Parametric Modeling and Analysis of Lightning Sferic Waveforms for D-Region Remote Sensing

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Introduction

The D-region (50-90 km) plays a critical role in propagation at HF and below and is significantly impacted by space weather events (solar flare, eclipse, etc.). VLF signals propagate within the EIWG, and thus the characteristics of such signals can be used to remotely extract information about the state of the D-region along the path of propagation. Two main types of VLF signals are used for this purpose:

- **Narrowband MSK transmitters**
- **Transient, pulse-like emissions from lightning discharges known as "sferics"**

We focus on sferics given that they occur, on average, over 40 times per second worldwide and possess wide spatial variation compared to the limited distribution of VLF transmitters.

Objectives

- **Develop an interpretable time-domain parametric model of lightning sferic waveforms.**
- **Show that the model can be used to extract information about changes in the D-region both spatially and temporally.**

Data Collection and Preprocessing

- A VLF receiver consisting of two orthogonal magnetic loop antennas deployed near Auburn, AL is used to collect the data used in this work.
- Data is bandpass filtered from **3-21 kHz** to remove 60 Hz harmonics and MSK transmitters.
- Sferics are detected by searching for time-domain signal spikes in the filtered band and are then digitally rotated for maximum SNR.

Parametric Model and Optimization

- Begin with a logarithmic frequency chirp:

$$c(t) = \sin\left[\phi_0 + 2\pi f_0 \frac{T k^{\frac{t}{T}}}{ln(k)}\right], \quad k = \frac{f_1}{f_0}$$

- Take a scaled Rayleigh distribution envelope:

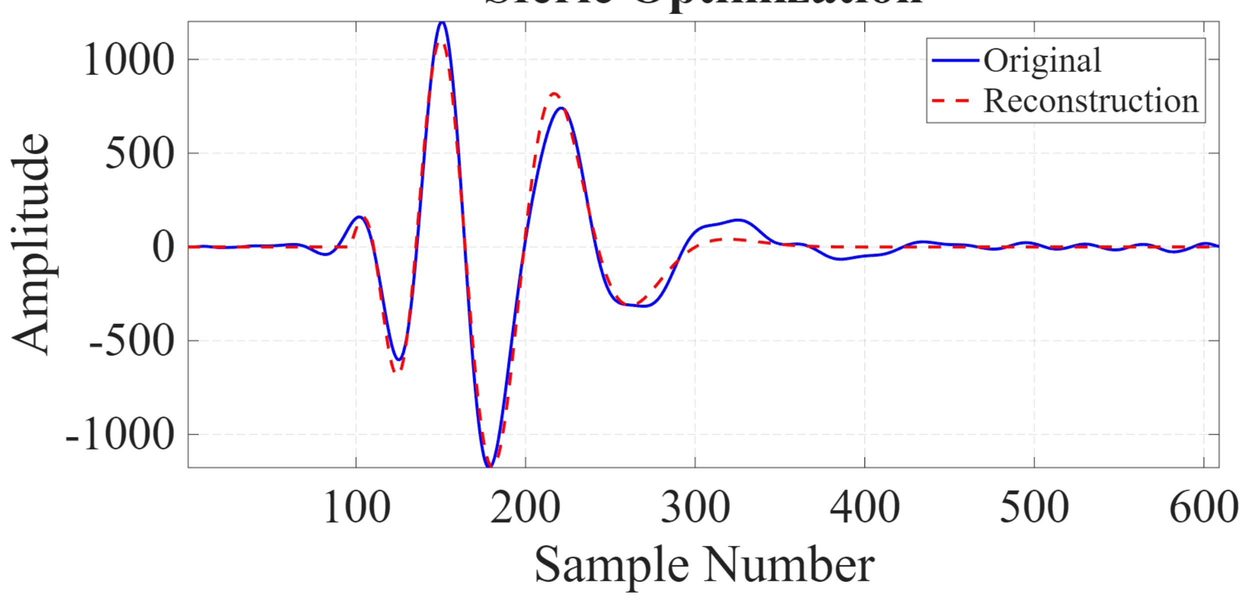
$$r(t) = \left(\frac{a\sigma}{e^{-0.5}}\right)\frac{t}{\sigma^2}\exp\left[-\frac{t^2}{2\sigma^2}\right]$$

