GROUP VELOCITY OF LIGHTNING INDUCED SFERICS, A COMPARISON
BETWEEN VERY LOW AND EXTREMELY LOW FREQUENCIES

by

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ABSTRACT

Modeling and understanding of the plasma physics in the Earth’s upper ionosphere has always been challenging for scientists. This is due mostly to the variability, complexity, and the inability to conduct direct measurements. The ionosphere is too far for weather balloons and too low for satellites to make direct measurements. Over the past 50 years, ground based stations have been used to obtain some information regarding the ionosphere.

The work done in this thesis adds onto previous work by placing two receivers side by side. One of the receivers records extremely low frequency (ELF: 3-300 Hz) and the other records very low frequency (VLF: 3-30 kHz). The receivers recorded data from July 19-21, 2016. The goal was to see if the group delay and time of arrival differed between the two receivers. This work also extended its analysis to compare differences between day and night with long and short distances.

The goal of this study was to use the time of arrival data to compute the group delay. These measurements could then be used to determine ionospheric height and conductivity.
The form and content of this abstract are approved. I recommend its publication.

Approved: Mark Golkowski
DEDICATION

I dedicate this thesis to my friends and family who have helped me up through my education. I especially want to thank my loving wife who has helped me through long nights of studying for classes and tests. Without the support of her my education might have gone a different path. I would also like to specially thank my grandmother who pasted away March 28, 2017 and my parents who supported my decision to become an Electrical Engineer. Though the path was long and intensive, they were there every step of the process.
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I'd like to specially thank my adviser Mark Golkowski who got me involved in this research. This challenged me to think outside of the text book and really analyze real world problems which helped me become a better engineer.
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CHAPTER 1

INTRODUCTION

1.1 Motivation

This thesis explores how extremely low frequency (ELF: 3-300 Hz) and very low frequency (VLF: 3-30 kHz) electromagnetic waves propagate in the Earth-ionosphere wave guide. Two types of receivers measure the two different frequency bands. These signals are generated from lightning discharges. The arrival time of these lightning induced waves along with information of their source location from lightning detection networks allows for the estimation of group velocity in the Earth-ionosphere wave guide and its frequency dependence. This work involves a comparison of recorded data to theoretical plasma physics as well as assessment of the hardware used in the receivers.

1.2 Scientific Background

1.2.1 Atmospheric Lightning

Meaningful comparison of group delays between VLF and ELF waves generated by lightning requires understanding the source of both waves. Atmospheric lighting is a common meteorological event which is caused by an accumulation of electric charge that occurs between the ground and clouds. A discharge occurs when the electric potential reaches a point in which the electric breakdown of air is exceeded. This causes a path to develop for current to flow from the cloud to the ground. The result is often visible and can carry a significant amount of current on the order of tens to hundreds of kA. Figure 1.1 illustrates this phenomena.
There are three main types of lightning discharges: cloud to cloud, cloud to ground, and ground to cloud. The discharges of interest consist of cloud to ground interactions since they radiate the most energy and thus produce the largest amplitude electromagnetic signals. Figure 1.1 depicts the more common cloud to ground discharge in which negative charge is transferred from the cloud to the ground. This type of discharge is called a negative cloud to ground (-CG) discharge and is more common than the opposite polarity (+CG) since the cloud is typically polarized with negative charge closer to the ground and positive charge at higher altitude. Positive cloud to ground discharges occur less frequently, but can often have a larger peak current. Both -CG and +CG events generate broadband electromagnetic waves with significant content in the ELF and VLF bands. Sometimes, +CG events radiate more ELF content because the process is longer in time. Details on this are presented in Chapter 2.

Chapter 1.2.2 presents further discussion of what frequencies that are trapped in the Earth ionosphere waveguide and which frequencies propagate out into outer space. For now, it is sufficient to say that the ELF and VLF portion of the electromagnetic wave can travel great lengths along the surface of the Earth (sometimes around the
Earth). This is important in the studies of the ionosphere because how these wave propagate can provide information about the physics of the ionospheric plasma.

### 1.2.2 Ionosphere

The ionosphere forms part of the upper atmosphere and gets its name from the word “ion.” An ion is defined as "an electrically charged atom or group of atoms formed by the loss or gain of one or more electrons, as a cation (positive ion) which is created by electron loss and is attracted to the cathode in electrolysis, or as an anion (negative ion) which is created by an electron gain and is attracted to the anode" [4]. The ionosphere is made of electrons and ions, which together form what is known as a plasma.

Plasma can be thought of as the fourth state of matter. Figure 1.2 illustrates the fundamentals of what a plasma is and how it differs from the more common states of matter.

![Figure 1.2: 4th state of matter, plasma [4]](image)

As seen in Figure 1.2 the plasma state is achieved from the gas state after enough energy has been introduced so that electrons are no longer bound to the nucleus. This is because the electrons have enough kinetic energy that they are no longer trapped in the potential energy created by the nucleus. To understand the source of this additional electron energy in the ionosphere, it is important to mention the larger context of the upper atmosphere as shown in Figure 1.3.
The ionosphere is the region in between the gas rich environment that life resides in and the much emptier region of space around the planet. The ionosphere is the region where cosmic radiation from space and solar radiation from the sun interact with the gasses here on Earth. These two types of radiation are the source of the plasma that forms the ionosphere.

The main driver is the sun. Ultraviolet radiation from the sun is absorbed by the atmosphere whose density increases as one gets closer to the surface of the Earth. The increasing neutral gas density causes a peak in the density of free electrons (plasma state) to occur at around 350 km altitude in what is known as the F-region of the ionosphere. The photoionization process causes significant ionization all the way down to the D-region (60 – 90 km).

At night, the sun cannot excite any of the gas and therefore the amount of ionizing energy drops significantly. However, there are other sources from outer space that still have the potential of maintaining a plasma state. The main effect of nighttime radiation is that the D-region no longer resides around 60 km from the surface of the Earth. The D-region is restricted to higher elevations near 90 km.

In this work, the effective height of the ionosphere will be mentioned and calcu-
lated. This is in reference to the height of the D-region since it is the lowest region and the altitude at which ELF/VLF waves reflect as discussed in Chapter 1.2.3.

