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

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Abstract

The ionosphere's D-region and the Earth's surface form what is known as the Earth-ionosphere waveguide (EIWG), facilitating long-distance propagation of very low frequency (VLF) signals within this waveguide. Lightning discharges emit VLF signals, known as sferics, which can travel hundreds or thousands of miles in the EIWG with little degradation. The characteristics of lightning sferic waveforms are impacted by the D-region along the path of propagation between the source of the strike and the receiver. Thus, sferics are exceedingly useful for remote sensing of the D-region. In this work, we present a parameterized time-domain model of lightning sferics to aid in the analysis of the D-region. The model is then applied to large VLF datasets obtained under typical atmospheric conditions and during abnormal geophysical events, and the resulting variation in sferic parameters is analyzed.

Background

The D-region (50-90 km) plays a critical role in propagation at HF and below and is significantly impacted by space weather events. 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 posses wide spatial variation compared to the limited distribution of VLF transmitters.

The main objectives of this research are to:

- **Develop a physically-meaningful, time-domain parametric model of lightning sferic waveforms.**
- **Show that the model can be used to extract information about changes in the D-region.**

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 **3-20 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:

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

- Take a scaled Rayleigh distribution envelope:

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

- The final expression is:

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

These parameters are optimized using nonlinear constrained optimization in MATLAB such that the correlation between the original and reconstructed sferic waveform is maximized. An example depicting a sferic and its corresponding reconstruction after parameter optimization is shown below.

Sferic Optimization
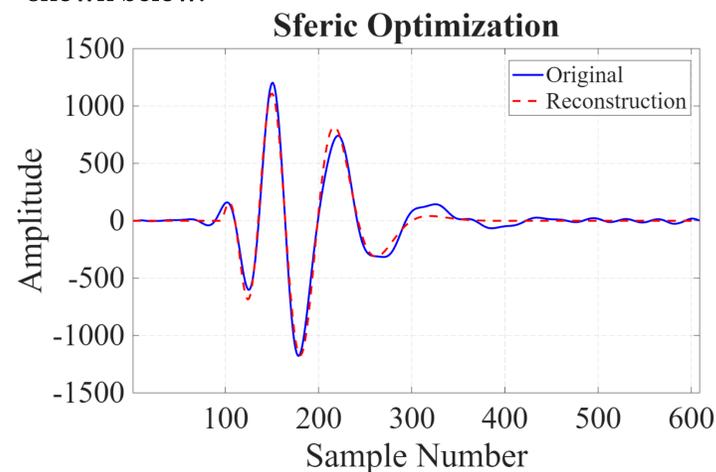
Post-optimization correlation on a selection of tested dates is found to typically be in the **+/- 90%** range during the day when the D-region is most stable. While correlation drops somewhat during the more volatile nighttime hours, correlation generally remains at 80% or better during this period.

Sferic Reconstruction Correlation
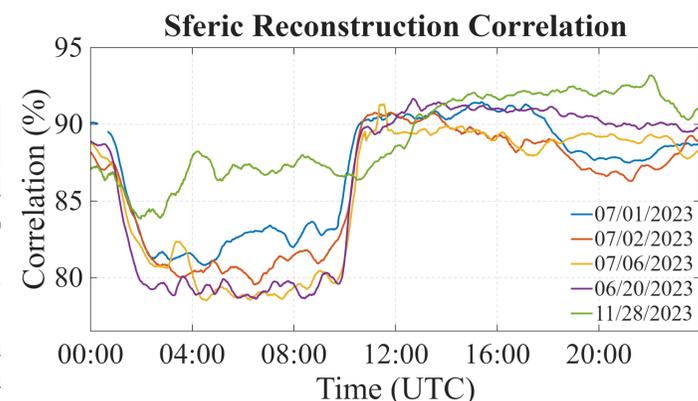
Multi-day Analysis

Sferics detected on three days in July 2023 with little space weather activity 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. Consistent diurnal patterns are observed on each date, and distinct jumps in parameter values are seen at sunrise and sunset, corresponding to changes in D-region characteristics at the day-night terminator.

