Broadband Integrated D-Region Remote Sensing as an Optimization Problem

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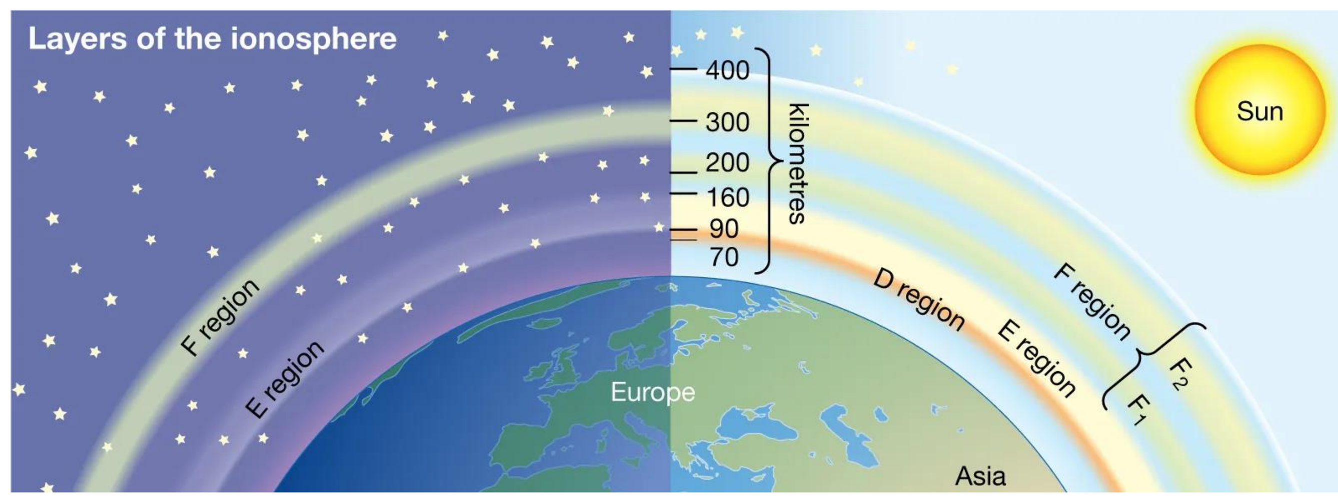
Abstract



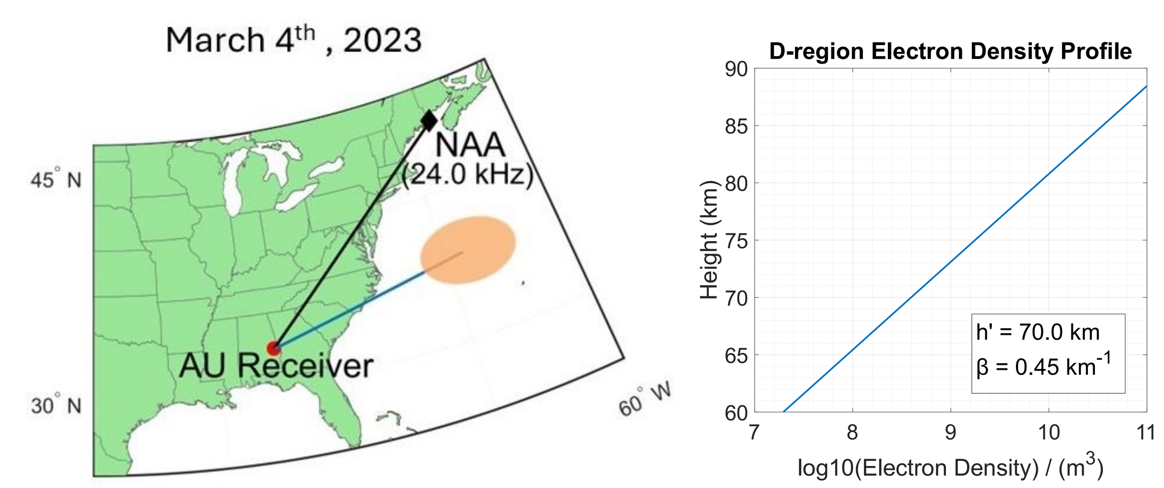
The radio spectrum across the Extremely Low Frequency (ELF) to Very Low Frequency (VLF) ranges defined as ~1 Hz - 30 kHz is rich in signal sources historically used in remote sensing of the D-region ionosphere (60 - 90 km). Radio waves in this band have the property of propagating large distances with low attenuation, where ionospheric information is contained in the path-integrated measurements taken using a VLF receiver. Previous D-region remote sensing techniques have harnessed data received from isolated signal sources, which primarily include VLF MSK modulated transmitters operated by the Navy and lightning-generated radio emissions (sferics). Measurements of these sources have established techniques for producing D-region electron density profiles and have been shown to respond to sudden ionospheric disturbances due to space weather events. As signal sources overlap spectrally and temporally in data, it is often difficult to make a clean measurement of the specified signal of opportunity. We propose an integrated broadband remote sensing technique which aims to re-frame the signal processing problem as an optimization problem to concurrently analyze signal sources for the purposes of ionospheric remote sensing.