Plasma has a special property that allows electromagnetic waves to travel in the Earth-ionosphere wave guide. This is because plasma acts as a conductor or an insulator at different frequencies. To better understand, let's first explore what makes a plasma conductive. An important metric in plasma electrodynamic behavior is the plasma frequency which is defined as

$$\omega_{pe} = \sqrt{\frac{N_e e^2}{m \epsilon_0}}$$  \hspace{1cm} (1.1)

Where $N_e$ is defined as the electron density, $e$ is charge of an electron, $m$ is effective electron mass, and $\epsilon_0$ is the permittivity of free space. If an electromagnetic wave has a lower angular frequency than the plasma frequency, the plasma can adapt quick enough to accommodate the changes in amplitude and thus acts like a conductor which can reflect an incident wave. At higher angular frequencies, the plasma cannot react fast enough to the changing fields and thus higher frequencies propagate through the plasma. To visualize this effect, Figure 1.4 which shows the relationship between $\omega_p$ and $k$ which is defined as the wave number.
In Chapter 2 it will be shown that the slope of the dispersion curve provides the group velocity of the wave. For this thesis, this will be a measurable quantity in the VLF and ELF data.

1.2.3 Earth-Ionosphere Waveguide Model

Now that the ionosphere has been shown to act as a good conductor for ELF and VLF waves, let’s examine what makes the Earth a good conductor. Refer to 1.2

\[ \gamma = \alpha - j\beta \]  

(1.2)

Where \( \gamma \) is referred to as the propagation constant while \( \alpha \) is defined as the attenuation constant, and \( \beta \) is defined as the phase constant. Now let’s define what \( \alpha \) and \( \beta \) equal for a good conductor in equation 1.3 and 1.4
\[
\alpha \simeq \sqrt{\frac{\omega \mu_0 \sigma}{2}} \quad (1.3)
\]

\[
\beta \simeq \sqrt{\frac{\omega \mu_0 \sigma}{2}} \quad (1.4)
\]

Where \( \sigma \) is defined as the conductivity of the medium, \( \omega \) is that the angular frequency, and \( \mu_0 \) is the permeability of free space. For VLF and ELF electromagnetic waves the angular frequency is small. For wet soil, the conductivity is roughly \( 10^{-2} \). The result is the attenuation losses and phase constants are relatively small. For a perfect conductor, \( \alpha = \infty \) and \( \beta = \infty \) because \( \sigma = \infty \). Therefore, it is safe to say that the Earth at low frequencies acts as a good conductor.

We can simplify the Earth-ionosphere waveguide by modeling it as a parallel plate waveguide. In this model, a wave can travel in three different types of modes, \( TEM \) or \( TM_0 \), \( TE_m \), and \( TM_m \). To explain what these modes mean it’s useful to visualize as in Figure 1.5.

![Figure 1.5: Propagation modes in Earth ionosphere waveguide][1]

The \( T \) in the modes stands for transverse which means that certain field components will be fully perpendicular to the direction of propagation. The \( E \) and \( M \) refer to electric and magnetic field, respectively. Since lightning discharges, otherwise known as sferics, occur vertically between the so called "plate," the majority of
discharges propagate in the $TM$ and $TEM$ modes.

The effective height of the D-region determines the height of the wave guide. This height can be used to calculate in which modes the wave can travel in. This can be defined using the cutoff frequency which can be equated to,

\[
\omega > \omega_c = \frac{m\pi}{a\sqrt{\mu\epsilon}}
\]

(1.5)

Where we define $a$ to be the height of the wave guide and $m$ as the mode number. The higher the mode number the less the wave guide will support lower frequencies. For ELF and VLF waves, multimode propagation can be supported to about 10 modes.

### 1.3 Comparison to Previous Work

In previous works like that by Mackay [1] VLF and ELF observations of lightning induced waves were compared. The data used in Mackay’s analysis was taken from a single station in Antarctica. The location of this receiver will be further examined in Chapter 2, but for now it’s sufficient to say the data has very little noise. With the low noise environment, Mackay could low pass filter the data to isolate ELF content.

The motivation for this thesis came from conducting a different experiment than was done by Mackay. Mackay was interested in using single station observations as a method of global lightning geolocation. Here we investigate the inverse problem in that we use lightning location data from the GLD360 network and compare the observed propagation velocity to ionospheric conditions. In this experiment, two different receivers will be used. As stated before, a VLF and an ELF station will be deployed next to one another. This is done for a few reasons. First, the ELF receiver is specifically designed to record ELF data. This is important because the traditional wire loop antennas and hardware related configurations used in the VLF systems have poor performance in the ELF range. Using the ferrite magnetic antennas, the quality
of the ELF data is increased. Secondly, the path of propagation will be the same for the two receivers. This allows a one to one comparison on the group delay since they will be traveling on the same path.

1.4 Outline

Chapter 2 will give some background on how the ionosphere affects sferic propagation. In Chapter 3, a discussion about the experimental work that recorded the data for both ELF and VLF receivers. This will include a brief summary of the equipment, location, and process of how the data was obtained. Chapter 4 is dedicated to presenting the recorded data. This includes 10 cases of daytime short distances, 10 cases for daytime long distances, 10 nighttime short distances and finally 10 nighttime long distances. In the last chapter, the recorded data will be compared to the theory presented in Chapters 1 and 2. Statistical tests are used to quantitatively compare and contrast all four cases.
CHAPTER 2

SLOW TAIL PROPOGATION

In this chapter, analysis of VLF and ELF waves in the Earth-ionosphere waveguide will be presented. This will include an in depth look at a sferic in the time domain in Chapter 2.1. In Chapter 2.2, the sferics will be broken down into their respective VLF and ELF content, and it will be shown how the time of arrival for ELF electromagnetic waves often lags that of the VLF portion. Lastly Chapter 2.3, will present equations derived from other works that can compute characteristics of the ionosphere using the time of arrival and group delay.

2.1 Sferics in Time Domain

There are often two ways to look at a signal: in the time domain and in the frequency domain. For the purposes of this thesis, the time domain will be used exclusively. This is because the purpose of this work is to determine the arrival time and group delay of the sferics. While spectrograms (frequency domain with time information) can be used as well, the sferics often can last up to a couple of milliseconds. Determining the time of arrival on a spectrogram, while not impossible, tends to be limited by the length of window in the short-term Fourier transform and is therefore inaccurate.

