The Effects of Space Weather Events on Lightning Generated VLF Sferic Propagation Characteristics

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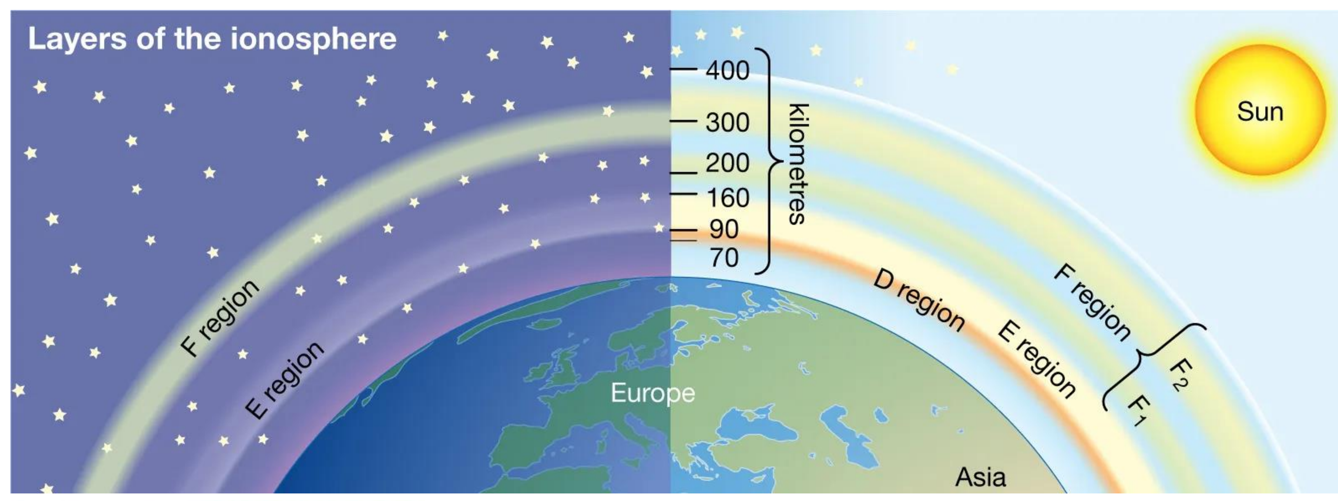
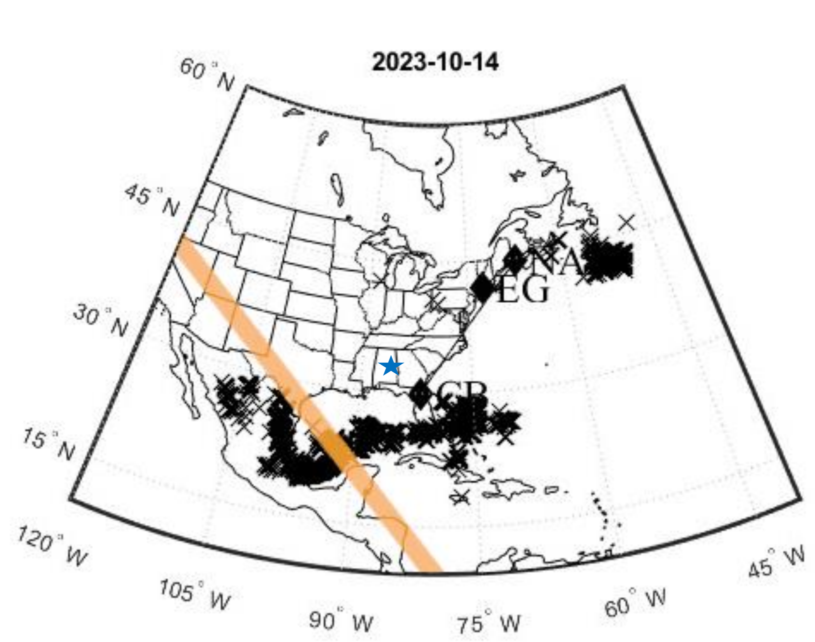
Abstract