Receiver Hardware and Data Collection

Propagating VLF signals are Measured using a two-channel VLF magnetic field receiver located near Auburn, Alabama. Time-varying magnetic fields are sampled on two orthogonal air-core magnetic loop antennas oriented in the North/South and East/West directions, respectively. Due to the sine/cosine directional dependence of the loop antenna's radiation pattern, the full horizontal magnetic field at the ground of a propagating electromagnetic wave can be reconstructed from the two channels. The ADC samples at a rate of 100 kS/s, allowing us to digitally represent frequency content in the range of 0 kHz - 50 kHz.

Remote Sensing via VLF Measurements

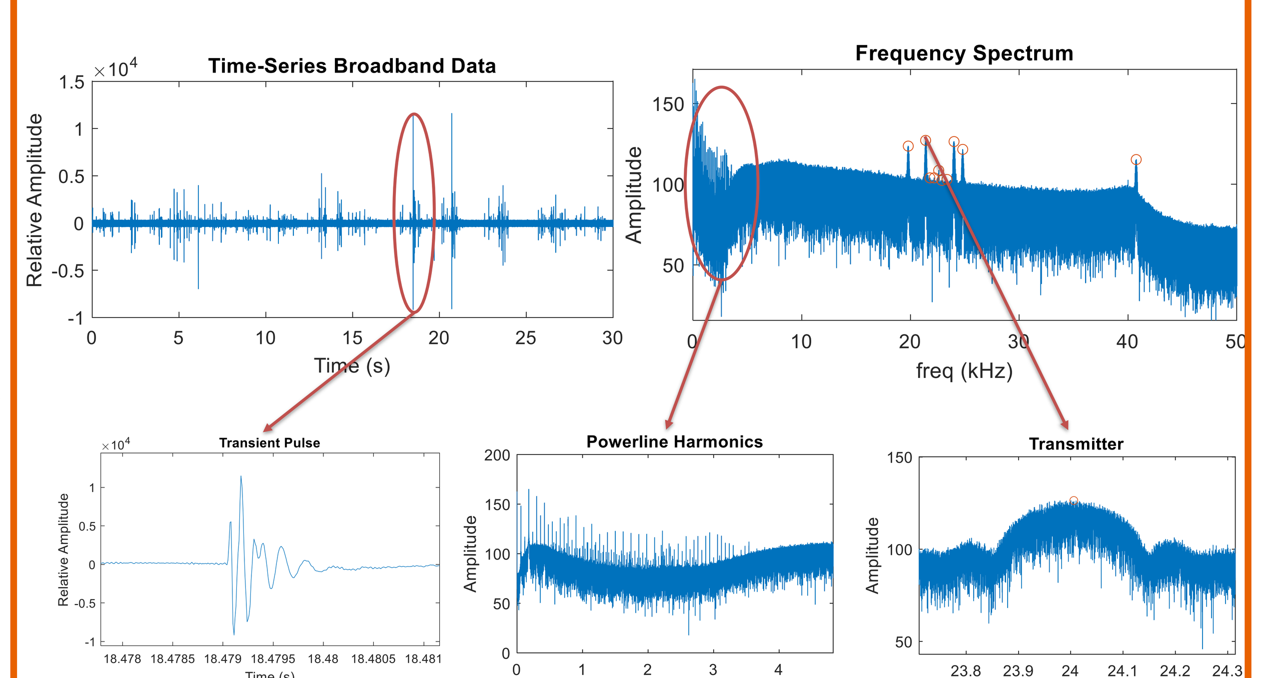
Measurements are made of the VLF modal content produced by some source as it propagates over the receiver. A propagation model is used to find the electron density profile that would have resulted in the most similar measurement to that observed at the receiver. This is commonly reported using a two-parameter model.