A typical sferic waveform is shown in Figure 2.1. The VLF receiver was designed to record up to 50 kHz signals. The data is sampled at 100 kHz. This gives rise to detailed waveforms and thus detecting time of arrival is considered to be more accurate than ELF signals which will be discussed later on in this section.
Figure 2.1: Time domain of VLF sferic

The figure presented in 2.1 plots an averaged amplitude over a period of time (in this case 3 ms). The reason the amplitude is averaged is so that the positive and negative values can be represented. We can see that the sferic spans a time of about 0.5 ms. That being said, there is a lot of activity that can be seen at the beginning of the signal and then attenuates near the end.

The waveform of these signals depicts how these signals propagate. Each peak that represents different reflections off the Earth ionosphere wave guide. The first peak in this figure is the wave that has little or no reflections off the wave guide and is known as the ground wave. Hence, it is the fastest traveling part of the wave. The following peak is the part of the wave that may have bounced off the wave guide a couple of times and therefore arrives later. This continues until all of the wave has arrived at the recorded station. For such a complicated waveform it is important to define a time of arrival. Here it is defined by the first sharp peak. In figure 2.2 the time of arrival is defined at 9.53 ms. This will be the metric as to when all VLF signals time of arrival occurred.
Now let’s look at what the ELF data looks like in the time domain. The recorded ELF data is coarser in nature due to its low sampling frequency which is about 800 Hz. Compared to the VLF sampling frequency, the time of arrival is harder to resolve. This will be explained further in Chapter 3. However, in Figure 2.3 the time of arrival can still be determined by picking the first peak of the waveform. Figure 2.2 and 2.3 are recordings of the same sferic. Time of arrival was calculated for 2.2 as being 9.53 ms, but in 2.3 this is found to be 14.64 ms. This is not compensating for any hardware corrections that will need to be done which will be discussed in Chapter 3 in detail.

2.2 Slow Tails

In this chapter, the waveform of a sferic will be characterized into its VLF and ELF content. The figures presented here come from the work by Mackay [1] and Mark Golkowski’s course lecture notes [2] which highlight what portion of the waveform is characterized as the slow tail. This is best summarized in Figure 2.4, which shows a sferic VLF and ELF content.
Figure 2.4: The upper plot shows an example sferic. The bottom is a low passed sferic highlighting the ELF content and the slowtail \cite{1}

The slowtail can be seen as the ELF content of the waveform that is delayed in time from the initial VLF content.

The bottom panel of Figure 2.4 was created by applying a low pass filter to the data in the top panel. In Chapter 1.2.3 the Earth ionosphere wave guide was defined, and it was stated that it can be approximated as a parallel plate waveguide. This can also be shown using a spectrogram which combines frequency and time domain as illustrated in 2.5
Figure 2.5: Spectrogram of sferics highlighting group velocity near cutoff [2]

The red and yellow in 2.5 represent the magnitude of the sferics that are represented by the vertical lines. From 2.5 we can see that around 1.8 kHz the sferic is no longer vertical. This indicates that the waveform is being slowed down. For the lowest $TE_1$ and $TM_1$ modes this occurs around 1.8 kHz.

Up to this point, effects of the plasma on the sferic have been negated. It has been shown that in an ideal parallel wave guide that the group velocity decreases near the cutoff frequency. This assumes the boundaries are perfectly conducting materials and therefore the sferic sharply reflects off the ionosphere. In reality, this is not the case. Rather at lower frequencies, the sferic’s waveform travels deeper into the plasma causing greater dispersion which in turn causes a decrease in group velocity.

In Chapter 1.2.2 the dispersion relationship of a plasma was presented. This is shown in Figure 1.4. Here, it was shown that the slope of the line was related to the group velocity of the wave propagating through the plasma. At lower frequencies above the plasma frequency, the slope is shown to be less than that of higher frequencies. This
effect can also be seen in 2.6.

2.3 Earth-Ionosphere As A PEC Waveguide

For VLF waves, the bounds of the Earth-Ionosphere waveguide can be thought of as a perfectly electric conductor (PEC). Reviewing waveguide theory examine Equation 2.1 which defines what the cut off frequency is.

\[ F_c = \frac{mc}{2h} \]  \hspace{1cm} (2.1)

Here, \( c \) is the speed of light, \( m \) is mode number, and \( h \) is the vertical height of the wave guide. For the daytime ionosphere height, we can assume the D-region resides at 70 km. The cut off frequency for the first mode using these values computes to 2.14 kHz.

The wave speed can then computed by using Equation 2.2. As the frequency increases, the wave speed increases until it reaches the speed of light. This is shown in Figure 2.3

\[ v_g = c \sqrt{1 - \left(\frac{F_c}{f}\right)^2} \]  \hspace{1cm} (2.2)
The way scientists have validated that the ionosphere acts like a PEC is through measurements of ground based stations. If the ionosphere was a PEC for VLF sferics, then the waves would be sharply reflected. This would then validate Equations 2.1 and 2.2 because those are the models for a PEC parallel plate waveguide. This can be seen in data recorded in this thesis on July 20th in Hugo.
Figure 2.8: VLF data recorded on July 20, 2016 in Hugo. Red line indicates the arrival time traveling at the speed of light.

The beginning of the time plot indicates when the GLD network detected the sferic. The vertical red line takes the distance from the sferic and receiver and divides by the speed of light. This gives the time of arrival. What is shown is that the waveform lines up exactly with the theoretical time of arrival if it were traveling at the speed of light. Ultimately, this proves the Earth-Ionosphere waveguide can be thought of as a PEC parallel plate for VLF sferics.

### 2.4 Realistic Model Of Waveguide At ELF

ELF sferics propagate differently in the Earth-Ionosphere waveguide. This is because the interactions with the plasma cannot be represented with the PEC model. As stated in Chapter 2.2, there are plasma effects that alter the height of the wave guide. This is frequency-dependent and can be seen in Figure 2.9. From this, it is notable that lower frequencies from the top plot, the magnetic field goes propagates deeper into the plasma. This in turn causes the bottom plot which shows how the group velocity slows down compared that of the higher frequencies.
This is shown mathematically by defining the boundaries. There are the conduction boundary which acts on the electric field height $h_e$ and the diffusion boundary which governs $h_m$. These two boundaries are defined by the height dependent conductivity within the plasma. $\sigma(z)$ represents this quantity which can be explained by Equation 2.3.

$$\sigma = \varepsilon_0 \omega$$  \hspace{1cm} (2.3)

$$\omega = \frac{1}{4\mu_0 \xi^2}$$  \hspace{1cm} (2.4)

$$\xi = \frac{1}{\sigma} \frac{d\sigma}{dz}$$  \hspace{1cm} (2.5)