The D-region of the ionosphere (60-100 km altitude) exists at the boundary between Earth's neutral gas atmosphere and the plasma environment of near-earth space. Very low frequency (VLF, 3-30 kHz) radio waves propagate to great distances with low attenuation in the Earth-Ionosphere waveguide (EIWG) formed by the D-region ionosphere and the surface of the Earth. Propagation characteristics depend on waveguide characteristics (e.g., electron density profile of the D-region) and thus measuring propagating waves allows for ground-based remote sensing of the ionosphere. VLF waves propagating through the EIWG experience modal interference. As a part of the analysis, Stokes parameters will be used as a heuristic for modal content. Lightning is an abundant source of VLF radio waves (radio atmospherics, or sferics) with diverse frequency content and source geometry, which makes it ideal for remote sensing. In this work, we present comparisons of more established VLF remote sensing techniques evaluating the amplitude and phase of VLF transmitters to observations of lightning sferics and discuss how those changes might be interpreted as changes in the D-region ionosphere.

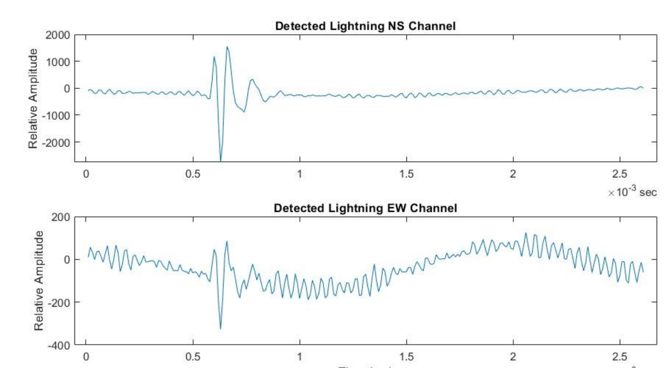
Experiment Setup

On October 14th, 2023, a solar flare and annular solar eclipse occurred. The solar flare peak was recorded at 16:32 UTC while the solar eclipse occurred between 16:41 and 19:46 UTC with a maximum at ~18:00 UTC. There were three active thunderstorms near the coastal United States on October 14th. The receiver is located in Auburn, AL. GOES x-ray flux and NLDN data is acquired as a part of this work [1][2].



Sferic Detection

A magnetic double loop antenna, oriented in the North/South and East/West directions is used to receive and record broadband signal data in the range of 0-50 kHz at a sampling rate of 100 kHz. This data is bandpass filtered to isolate lightning's highest energy frequency band (2-18 kHz). Sferics are then identified by their large amplitude and stored in short time samples.



Sferic Characterization

The FFT is taken of each detected lightning strike. For each frequency-domain value within lightning's primary frequency band, a value is calculated for each stokes parameter (S_0 ,S_1, S_2, S_3). The stokes parameters measure signal intensity, linear waveguide polarization, linear waveguide polarization on a 45-degree rotated axis, and circular waveguide polarization respectively[4]. The direction of arrival (θ) and total linear polarization (TLP) are calculated from the linear polarization parameters, yet it is important to note that each calculated θ value results in two solutions 180-degrees apart from each other. TLP measures direction ambiguous linear polarization of the reconstructed signal. These values are taken to be characteristic values for each lightning strike.

