-Region is also used in measuring a host of geophysical phenomena, including solar flares, acoustic gravity waves, electron precipitation, among others [3]–[5].

The High Frequency (HF, 3-30 MHz) band is commonly used for ionospheric sensing and for long-range communications such as shortwave broadcasting and transoceanic aviation communications [6], [7]. Because HF frequencies are significantly attenuated by the D-Region, however, a strongly ionizing solar event drastically increasing D-Region electron density may render HF propagation infeasible.

Very Low Frequency and Low Frequency (VLF/LF, 3-300 kHz) signals propagate efficiently to global distances in a waveguide formed by the ground and the D-Region, and reflect from the D-region itself. Signal fidelity typically increases with stronger D-Region electron density, such as from a solar flare, thereby making VLF more resilient in instances when HF signals are weaker. VLF signals, however, are difficult to generate because of long wavelengths (10 km at 30 kHz) and have therefore been mostly restricted in terms of applications to submarine communications [8] and an early global navigation system [9].

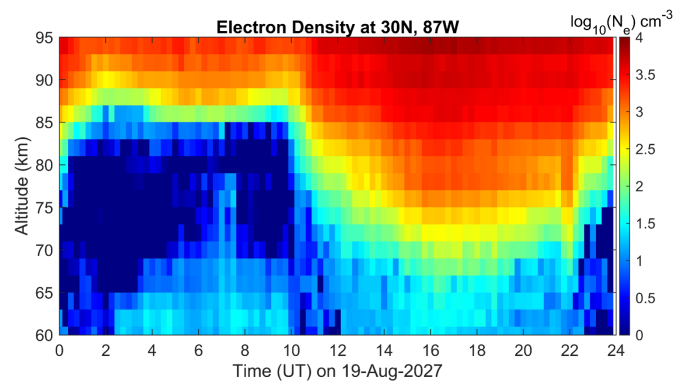


Fig. 1: Tomography at Eglin, Florida, on August 19, 2017

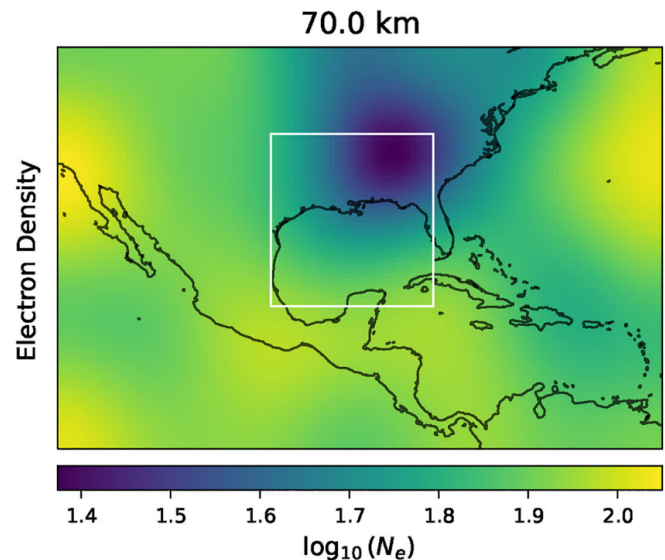


Fig. 2: D-Region electron density of August 21 solar eclipse at 70 km, 18:30 UT. From Richardson, [10]

VLF remote sensing is, nonetheless, useful to characterize the D-Region. A recently-developed set of algorithms [10]–[14] utilizes an array of VLF receivers detecting two signals of interest: (1) VLF transmitters, which are operated by the Navy for communications, and (2) sferics, or wide-band impulsive emissions from lightning strokes, both of which propagate from global distances to the receiver. By processing and aggregating sferics and VLF transmitter signals, we construct, via machine learning, a tomography of the D-Region electron density.

In this study, data is analyzed from August 19 to 31, 2017, during which time multiple solar flares and a total solar eclipse across the southern United States occurred.

The receiver consists of two orthogonal, air-core, wire-loop antennas, sensitive to the 500 Hz - 500 kHz band, with ~ 20 ns timing accuracy, and few fT/rt-Hz sensitivity [15].