Adapted from Thomson [1]

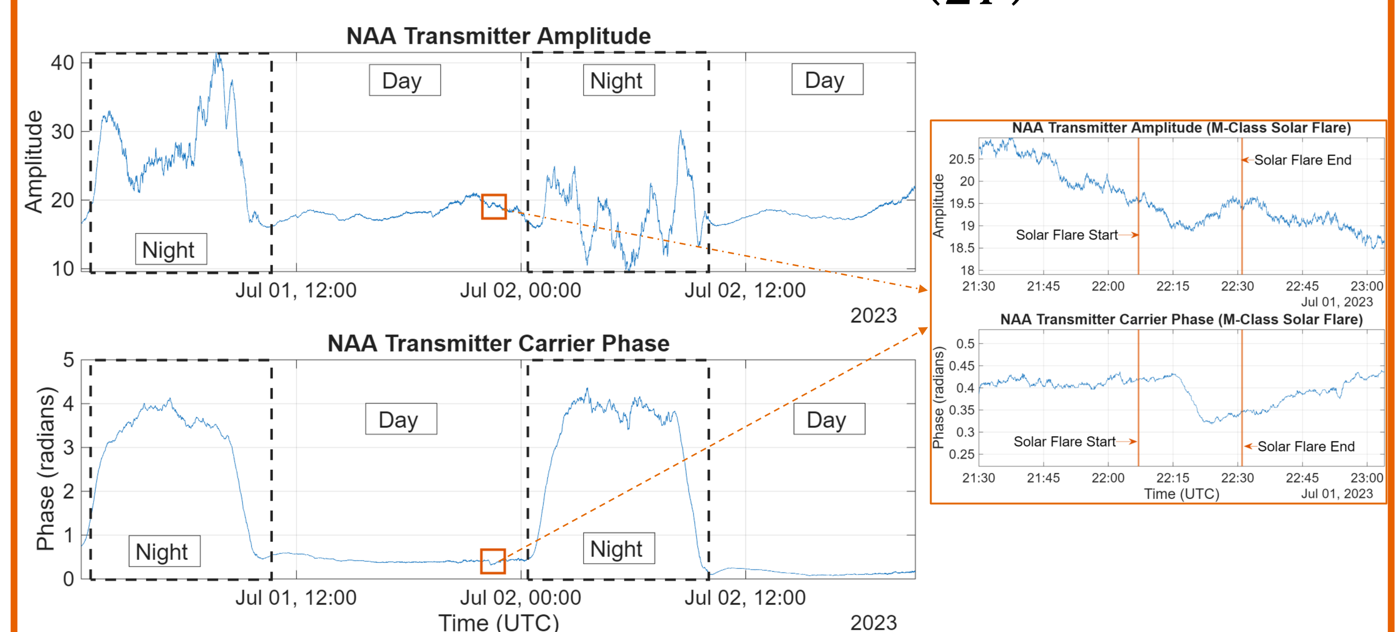
VLF Signal Sources

We consider the majority of signal content to be broken up into three categories: Continuous Wave Transmitters, MSK modulated transmitters, and Transient Pulses. CW transmitters take the form of powerline harmonics prevalent at lower frequencies. There exists various VLF transmitters, generally operated by the US navy, that transmit using MSK modulation and are present above ~18 kHz. The dominant source of transient pulses in our data are radio waves generated by lightning discharges, known as radio atmospherics or sferics. Lightning produced electromagnetic radiation is extremely broadband and sferic signals exist in our data across the entire available range.