$$S_0 = |B_x|^2 + |B_y|^2$$

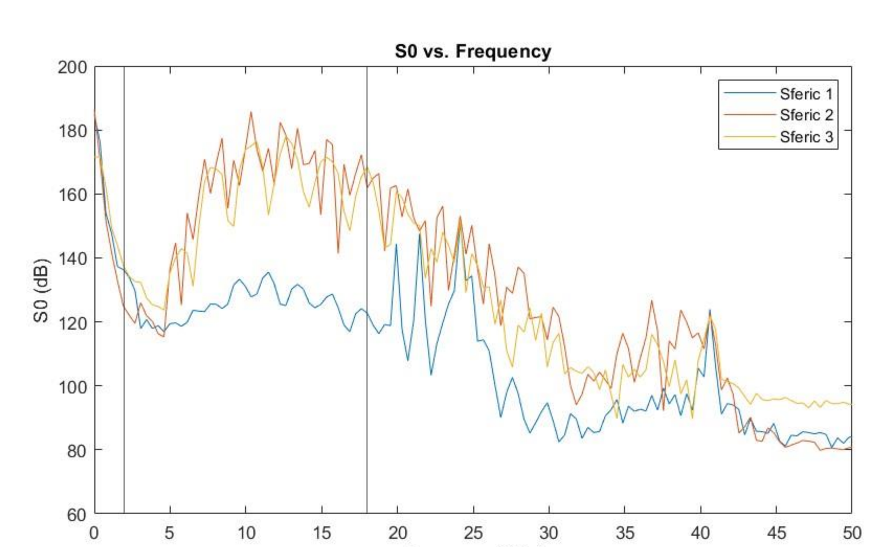
$$\widetilde{S_1} = \frac{|B_x|^2 - |B_y|^2}{S_0}$$

$$\widetilde{S_2} = \frac{2 \cdot \Re\{B_x B_y^*\}}{S_0}$$

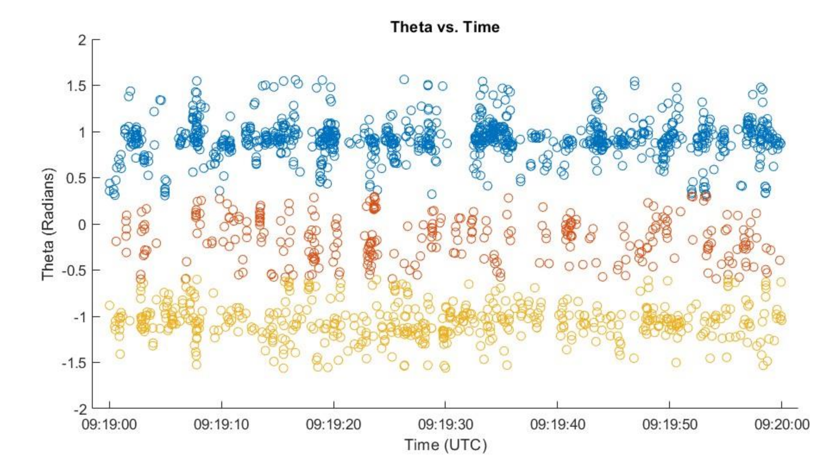
$$\widetilde{S_3} = \frac{2 \cdot \Im\{B_x B_y^*\}}{S_0}$$

$$\theta = \frac{\angle(\widetilde{S_1} + j\widetilde{S_2})}{2}$$

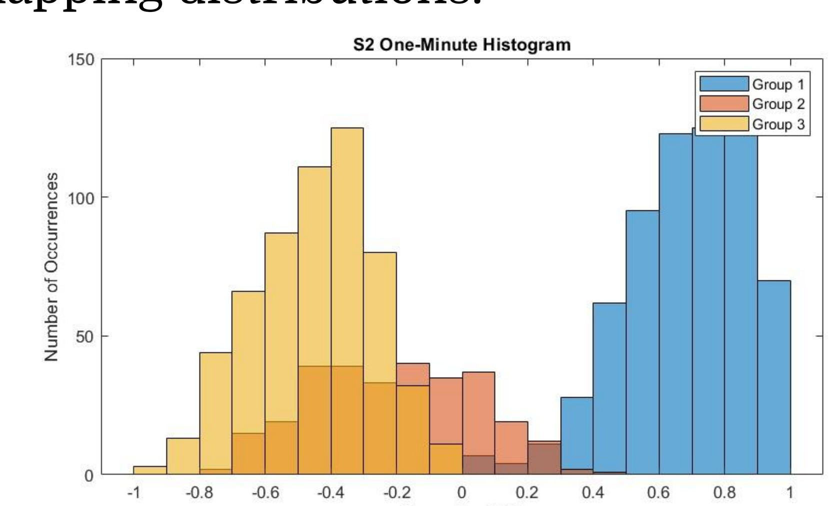
$$TLP = \sqrt{|\widetilde{S_1}|^2 + |\widetilde{S_2}|^2}$$