- The final expression is:

$$s(t) = c(t) * r(t)$$

These parameters are optimized so that correlation between the original and reconstructed waveform is maximized. Daytime correlation is generally **~=90%**. While correlation drops somewhat during the more volatile nighttime hours, it generally remains at 80% or better during this period.

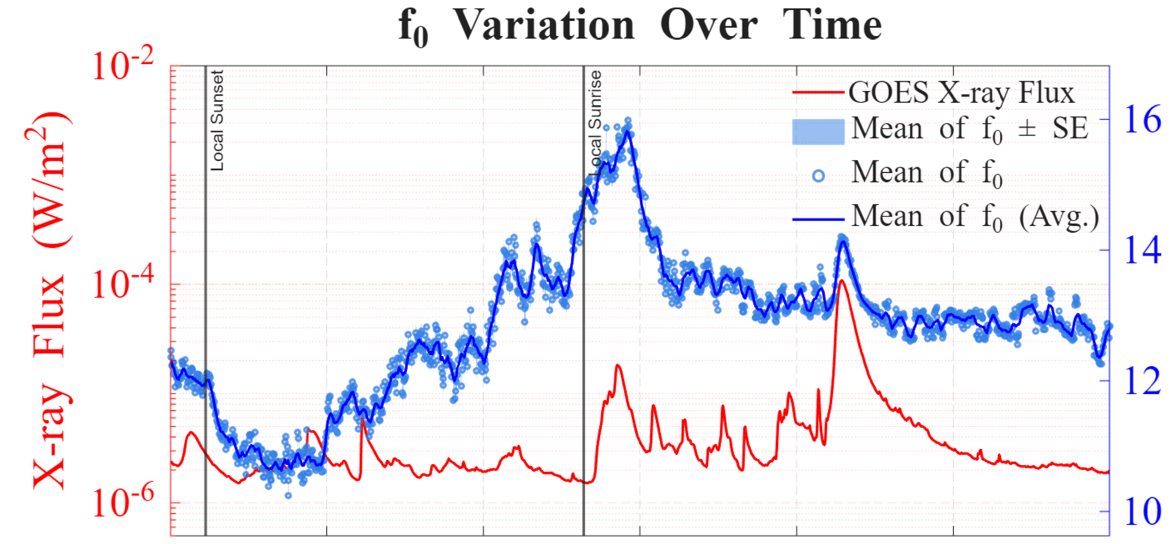
Sferic Optimization



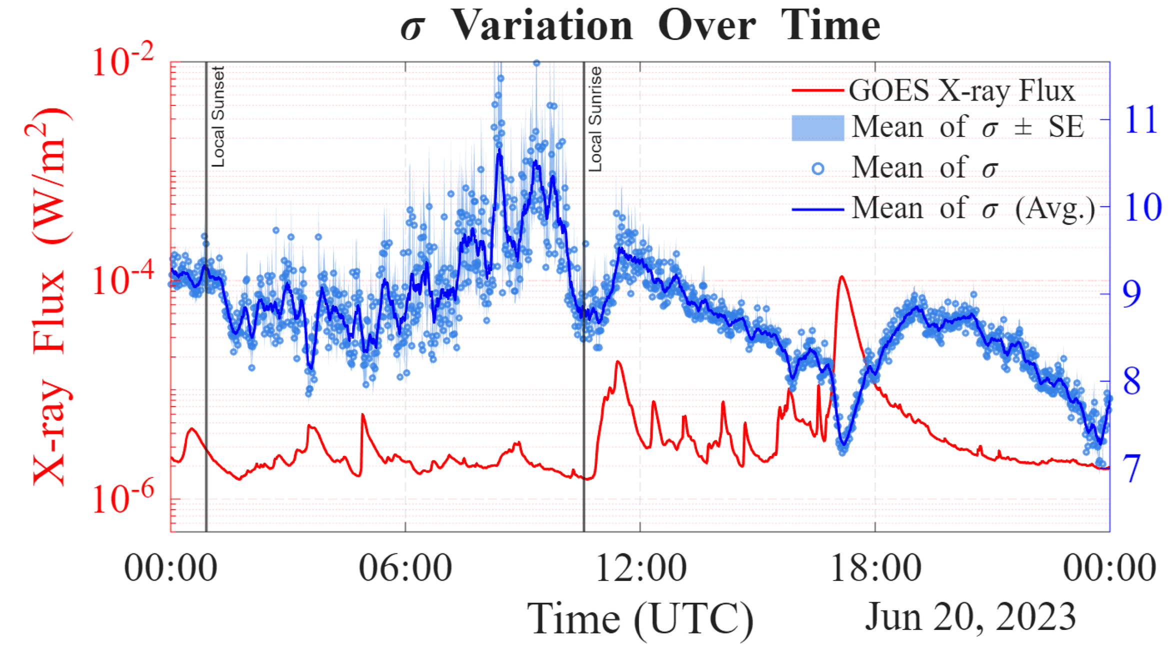
Response to Flare

Sferics detected on **June 20, 2023**, are parameterized and optimized, and sferics with a correlation of <80% are discarded. The one-minute mean is then computed for parameters f_0 and σ, as shown below. Distinct jumps in parameter values are noted at sunrise and sunset, corresponding to changes in D-region characteristics at the day-night terminator, as well as at the time of a mid-day X-class solar flare.