Let us now explore how this affects the arrival time of the sferic. In Mackay [1] the time of arrival is a function of propagation distance $\rho$, reflection height $h$, conductivity $\sigma$ which was defined in 2.3, and pulse width (in seconds) denoted as $\delta$. Together, these form Equation 2.6.

$$t_s = 0.09 \left( \frac{\rho}{2h} \sqrt{\frac{\varepsilon_0}{\sigma}} + \sqrt{\delta} \right)^2$$  \hspace{1cm} (2.6)
2.5 Chapter 2 Conclusion

In this chapter, the propagation of slowtails was examined. Chapter 2.1 highlighted time domain information which defined the arrival time for both VLF and ELF waves. This will be important in further chapters because the statistical modeling will investigate these arrival times. In Chapter 2.2, slowtails were isolated by their frequency content. VLF waves account for the portion of the sferic that arrives the quickest. The ELF content of the wave doesn’t arrive until later in time. This was explained by looking at what happens near the cutoff frequency in the lower modes. It was found that this gives rise to what defines a slowtail. In Chapter 2.3, the Earth-ionosphere waveguide was modeled as a PEC parallel plate waveguide, which is a reasonable first order approximation for VLF wave propagation. Lastly, Chapter 2.4 examined how ELF sferics propagate in the Earth-ionosphere waveguide. It was shown that these waves travel further into the plasma. This results in using alternative equations to determine time of arrival as shown by Mackay [1].
CHAPTER 3

EXPERIMENTAL SETUP

This chapter highlights the authors contribution to the study of slowtails. In Chapter 3.1, the Electromagnetics and Plasma Physics Research Groups VLF receiver sites will be presented. Chapter 3.1.1 will explain the VLF receivers hardware. This will include calibrations, setup, and the network of receivers the University of Colorado Denver (UCD) Electromagnetics and Plasma Physics Research Group currently operates. Chapter 3.2 will discuss the ELF receiver used. This will include the design of the Krakow ELF group from Poland which is hosted by UCD. Chapter 3.3 will then cover how the experiment was designed and executed.

3.1 VLF Receivers

The Electromagnetics and Plasma Physics Research Group has five VLF receivers. One of the sites resides on a small island south of Kodiak Island named Akhiok in Alaska. Akhiok is a small village of Alaskan natives whose population is less than 100. The receiver is setup inside the school house which houses about 20 students ranging from kindergarten to high school. We were able to obtain this location by coordinating a series of outreach programs designed to get students interested in science and math. So far, these interactive programs have involved educating students on the fundamentals of static electrical charges using Van de Graff generators. Our efforts also lead students to learn basic programming and digital hardware implementations using Arduino micro-controllers. The VLF antenna at this site can be seen in Figure 3.1. This site was deployed in 2013 by the author and undergraduate research assistant Brad Fox.
North of that location in Alaska resides the group’s Paxson site near the High Frequency Active Auroral Research Program (HAARP) facility in Gakona, Alaska. The Paxson site was originally operated and maintained by the Stanford VLF research group. In 2014, UCD’s Electromagnetics and Plasma Physics Research Group flew out there and brought the receiver back online and has maintained it since. This site can be seen in Figure 3.2
Moving to the Eastern United States, the group hosts a VLF receiver on the roof of the North Classroom building located on the Auraria campus home to the Electrical Engineering department. This site was established mainly for hardware testing of existing and future systems. While the data is often noisy due to the power consumption of the building itself and being in the heart of downtown Denver it still processes valuable information the group can use in their study of the ionosphere.

On the East coast, the group has a VLF receiver near Warsaw, Virginia. This was the group’s second receiver to make up their VLF network. The site is located on a technical high school facility called Rappahannock Community College. Like Akhiok, outreach programs have been implemented to get students involved with science and math. Ashanthi Maxworth, one of the groups PhD students has worked with the students to record mosquito mating calls to generate spectrograms which help students locate and better understand biology. The school is heavily involved in biology studies so the programs are tailored to their curriculum. This site can be seen in Figure 3.3.
The group’s first receiver was deployed in Ithaca, New York in a remote location on private property. This site provides valuable data because the site is not near major power lines and other electromagnetic sources of noise. Since this site is so remote, internet connection is slow and impossible to transfer data over the network. Because of this, the only way to transfer data between the site and the groups servers is hard drive exchanges via the postal service.

These five sites mark the Electromagnetics and Plasma Physics Research Group at UCD VLF network. A complete map of these locations can be found in Figure 3.12.
3.1.1 VLF Hardware

The receiver system is based on a legacy design out of Stanford University called Atmospheric Weather Electromagnetic System for Observation, Modeling, and Education or AWESOME system [10]. The specific design used by the UCD group was obtained from the University of Florida and is referred to as the Nemesis. This system was designed to record frequencies 300 Hz-48 kHz. This system includes a desktop computer with a National Instruments DAQ PCI card. The computer is connected to the receiver and GPS module. The GPS sources the sampling frequency that is synched with a time synchronized 1pps waveform. This allows all receivers to be synchronized in timing when recording data. The receiver is then attached to the pre-amp box which then in turn is connected to two wired loop antennas. A basic overview can be seen in Figure 3.5.

![Figure 3.5: Simple outline of Nemesis receiver](image)

To begin, let us first look at the antennas. The receiver consists of two orthogonal wired loop antennas. Since the wavelength of the frequencies recorded by this receiver
are so large compared to the size of the antennas, they can be considered as electrically small magnetic dipoles. FEKO software was used to show what the radiation pattern looks like for a small magnetic dipole. This is shown in Figure 3.6. The antenna is sensitive to horizontal magnetic fields and has a directivity in the plane of the loop.

![Radiation pattern of small magnetic dipole](image)

**Figure 3.6: Radiation pattern of small magnetic dipole**

The simulated antenna was the smallest antenna size used for the Nemesis which is a 12 turn wired loop antenna. The antenna can be simplified into a circuit model in the receiving mode like in Figure 3.7.
Mathematically the input impedance can be shown to be \( Z_{in} = R_a + jX_{in} = (R_r + R_l) + j(X_a + X_i) \) in which \( R_r \) is denoted as the radiation resistance, \( R_l \) is the ohmic resistance, \( X_a \) is the external inductance and finally \( X_i \) is the high frequency inductance.