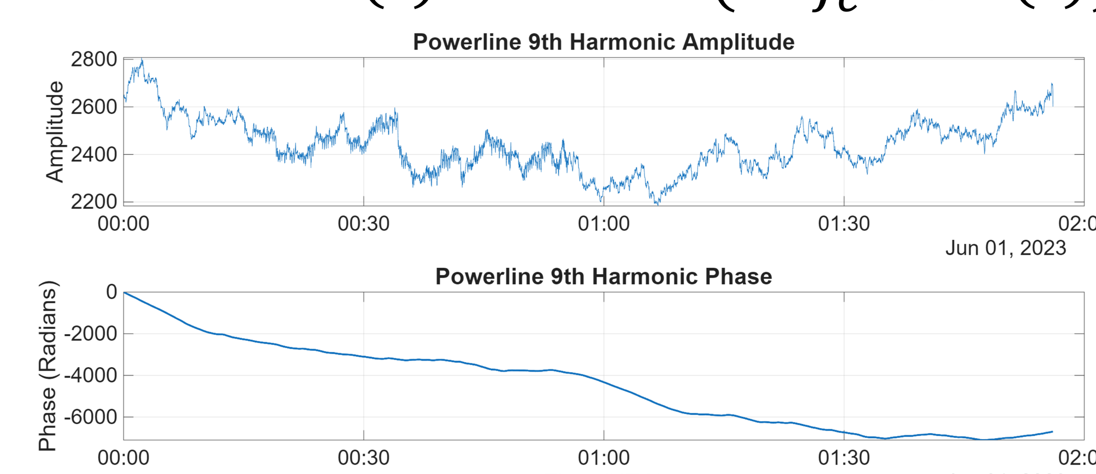


Signal Parameterization

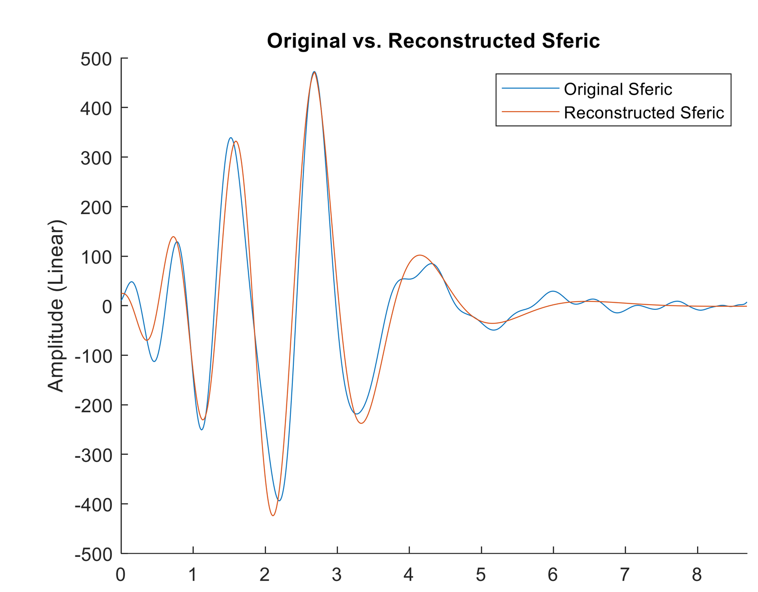
$$MSK: s(t) = A \cdot \cos\left(2\pi f_c t + b(t)\left(\frac{\pi t}{2T}\right) + \theta(t)\right)$$