II. MCCORMICK-GROSS-RICHARDSON MODEL

The VLF transmitters are first processed by demodulating the Minimum Shift Keying (MSK) modulation signal, yielding the amplitude, carrier phase, and clock phase. These outputs, on two orthogonal loop antennas, allow reconstruction of the polarization ellipse [16] even with the 90-degree ambiguity inherent in MSK. The amplitude and phase of the extracted VLF signal is then fed into a pre-trained artificial neural network (ANN) [11], yielding an estimate of two parameters of the electron density, for each transmitter-to-receiver path [17].

Next, the sferics are processed. In this stage, the MSK transmitter signals previously calculated are removed. Events from a lightning location detection system such as GLD360 [18], [19] are then matched with sferics in the VLF data. Sferics from the same storm and close in time are clustered and precisely time-aligned to account for variability in lightning current and the error of the lightning location [12]. This time-aligned sferic carries the average characteristic information about the ionosphere along the path from the thunderstorm location to the receiver. This information is then matched to a preexisting table of calculated sferics, for each storm-to-receiver path, for a set of four-parameter, D-Region profile models [13]. The best-fit profile is then selected. Using a neural network, an electron density tomography is then built by aggregating the many path-averaged D-Region profiles along the storm-receiver paths [10]. Finally the results of the VLF transmitters and VLF sferic analyses are unified, and a final tomographic reconstruction is produced [14].

With roughly forty lightning strikes occurring every second [20] and the additional active VLF transmitters transmitting during the time of this study, there are enough source-to-receiver paths every five minutes to build a high-resolution profile of electron density across the continent [21], [22].

Two depictions of this tomography are shown in Figure 1 and Figure 2. Figure 1 shows this tomography near Eglin, Florida (30° N, 87° W) across altitude and time. Figure 2 shows this tomography at an altitude of 70 km and at 18:30 UT across North America.

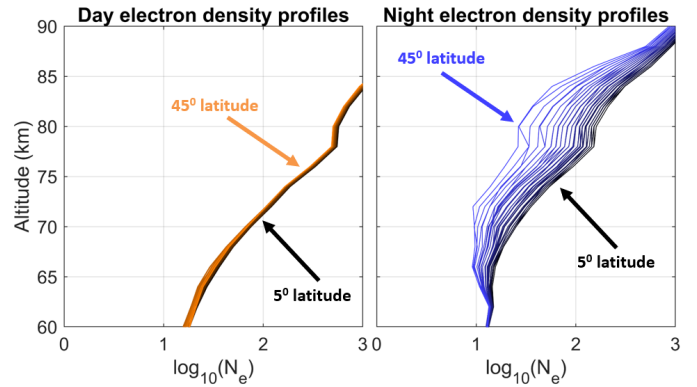


Fig. 3: Initial Climatology Results for the D-Region

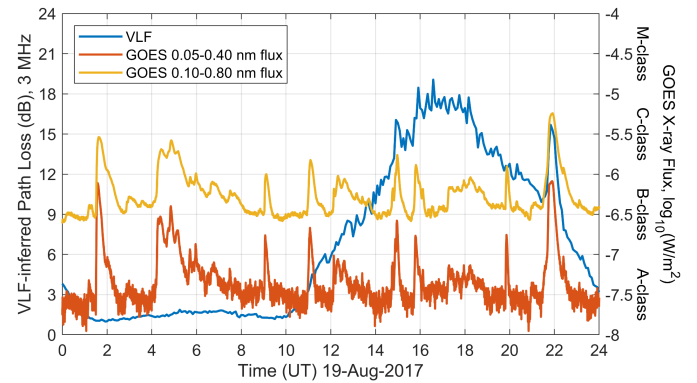


Fig. 4: VLF inferred absorption (O-Mode) and X-Ray flux plotted for August 19, 2017

III. D-REGION CLIMATOLOGY

Figure 3 shows initial efforts to build a D-region climatology with the results. For each 5-minute block of time, we average the electron density profile across all longitudes, and then average all the profiles for either daytime (left panel) or nighttime (right panel). The figure shows the electron density profile as a function of latitude, between 5° N and 45° N. During the daytime, the electron density profile changes by a very small amount only. During the northern hemisphere summer months, the sun is nearly overhead over much of these latitudes, hence the zenith angle variation is relatively small. If repeated in the wintertime, there will be a larger difference between low and mid latitudes on the northern hemisphere.

However, at nighttime, a more significant dependence on latitude appears, with mid latitudes being lower in electron density by about half an order of magnitude compared to low latitudes.