It is important to note that the antennas can be constructed in different sizes. Larger antennas typically yield an improved signal to noise ratio so when possible, the larger sizes are used. A breakdown of the different sizes with their antenna characteristics can be shown in Table 3.2. The antenna used in this thesis was the right isosceles triangle with an area of 1.695 \( m^2 \) in Table 3.2.
Table 3.1: Possible antenna sizes and their properties [8]

<table>
<thead>
<tr>
<th>Shape</th>
<th>Size, side or base</th>
<th>Wire AWG</th>
<th>$N$</th>
<th>$R_a$</th>
<th>$L_a$</th>
<th>$f_a$</th>
<th>$A$</th>
<th>$S_0$</th>
<th>$M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>square</td>
<td>16.0 cm</td>
<td>20</td>
<td>47</td>
<td>1.002</td>
<td>0.998</td>
<td>159.8</td>
<td>0.02563</td>
<td>5.03x10^{-3}</td>
<td>0.132</td>
</tr>
<tr>
<td></td>
<td>56.7 cm</td>
<td>18</td>
<td>21</td>
<td>1.006</td>
<td>0.994</td>
<td>160.9</td>
<td>0.3219</td>
<td>8.96x10^{-4}</td>
<td>0.331</td>
</tr>
<tr>
<td></td>
<td>1.70 m</td>
<td>16</td>
<td>11</td>
<td>0.987</td>
<td>1.013</td>
<td>155.0</td>
<td>2.892</td>
<td>1.89x10^{-4}</td>
<td>0.831</td>
</tr>
<tr>
<td></td>
<td>4.90 m</td>
<td>14</td>
<td>6</td>
<td>0.972</td>
<td>1.029</td>
<td>150.5</td>
<td>24.05</td>
<td>4.13x10^{-5}</td>
<td>2.09</td>
</tr>
<tr>
<td>right</td>
<td>2.60 m</td>
<td>16</td>
<td>12</td>
<td>0.994</td>
<td>1.005</td>
<td>157.5</td>
<td>1.695</td>
<td>2.97x10^{-4}</td>
<td>0.838</td>
</tr>
<tr>
<td>isosceles</td>
<td>8.39 m</td>
<td>14</td>
<td>6</td>
<td>1.004</td>
<td>0.996</td>
<td>160.3</td>
<td>17.59</td>
<td>5.74x10^{-5}</td>
<td>2.15</td>
</tr>
<tr>
<td>triangle</td>
<td>27.3 m</td>
<td>12</td>
<td>3</td>
<td>1.035</td>
<td>0.967</td>
<td>170.3</td>
<td>187.0</td>
<td>1.10x10^{-5}</td>
<td>5.56</td>
</tr>
<tr>
<td></td>
<td>60.7 m</td>
<td>10</td>
<td>2</td>
<td>0.959</td>
<td>1.043</td>
<td>146.3</td>
<td>920.9</td>
<td>3.22x10^{-6}</td>
<td>13.1</td>
</tr>
<tr>
<td></td>
<td>202 m</td>
<td>8</td>
<td>1</td>
<td>1.005</td>
<td>0.995</td>
<td>160.9</td>
<td>10164</td>
<td>5.97x10^{-7}</td>
<td>34.5</td>
</tr>
</tbody>
</table>

The antennas connect to the N/S and E/W channel of the pre-amp box. The pre-amp box design consists of the daughter board, line-matching transformers, and pre-amp cards. The inside of the pre-amp box is shown in Figure 3.14. Each channel has a pre-amp card to amplify the signal. The pre-amp cards have a gain of approximately 10 dB. The signal is sent in differential form in order to reduce noise coupling when the signal is sent to the receiver. The signal is sent through a 1000 foot 14 pin cable that is normally fed through a building to the receiver. The cable is often as long as possible in order to place the antennas as far away from noise sources.

Figure 3.8: Inside the pre-amp box of Nemesis system
Once the signal enters the receiver, it then travels through the filter cards. This acts as an anti-aliasing filter restricting the bandwidth before the analog to digital converter so that the Nyquist theorem can be satisfied. The filter cards have a 12th order elliptical filter that has a -3 dB roll off at 47 kHz. The frequency response and group delay of the Nemesis can be shown in Figure 3.9.

![Frequency and group delay of VLF receiver](image)

The receiver also takes in a series of timed pulses used for synchronizing of time and sampling. The signals are fed in from the programmable GPS module. The GPS module outputs a 1 pps and a 100 kHz pps. The 1 pps syncs the GPS time for accurate timing. The 100 kHz pps synchronizes the sampling frequency at the NI DAQ card. The receiver has a series of optional op-amps to provide an extra 30 dB gain to the signals.

Finally the signals are combined and sent to the computer via National Instruments cable that feeds into the DAQ card. A RS-232 serial cable also feeds into the computer from the GPS module to send in the UTC time which is used as a header within the .mat files. The recording software from University of Florida allows configuration of the recordings. This includes narrowband configuration to tune into Navy transmitters and continuous/synoptic recording settings.

In 2015, the Stanford VLF Group officially disbanded their research. In the fall of 2016, the author had the opportunity to fly out to Stanford University and retrieve
old equipment. It was here that the group began implementing a hybrid system. The Stanford receivers were similar to the Nemesis system, but had several changes in order to get better performance in frequency response and noise reduction. The Stanford receivers are shown in Figure 3.10.

Figure 3.10: Stanford receiver system. Antenna structure (upper left), pre-amplifier (upper middle), receiver (upper right), and block diagram (bottom).

The major system difference between the Nemesis and Stanford receiver was the use of an internal GPS module. In Stanford’s receivers, a FPGA and crystal oscillator were used to generate the 1 pps and 100 kHz pps signals. While this made the receivers more compact and cheaper to produce, the leading issue was the timing synchronization with the GPS. Since the receiver used the crystal oscillator, it was susceptible to temperature variations. This would cause drifts in timing. Since the purpose of this work was to obtain very accurate timing data acquisition to determine time of arrival of the sferics, a hybrid system was devised.

The hybrid system would use the pre-amplifier of the Stanford system and the
receiver, GPS module, and software of the Nemesis system. This allowed for low noise response and precise timing of data. The hybrid system was used for the observations presented in this thesis.