Source Separation

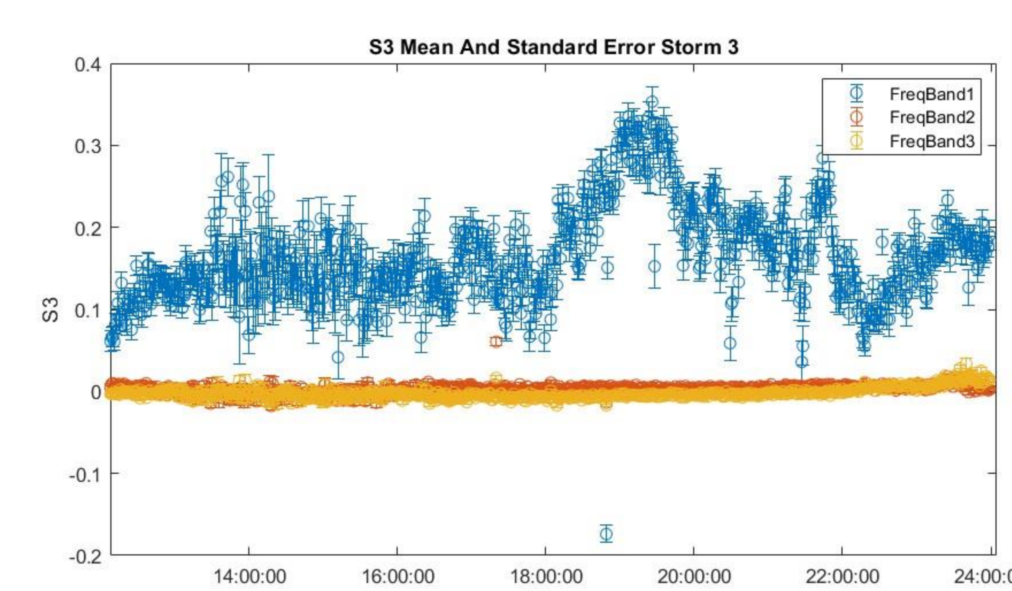


Lightning strikes occurring in storm cells with different source characteristics produce results with overlapping distributions. In order to separate sferics by their source, sferic direction of arrival values are plotted against time over the period of interest. The data is manually grouped into three "looking directions" to isolate sferics resulting from different thunderstorms. The values from each "thunderstorm group" are plotted on a histogram and results in the separation of overlapping distributions.