f_0 Variation Over Time

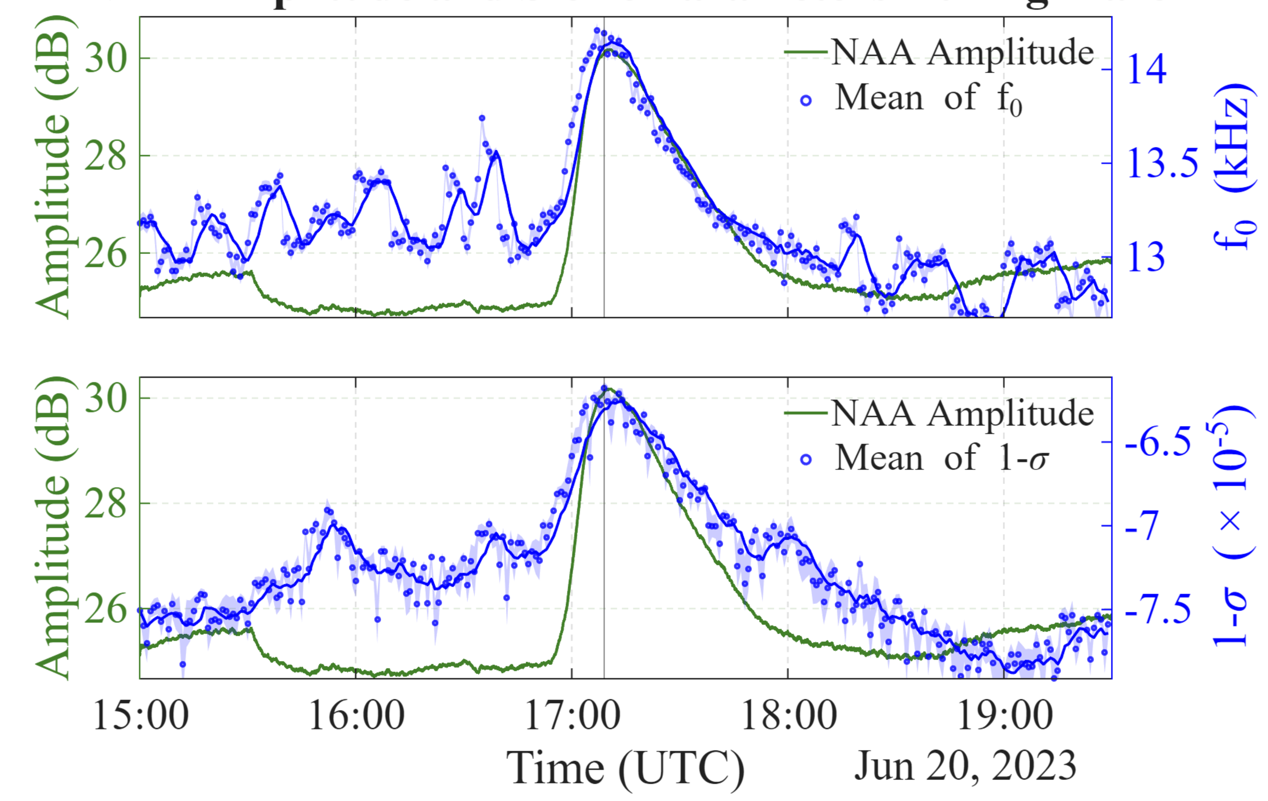


σ Variation Over Time



The mean of the parameters is compared to the amplitude of VLF narrowband MSK transmitter NAA, located in Culter, Maine. Tracking the amplitude of such transmitters is a well-established technique for performing D-region remote sensing. A notable correlation between