Before the system could be used, a calibration needed to be done to ensure accurate data was being recorded in post-processing. To conduct the calibration, MATLAB was used to interface with a signal generator. The signal generator was fed into the pre-amp box via a BNC connected to a dummy loop. The dummy loop was designed to use a voltage divider to divide the signals amplitude down to levels normally seen by the receiver. The dummy loop also imitated the impedance of the antenna by using inductors and capacitors. The calibration code would then frequency and amplitude sweep signals that were being recorded by the software at the same time. This allowed the frequency response to be determined and therefore allow correction factors to be implemented. The calibration used in this experiment can be shown in Figure 3.11.
3.2 ELF Receiver

The ELF receiver used in this experiment came from the Krakow ELF group in Poland [11]. The group is comprised of two institutions, Astronomical Observatory of the Jagiellonian University (JU) and Faculty of Electronics of the AGH University of Science and Technology (AGH). The group began their measurements back in 1992. So far, the group has won two awards for their work: 2010 - Bronze medal on Geneva Inventions Salon and 2011 - Congratulation Letter from Polish Ministry of Higher Education. Their work has also been important in the investigation of gravity waves that were detected in 2016 [12].

Today, the group has a total of three ELF receivers. The first station deployed was in Poland in the group's home country. The group, with the help of Mark Golkowski, partnered up with the UCD Electromagnetics and Plasma Physics Group. The collaboration led to the second receiver deployment in Hugo, Colorado where the UCD Electromagnetics and Plasma Physics Group now services the station. The site started recording data in 2015. The newest station the Krakow group deployed was in Patagonia in Argentina. A map of their sites can be found in Figure 3.12.

![Map of ELF receivers](image)

Figure 3.12: Map of ELF receivers [9]

3.2.1 ELF Hardware

While the Krakow ELF group have has six different editions of their receiver, the systems operate in a similar fashion. To start, the antennas used are made out of a
ferrite material that generates a constant magnetic field with a DC voltage supply. The magnetic field is disrupted when the magnetic field of the sferic interacts with the constant magnetic field. It is here that a signal can be generated. Since these antennas are very sensitive, the antennas are buried underground. This prevents any movement that might occur. Even moving the antennas slightly would induce noise as the Earth’s magnetic field perturbs the constant magnetic field generated by the antennas. From the antennas, the signal then travels down a cable and feeds into its respective channel, N/S and E/W. The antenna’s characteristics can be found in Table 3.2.

Table 3.2: ELF antenna parameters [9]

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>AE1000</th>
<th>AE600</th>
<th>AA1000</th>
<th>AA1130</th>
<th>AA1500</th>
<th>AA1130</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of units</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>6</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>bandwidth (-60dB)</td>
<td>50 Hz</td>
<td>60 Hz</td>
<td>150 Hz</td>
<td>150 Hz</td>
<td>75 Hz</td>
<td>400 Hz</td>
</tr>
<tr>
<td>length</td>
<td>1000 mm</td>
<td>600 mm</td>
<td>1000 mm</td>
<td>1130 mm</td>
<td>1500 mm</td>
<td>1130 mm</td>
</tr>
<tr>
<td>diameter</td>
<td>100 x 100 mm</td>
<td>150 mm</td>
<td>60 mm</td>
<td>90 mm</td>
<td>90 mm</td>
<td>90 mm</td>
</tr>
<tr>
<td>weight</td>
<td>25 kg</td>
<td>12 kg</td>
<td>13 kg</td>
<td>20 kg</td>
<td>13 kg</td>
<td></td>
</tr>
<tr>
<td>noise at 10 Hz</td>
<td>0.2 pT/Hz^1/2</td>
<td>0.05 pT/Hz^1/2</td>
<td>0.05 pT/Hz^1/2</td>
<td>0.01 pT/Hz^1/2</td>
<td>0.015 pT/Hz^1/2</td>
<td></td>
</tr>
<tr>
<td>power supply</td>
<td>-</td>
<td>-</td>
<td>10 V/25 mW</td>
<td>10 V/25 mW</td>
<td>10 V/25 mW</td>
<td>10 V/120 mW</td>
</tr>
</tbody>
</table>

The Krakow receiver system is fully autonomous. The receiver runs off of three deep cycle marine batteries that are connected in parallel. The station can run on this battery bank for two months at a time. After those two months, a new set of fully charged batteries need to be installed. The data is stored on a SD card which is retrieved at the same time as the battery swap occurs. The specifications of the receiver can be found in Table 3.3. The version deployed in Hugo is the ELA10.
Table 3.3: ELF receiver specifications for all six editions [9]

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>ELA1</th>
<th>ELA2</th>
<th>ELA4</th>
<th>ELA6</th>
<th>ELA7</th>
<th>ELA9</th>
<th>ELA10</th>
</tr>
</thead>
<tbody>
<tr>
<td>purpose</td>
<td>expeditions</td>
<td>expeditions</td>
<td>automatic recordings</td>
<td>continuous recordings</td>
<td>expeditions</td>
<td>continuous recordings</td>
<td></td>
</tr>
<tr>
<td>antennas</td>
<td>AB1000</td>
<td>AB600</td>
<td>AA1000</td>
<td>AA1000</td>
<td>AA1130</td>
<td>AA1130</td>
<td>AAS1130</td>
</tr>
<tr>
<td>ADC</td>
<td>12 bit</td>
<td>12 bit</td>
<td>16 bit</td>
<td>16 bit</td>
<td>16 bit</td>
<td>16 bit</td>
<td></td>
</tr>
<tr>
<td>bandwidth</td>
<td>0.03-60 Hz</td>
<td>0.03-20/40/60 Hz</td>
<td>0.03-60 Hz</td>
<td>0.03-60 Hz</td>
<td>0.03-60 Hz</td>
<td>0.03-300 Hz</td>
<td></td>
</tr>
<tr>
<td>sampling</td>
<td>185/240 Hz</td>
<td>50/100/130 Hz</td>
<td>175 Hz</td>
<td>175 Hz</td>
<td>175 Hz</td>
<td>950 Hz</td>
<td></td>
</tr>
<tr>
<td>data storage</td>
<td>laptop</td>
<td>laptop</td>
<td>card CF/1GB</td>
<td>card CF/4GB</td>
<td>card CF/4GB</td>
<td>card CF/32GB</td>
<td>card CF/32GB</td>
</tr>
<tr>
<td>GPS time</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>time error</td>
<td>minutes</td>
<td>30 s/month</td>
<td>30 s/month</td>
<td>500 µs</td>
<td>500 µs</td>
<td>200 µs</td>
<td></td>
</tr>
<tr>
<td>battery</td>
<td>6 x R20</td>
<td>12 V / 12 Ah</td>
<td>12 V / 260 Ah</td>
<td>12 V / 260 Ah</td>
<td>12 V / 260 Ah</td>
<td>12 V / 260 Ah</td>
<td></td>
</tr>
<tr>
<td>power</td>
<td>30 mW</td>
<td>1900 mW</td>
<td>860 mW</td>
<td>300 mW</td>
<td>300 mW</td>
<td>860 mW</td>
<td>860 mW</td>
</tr>
</tbody>
</table>

The inside of the military grade box where the receiver resides is shown in Figure 3.13.