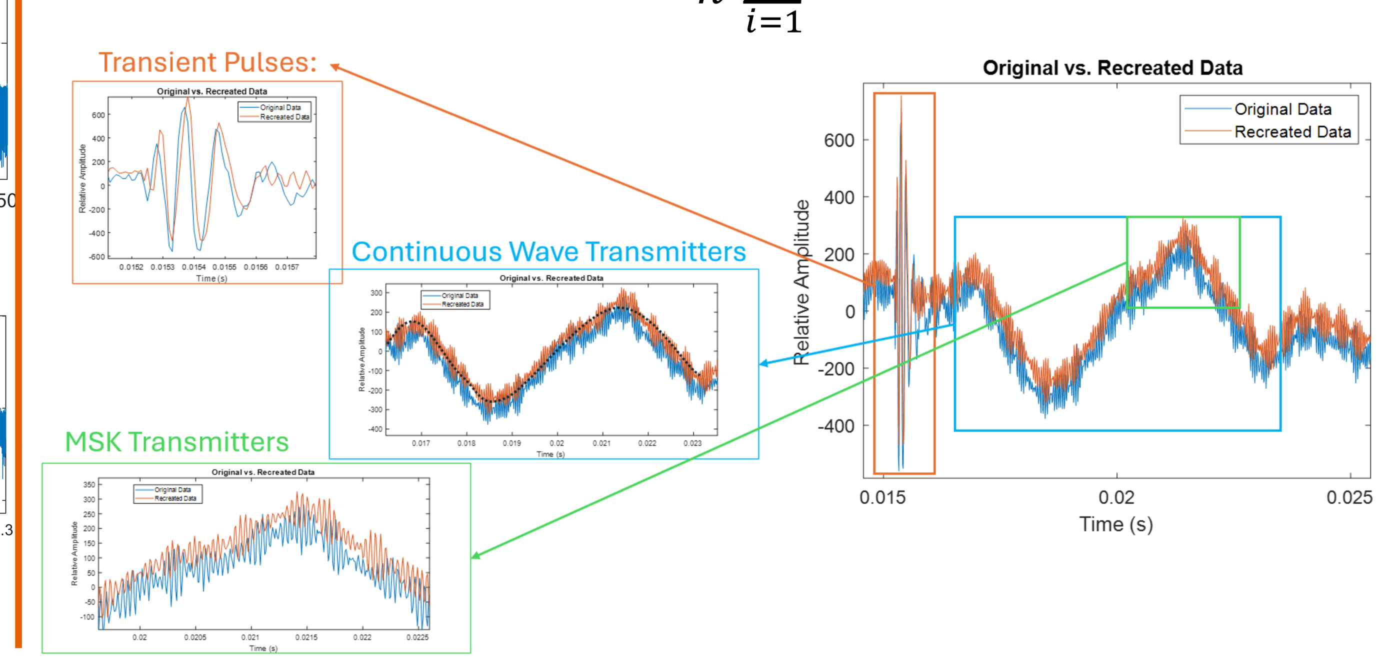
$$Powerlines: s(t) = A \cdot \cos(2\pi f_c t + \theta(t))$$



Sferic: $envelope = \left(\frac{a \cdot \sigma}{e^{-0.5}}\right) \cdot \frac{t}{\sigma^2} e^{-\frac{t^2}{2\sigma^2}}$, $chirp = \sin\left[2\pi f_0 \left(\frac{T k^{\frac{t}{T}}}{\ln(k)}\right) + \varphi_0\right]$