the incidence of the solar flare (which peaks at 17:09 UTC), a jump in NAA's amplitude, and an increase in f_0 and $1-\sigma$ is apparent. These results indicate that the model is indeed responsive to changes in the D-region triggered by ionospheric disturbances.

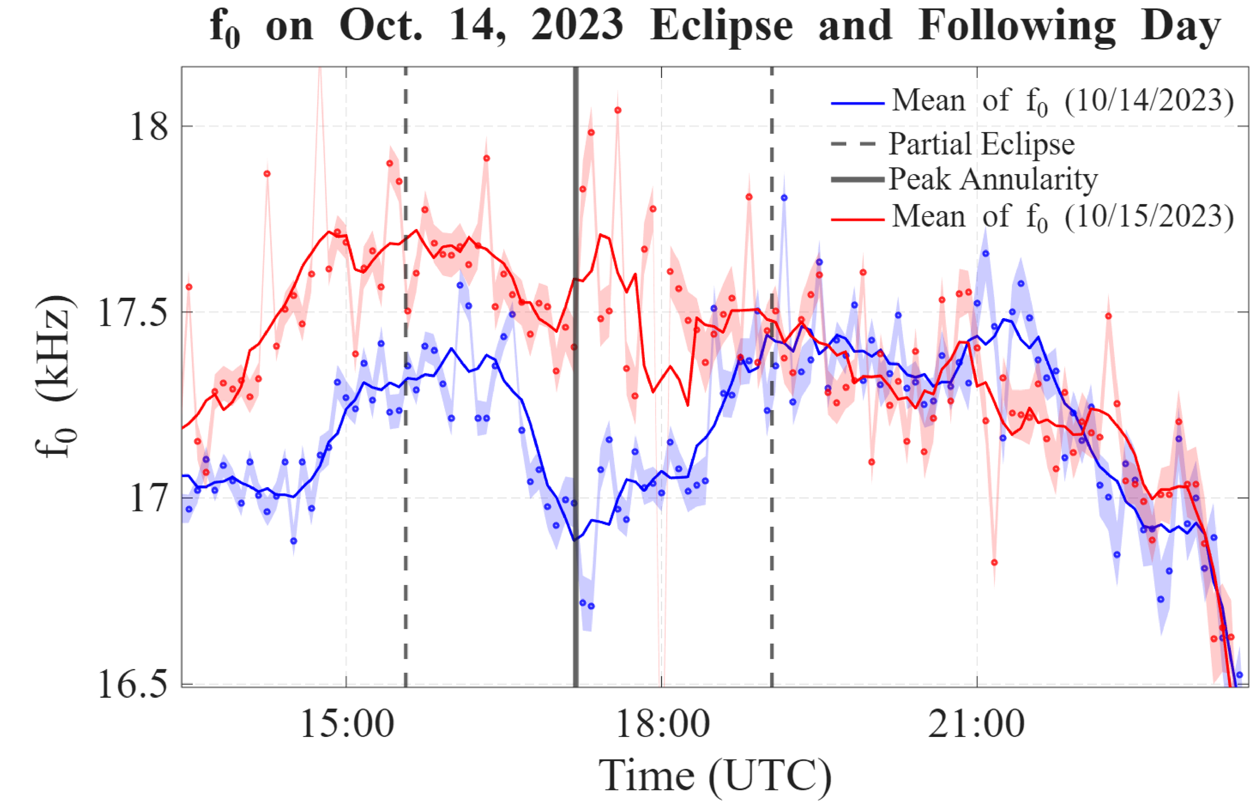
NAA Amplitude and Sferic Parameters During Flare