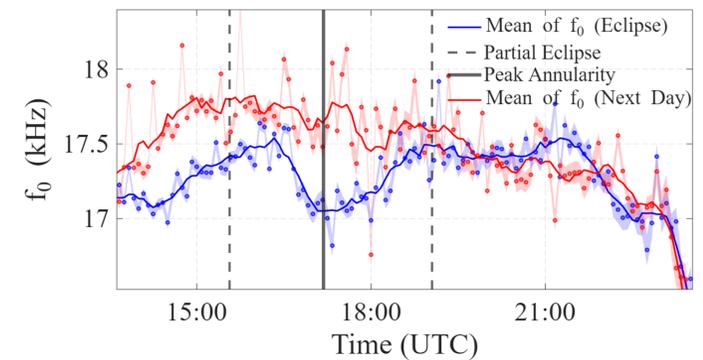**Three-day Sferic Parameter Variations**
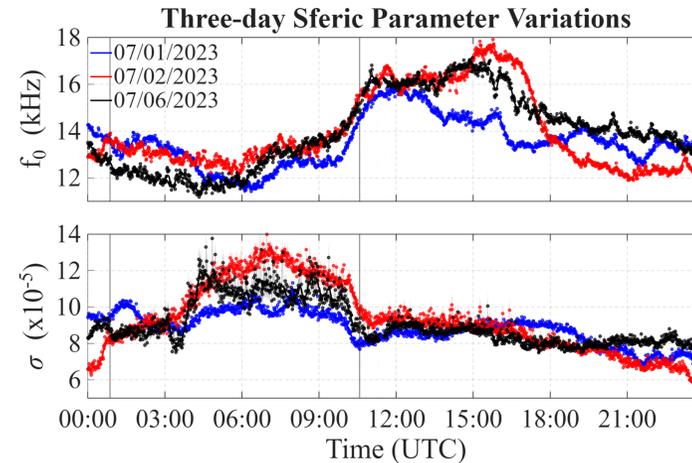
Response to Disturbances

The same process is applied to a date on which an X-class solar flare occurs. 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.

NAA Amplitude and Sferic Parameters During Flare
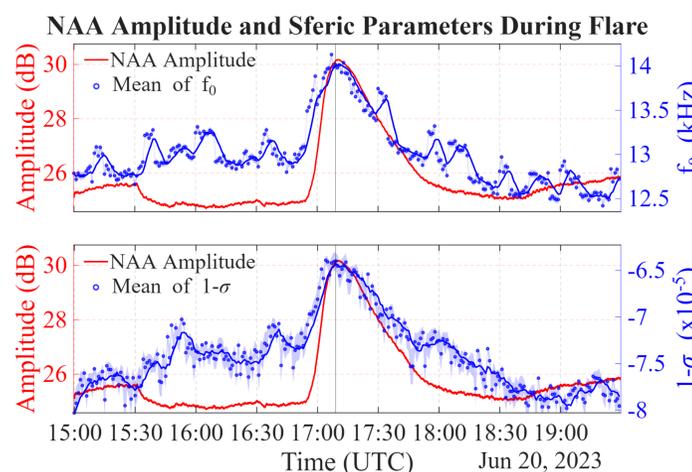
Sferics originating from near Southern Mexico are isolated based on their apparent angle of arrival during the October 14, 2023, eclipse and the following day. A perturbation in f_0 that is not seen on the subsequent day aligns with the time that the path of propagation crosses the path of the eclipse.
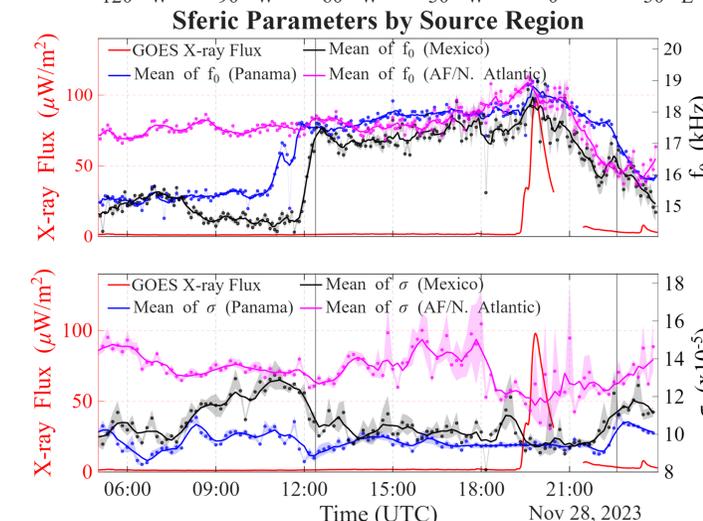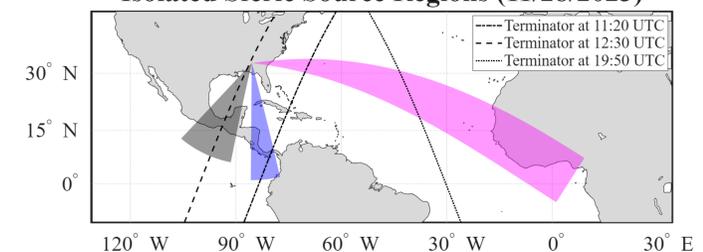
f_0 on 10/14/23 Eclipse and Following Day

Spatial Variations

Sferics from three geographic source regions are isolated and their corresponding parameter averages are plotted. The parameters demonstrate varying spatial and temporal characteristics appropriate for the selected propagation paths and known solar flare ionospheric disturbance.

Isolated Sferic Source Regions (11/28/2023)

Sferic Parameters by Source Region