IV. VALIDATION WITH HF

Obtaining validation data is difficult due to the lack of independent and direct measurements of the D-region. We present two methods to validate our D-Region electron density estimates. Our D-region estimates allow us to calculate/infer the HF absorption, by calculating the Appleton-Hartree index

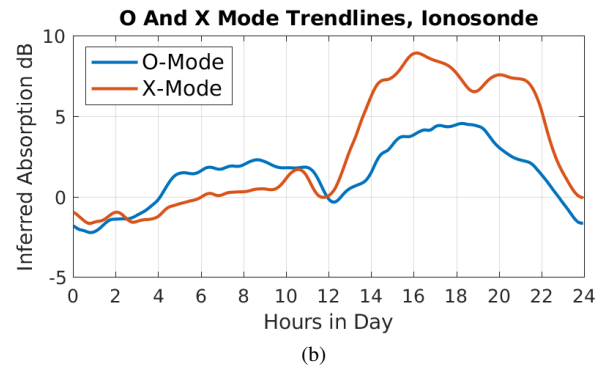
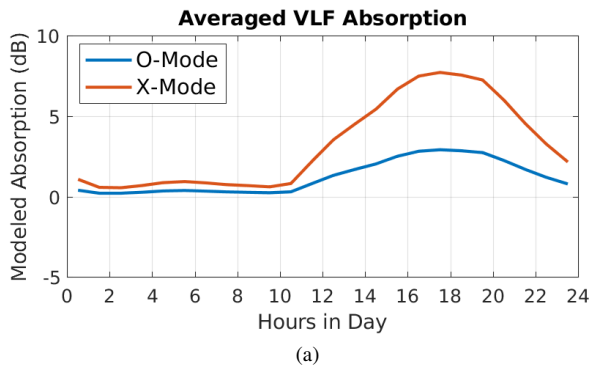


Fig. 5: A comparison of VLF and ionosonde inferred absorption; a days worth of averaged absorption values from August 19 to 31, 2017

of refraction, and integrating the HF absorption through the D-region. Since this is more readily observable, and correlated with respect to solar x-ray flux, we use this method for validation.

A. Solar Flare HF Absorption

Figure 4 displays GOES X-ray Flux in two different bands, which show an X-class solar flare at 22 UT on August 19, 2017. This large solar flare clearly corresponds with an increase in VLF-inferred HF absorption.

As observed throughout the daytime, and especially at 22 UT, there exists a strong correlation between X-Ray flux and observed D-Region absorption caused by an increase in ionization.

B. Correlation with an Ionosonde

Ionosondes are radars, typically used to interrogate the E and F regions by measuring the characteristic reflection ranges of a wideband signal from 1 to 10 MHz [23]. The ionosonde works by transmitting (and receiving) an Ordinary-Mode (O-Mode, LHCP) and Extraordinary-Mode (X-Mode, RHCP) polarized wave along zenith from a collocated ground transmitter and receiver.

The ionosonde also records the amplitude for each polarization, and 0.025 MHz-discretized frequency within the band. But this information is rarely used. Free-space loss accounts for a reduced signal strength by a factor of $1/r^2$ in addition to variable absorption in the D-Region. We multiply each received amplitude by r^2 , thereby adjusting for free-space loss and isolating absorption from the D-region, or other factors like focusing and irregularity scattering. We apply this technique to both single-hop and double-hop signals.

The inferred D-Region absorption from both the ionosonde data and VLF is averaged over a twelve day period from August 19 to 31, 2017 and an interpolated average spline is fit for both of the modes and is shown in Figure 5. A simple comparison reveals a strong correlation between the two disparate methods of D-Region absorption inference suggesting an accurate electron density model.

V. CONCLUSION

The McCormick-Gross-Richardson VLF tomography model make use of a global VLF array network which harvests pertinent D-Region information from VLF transmitters and lightning-based sferics around the world. The accuracy of this model is revealed through an observation of natural phenomenon within VLF inferred absorption, an investigation of D-Region climatology, and correlation between VLF inferred and ionosonde inferred D-Region absorption. Such a verification supports the installation of more VLF array receivers, of which receiver installments north into the Arctic and south into the Caribbean are pending. A more robust data-set of the D-Region will provide a foundation for VLF communication and positioning technologies while also allow users of HF technologies to infer absorption in the D-Region in the event of a high ionization event such as a geomagnetic storm.

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