Response to Eclipse

Sferics originating from near Southern Mexico are isolated based on their apparent angle of arrival during the **October 14, 2023**, eclipse and the following day. A perturbation in f_0 that is not seen on the subsequent day aligns with the time that the path of propagation crosses the path of the eclipse.

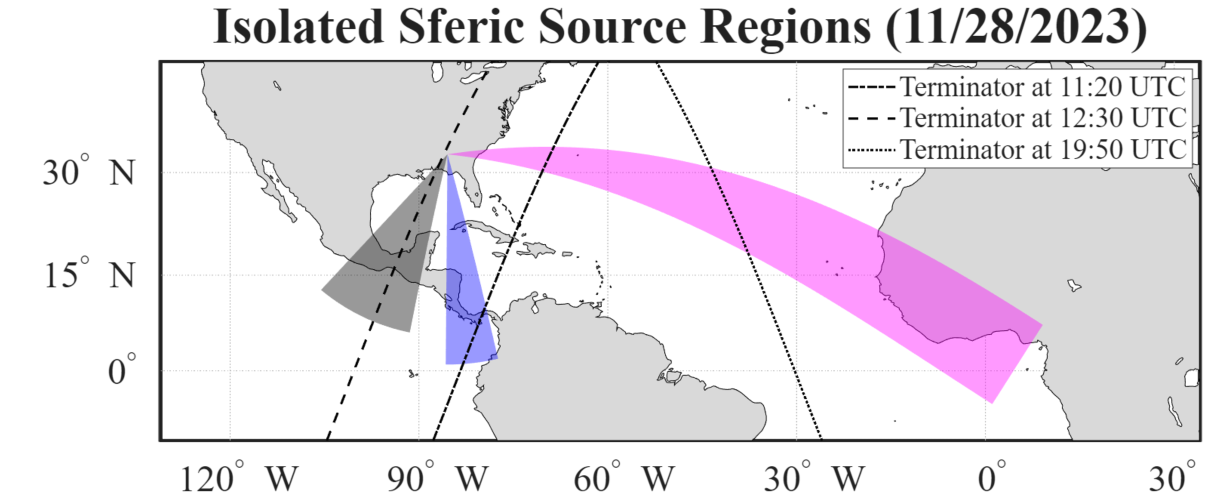
f_0 on Oct. 14, 2023 Eclipse and Following Day