Figure 3.13: Inside of ELF container

3.3 Experimental Methodology
The experiment conducted in this thesis involved setting up a VLF station next to the ELF station in Hugo, Colorado and recording for three days (July 19-21). As discussed in Chapter 3.2, Hugo is located about two hours east of Denver. The purpose of setting the receivers next to each other was to analyze the same paths of sferic propagation and observe how different frequencies arrive at different times.

The experiment first started by setting up a VLF hybrid receiver down in the UCD Electromagnetics and Plasma Physics Group laboratory. Here the receiver was calibrated before deployment. After that, a material list was made. This included the purchase of a small 750 watt 2-stroke gas generator and a solar panel kit. The generator served as a backup in case the solar panels were not able to power the VLF system. Unlike the ELF station, the VLF receiver consumed significantly more power because the system had to power a desktop computer, computer monitor, a GPS module, and of course, the receiver itself. It was measured that the VLF system drew 300 mA without the monitor and 430 mA with the monitor. This meant that a 45 Watt power system needed to be devised. The solar panel kit used was exactly 45 Watts which meant that during the day, the panels could power the system. This assumes clear skies and the panels be angled perfectly. Since these conditions could not be sustained all the time, the batteries were fully charged and thus the system would draw from the stored energy. To account for the night, an extra set of batteries were brought to sustain the system. If that failed, the generator would be used.

On July 19th at 4:00 am the author set out to Hugo to set up the VLF receiver. On arrival, the ELF station was examined and pronounced recording and working. After that, the setup began. First setup task was to unload the antennas and preamp box 75 feet away from the ELF antennas as to prevent mutual coupling between the two systems. This is shown in Figure 3.14.
1000 feet to the north, the rest of the equipment was unloaded. The power system was then placed another 50 feet north. This was done to ensure minimal electromagnetic radiation sourced from the inverter. The power system consisted of the solar panels connected to the solar charging regulator. The regulator was connected to the battery bank in parallel to the solar panels on the input terminals and the output terminals connected to the 1500 watt inverter. The whole system setup can be shown in Figure 3.15.
Using an extension cable, the inverter was connected to a power strip that housed the computer, monitor, and GPS module. This can be seen in Figure 3.16. It was a common practice to cover this segment of the system because it would overheat if it was in direct sun. It also protected the circuitry from the rain that occurred on July 20.
Subsequently, a 1000 foot cable connected the receiver and the pre-amp together. It was 1:00 pm once all the equipment was connected. The power supply was turned on and the initial data began recording to ensure everything was working properly. After verifying results, 1:20 pm marked the start time of recording data continuously.

On the hour, battery voltages were checked to ensure that the VLF system had sufficient power. For the most part, the solar system was able to supply the required power. On July 20 and 21 around 4:30 am the inverter alarm went off indicating that power was dropping both dates. A simple battery swap disabled the alarm. It was decided after the first time the power dropped to drive the spare batteries into the main town of Hugo and charge them at a rest area. This was beneficial because the gas generator and inverter would have added a significant amount of electromagnetic radiation near the antennas.

2:00 pm on July 21 marked the last recording. The power supply was turned off and cleanup of the camp site and the equipment began. Leaving the area, the ELF receiver was checked to verify it was recording data and did a battery check to evaluate the power levels of the batteries. It wouldn’t be until August that the data could be retrieved and processed.
CHAPTER 4

DATA RESULTS

In this chapter, the data from both VLF and ELF receivers data will be examined. Data from the Global Lightning Detection network (GLD) was used to get the location and time of the causitive lightning of observed sferics [13]. This network is comprised of multiple VLF receivers stationed all around the world to triangulate sferics. Using MATLAB script created by Mark Golkowski, this data can be filtered to set geographical bounds and specify peak current limits. This is useful because it allows for the analysis of the four classifications set forth in this thesis. These include daytime short distances, daytime long distances, nighttime short distances, and nighttime long distances. In this work, long distances are characterized as being greater than 1500 km and short distances are anything less than that. Using the map package from MATLAB, distance is calculated by entering the longitude and latitude of the receiver and sferic location.

In Chapter 4.1, site corrections will be presented. This includes looking at the hardware group delay so that a more accurate depiction of the arrival time can be calculated. In Chapter 4.2, a few examples will be presented on how group delay and time of arrival was computed. Tables will then be presented to capture all 40 cases. All 40 figures and their respective maps can be found in the appendix section of this thesis.

4.1 Site Correction

To accurately determine the group velocity of the sferic, the delay of the signals through the receiver must be determined. For the VLF receiver it was determined that the group delay is on the order of 25 µs for the VLF receiver. For the purpose of this work, this time is relativity small compared the group delay of the ELF system. From the Krakow group, we were told that the group delay though the ELF system
was roughly 4.5 ms and included delay in the antenna as well as filtering hardware. However, there was difficulty in fully confirming this with experiment and because of this, an averaged measurable group delay was determined. The timing synchronization of the ELF receiver is also done in a way that the exact time of a sample may be off by a fraction of the sampling time. This is because while the sampling frequency is tuned via GPS time, the precise timing of the first sample in a file is not guaranteed to be on the rising edge of 1 pps GPS signal.

One way to experimentally determine the group delay in the ELF receiver is to look at observations sferics that originate very close to the receiver. Propagation of such waves will be minimally affected by the ionosphere and ground wave propagation will dominate, which should be traveling at the speed of light. Using time of arrival, distance, and the speed of light we can determine when this wave should have arrived and when it was actually recorded. The difference between these two determines the group delay through the hardware.

To begin this analysis, let’s first look at a strike that occurred 109 km away from the ELF station. This can be found in the map in Figure 4.1.