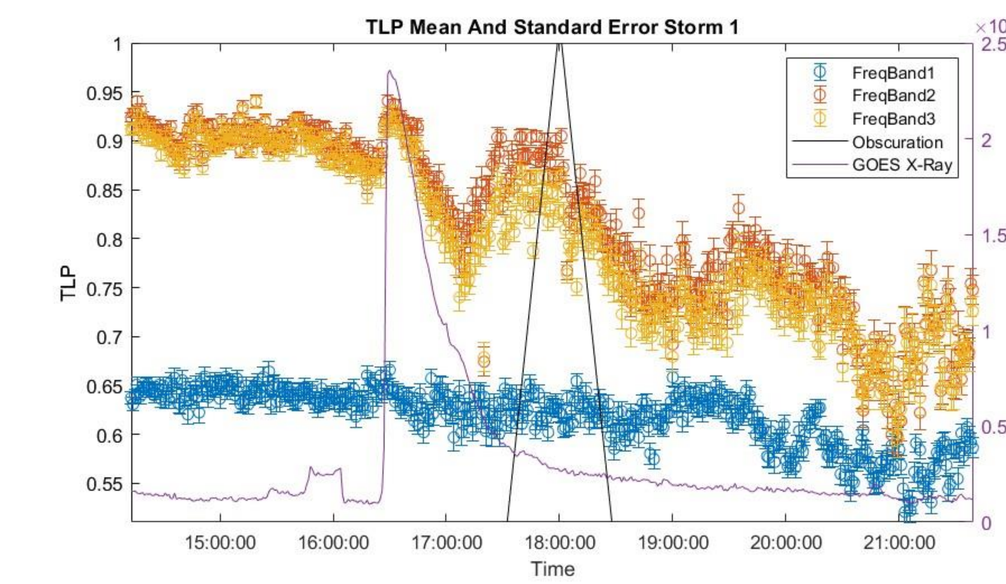


Frequency Band Analysis

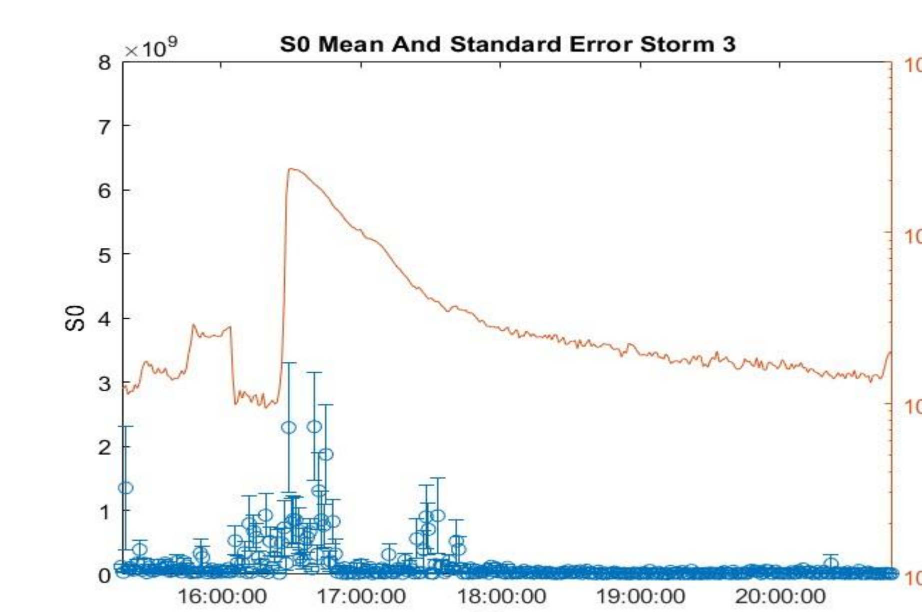
Lightning sferics range widely in frequency content which results in varying modes of propagation and degrees of attenuation. Averaging over three frequency bands, 2-6.5 kHz, 6.5-12 kHz, and 12-18 kHz, highlights the effects ionospheric disturbances have as frequency varies.



Discussion



After source separation and frequency band analysis, the mean and standard error are then taken of a minute of sferic characteristic values. These averaged characteristic values are plotted over the time of interest. A significant perturbation in TLP of storm group 1 is observed in conjunction with the solar flare. There is also a potential correlation observed between obscuration of the solar eclipse and sferic propagation characteristics. Future work will include further investigation into correlations between space weather and sferic propagation as well as the interpretation of the physical mechanisms resulting in these effects.



References

[1] https://www.ngdc.noaa.gov/stp/satellite/goes-r.html
[2] https://www.ncei.noaa.gov/products/lightning-products
[3] W. Taylor, "Vlf attenuation for east-west and west-east daytime propagation using atmospherics," Journal of Geophysical Research, vol. 65, no. 7, pp. 1933–1938, 1960.
[4] H. Burch and R. C. Moore, "The relationship between "large" early/fast vlf events and modal propagation nulls," IEEE Transactions on Geoscience and Remote Sensing, vol. 60, pp. 1–7, 2022.

Acknowledgments:

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