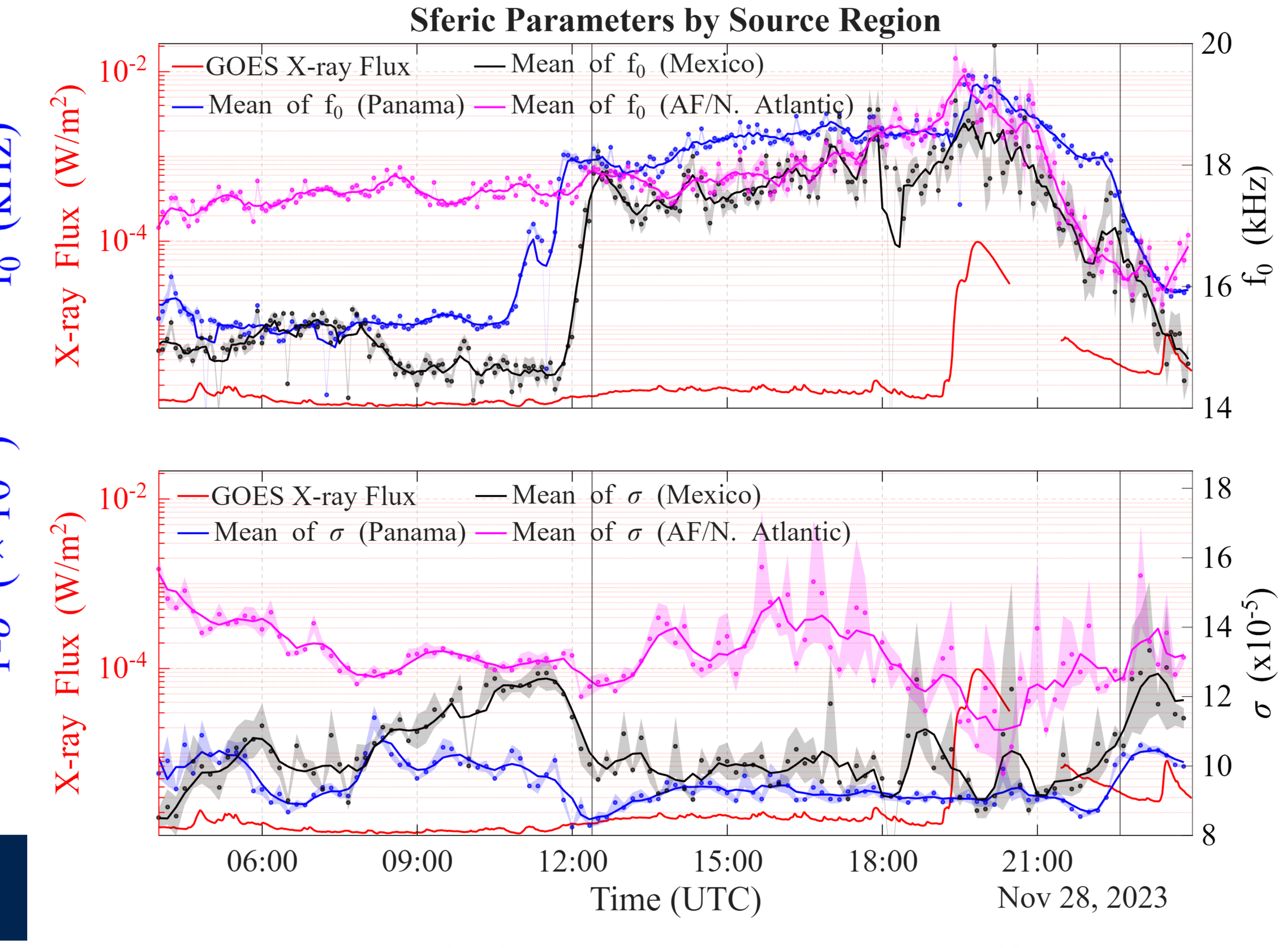
Spatial Variations

Sferics originating from three source regions on **November 28, 2023**, are isolated, and their parameter averages are plotted. The parameters demonstrate varying spatial and temporal characteristics appropriate for the selected propagation paths and known solar flare-triggered ionospheric disturbance.