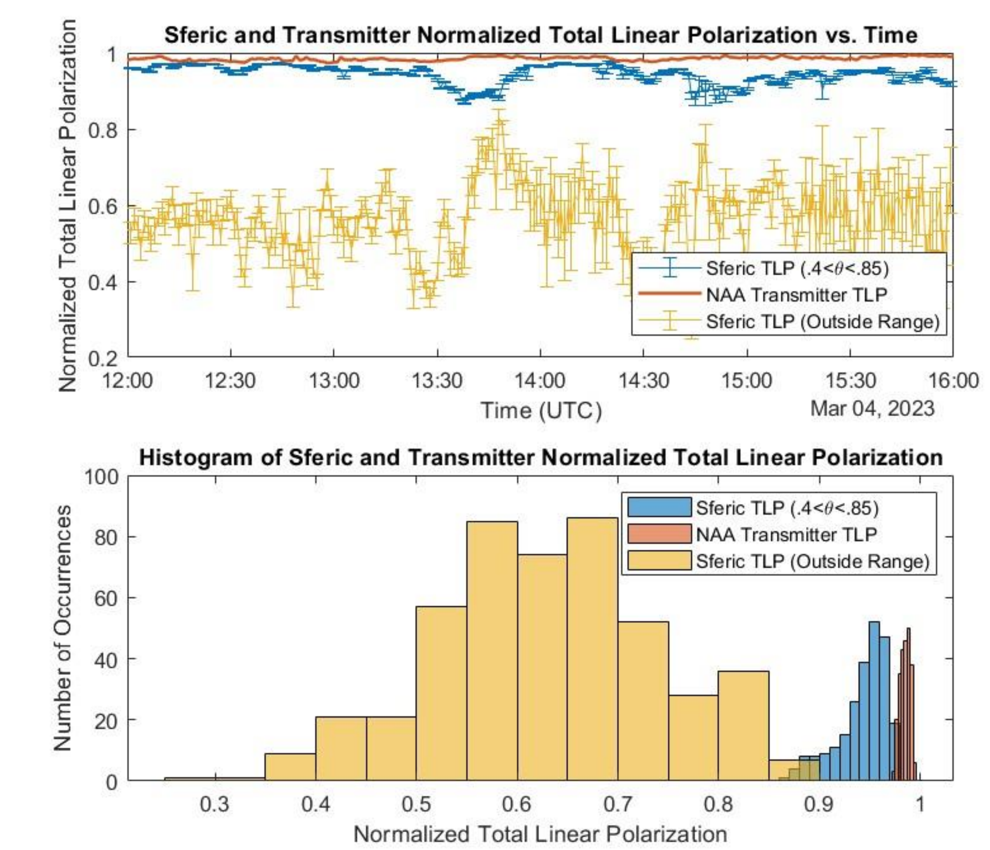


Optimization: $MSE = \frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2$



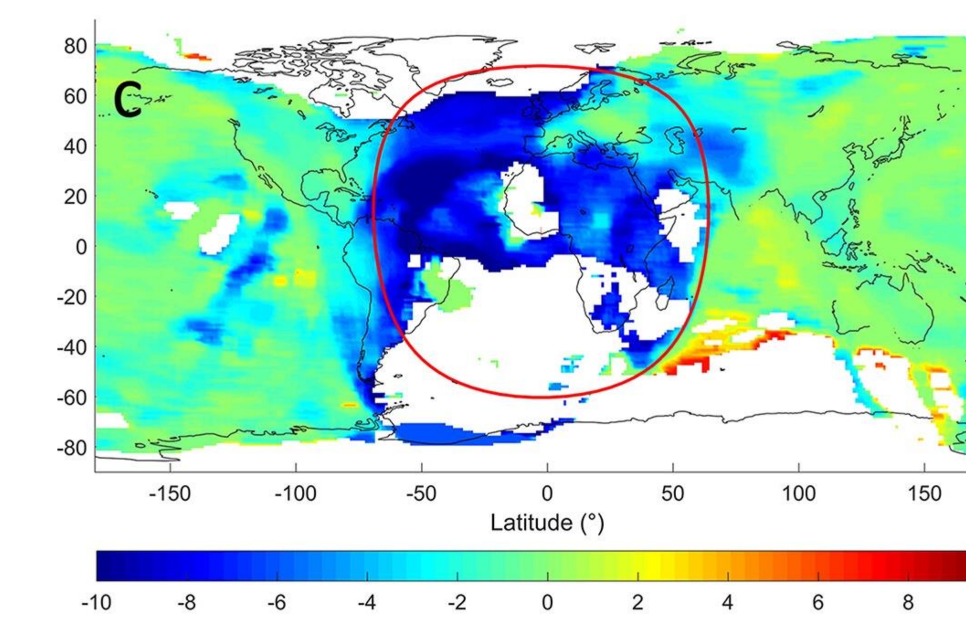
Polarization Measurements

Wave-guide polarization measurements are taken of transmitters and impulsive sferic samples averaged over time.



Next Steps

We would like to utilize clean measurements of each signal source to achieve wide-scale mapping of the D-region through modeling or neural networks.



Anderson, et al. [1]

[1] Thomson, N. R. "Experimental daytime VLF ionospheric parameters." Journal of Atmospheric and Terrestrial Physics 55.2 (1993): 173-184.
[2] Anderson, T. S., M. P. McCarthy, and R. H. Holzworth. "Detection of VLF Attenuation in the Earth-Ionosphere Waveguide Caused by X-Class Solar Flares Using aGlobal Lightning Location Network." Space Weather 18.3 (2020): e2019SW002408.

Acknowledgments:
We would like to thank Dr. Robb Moore at the University of Florida for providing
receiver data and additional assistance