Isolated Sferic Source Regions (11/28/2023)

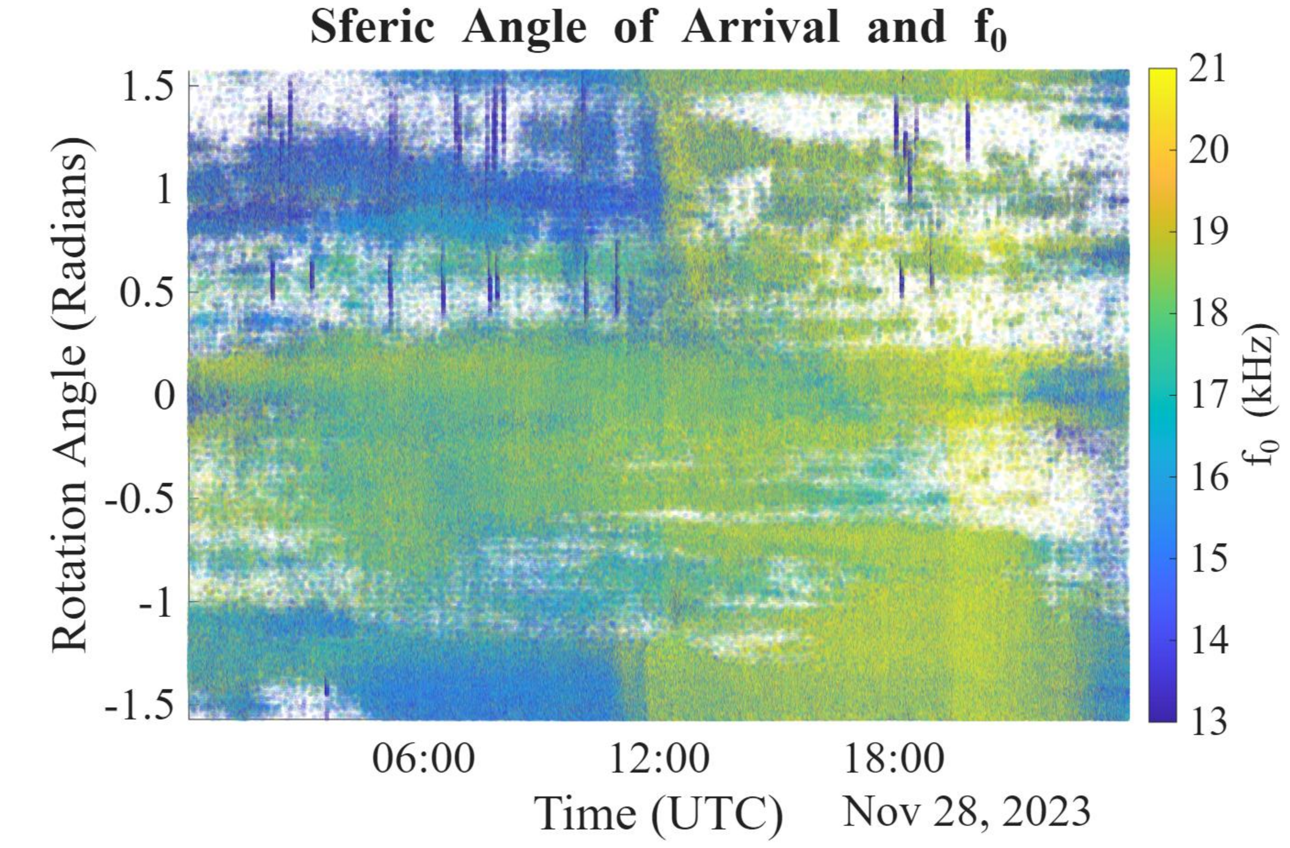


Sferic Parameters by Source Region

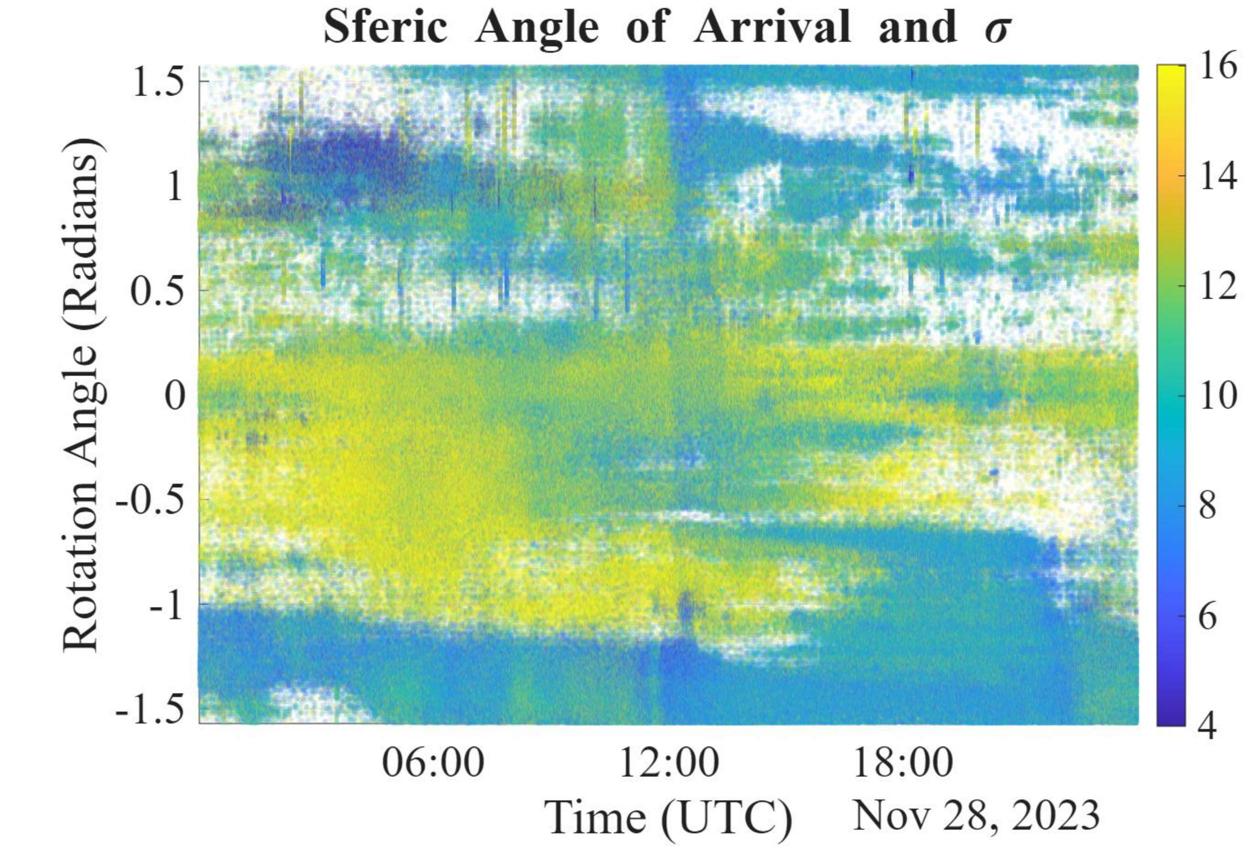


A scatter plot of sferics received from all directions on the same date is color-coded based on parameter values. The plots demonstrate how different storm clusters, and thus different paths of propagation, are often characterized by differing parameter values.

Sferic Angle of Arrival and f_0



Sferic Angle of Arrival and σ



Acknowledgments: The authors would like to acknowledge the use of VLF data collected using equipment provided by Dr. Robert Moore with the University of Florida.