![Figure 4.1: Location of sferic in proximity to ELF station](image-url)
We then look at the time domain of both channels and begin to determine the time of arrival by the first peak as explained in Chapter 2.1. This is found in Figure 4.2.

![Figure 4.2: Time domain of the ELF receiver looking at N/S and E/W channels](image)

A data point on the E/W channel indicates the first peak detected and its respective time. The vertical line indicates the time when the GLD360 network detected the discharge. This GLD360 determined sferic time will always mark the beginning of every subsequent plot. Next, the red vertical line takes the distance between the sferic and station and divides it by the speed of light. This will indicate when the sferic should have arrived at the station if it was propagating at the maximum possible velocity. From Figure 4.2 the legend tells us that the arrival time for travel at the speed of light should be 0.367 ms after the GLD detected the sferic. Next, the blue vertical line indicates the arrival time if the wave were to travel at 99.3% the speed of light. Since the sferic occurred very close to the station this value, this number is very close to the speed of light at 0.364 ms after the GLD detection. Finally we look at the data point. Here, the arrival time was found to be 4.506 ms after the GLD detection.
This means the group delay of the hardware is $4.506\,ms - 0.367\,ms = 4.139\,ms$.

This process was done for 13 different cases. Each following the same methodology. The goal was to average all 13 cases to determine an averaged group delay through the hardware.

**Table 4.1: Table of site corrections based on distance, speed of light, and arrival time**

<table>
<thead>
<tr>
<th>Distance [km]</th>
<th>Speed of light propagation time (ms)</th>
<th>Observed time of arrival (ms)</th>
<th>Correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>105.325</td>
<td>0.36466</td>
<td>4.506</td>
<td>4.14134</td>
</tr>
<tr>
<td>121.7092</td>
<td>0.40598</td>
<td>4.506</td>
<td>4.10052</td>
</tr>
<tr>
<td>75.52509</td>
<td>0.25192</td>
<td>3.379</td>
<td>3.12708</td>
</tr>
<tr>
<td>83.38046</td>
<td>0.27183</td>
<td>4.506</td>
<td>4.23417</td>
</tr>
<tr>
<td>37.1913</td>
<td>0.12406</td>
<td>3.379</td>
<td>3.25494</td>
</tr>
<tr>
<td>146.4526</td>
<td>0.4851</td>
<td>4.506</td>
<td>4.0209</td>
</tr>
<tr>
<td>179.2191</td>
<td>0.59781</td>
<td>4.506</td>
<td>3.90819</td>
</tr>
<tr>
<td>178.4539</td>
<td>0.59526</td>
<td>4.506</td>
<td>3.91074</td>
</tr>
<tr>
<td>180.5611</td>
<td>0.60229</td>
<td>4.506</td>
<td>3.90371</td>
</tr>
<tr>
<td>192.9641</td>
<td>0.64366</td>
<td>3.3379</td>
<td>2.69424</td>
</tr>
<tr>
<td>182.9056</td>
<td>0.61011</td>
<td>4.506</td>
<td>3.89539</td>
</tr>
<tr>
<td>212.1667</td>
<td>0.70771</td>
<td>4.506</td>
<td>3.79829</td>
</tr>
<tr>
<td>219.531</td>
<td>0.73168</td>
<td>4.506</td>
<td>3.77432</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td></td>
<td><strong>3.751063846</strong></td>
</tr>
</tbody>
</table>

From the table it was computed that on average, 3.75 ms should be subtracted from the ELF time of arrival in order to compensate for the group delay through the hardware. This can also be highlighted by looking at the distribution using a histogram as shown in Figure 4.3.
4.2 Recorded Data

The observations in this experiment fall into one of four classifications. This chapter will highlight examples for each classification and then present tables that reflect all 40 cases. Figures from all the cases, as stated before, will be available in the appendix.

Beginning with daytime short distances we first present a side by side comparison of the recorded VLF and ELF data. Figure 4.4 plots both time domain signals and identifies their respective first peaks which is classified as the times of arrival.
Just like in Chapter 4.1, data begins with the green vertical line indicating the time of the GLD detected CG discharge. The red and blue lines correspond with the arrival time at the speed of light and a fraction of the speed of light respectively. In Figure 4.4 we can see that the VLF (top plot) time of arrival was computed to be 1.36 ms after the GLD detection. Time of arrival for ELF (bottom plot) indicates a time of arrival at 4.506 ms. These times were recorded in Table 4.2. Within the table, time of arrivals are logged and site correction factor is added in. Lastly, the group delays are computed for corrected data for both ELF and VLF data.

**Table 4.2: Table of daytime short distances**

<table>
<thead>
<tr>
<th>Event</th>
<th>Index</th>
<th>Distance km</th>
<th>VLF time of arrival</th>
<th>ELF time of arrival</th>
<th>ELF site correction</th>
<th>Group Delay VLF</th>
<th>Group Delay site correction VLF</th>
<th>Group Delay ELF</th>
<th>Group Delay site correction ELF</th>
</tr>
</thead>
<tbody>
<tr>
<td>UCD072013000038</td>
<td>2</td>
<td>370.3184</td>
<td>1.36</td>
<td>4.506</td>
<td>1.39975</td>
<td>0.754930354</td>
<td>0.908217616</td>
<td>0.98838460</td>
<td>0.27414049</td>
</tr>
<tr>
<td>UCD072013000035</td>
<td>9</td>
<td>216.7889</td>
<td>0.77</td>
<td>4.506</td>
<td>0.76975</td>
<td>0.754930354</td>
<td>0.598341153</td>
<td>0.93156607</td>
<td>0.10348205</td>
</tr>
<tr>
<td>UCD072013000033</td>
<td>14</td>
<td>132.8566</td>
<td>1.26</td>
<td>5.625</td>
<td>1.27975</td>
<td>1.88908354</td>
<td>0.840598484</td>
<td>0.840598484</td>
<td>0.840598484</td>
</tr>
<tr>
<td>UCD072013000032</td>
<td>16</td>
<td>132.8566</td>
<td>1.58</td>
<td>4.506</td>
<td>1.57975</td>
<td>0.754930354</td>
<td>0.675950787</td>
<td>0.755293484</td>
<td>0.23735647</td>
</tr>
<tr>
<td>UCD072013000030</td>
<td>19</td>
<td>205.8766</td>
<td>1.06</td>
<td>5.625</td>
<td>1.06975</td>
<td>1.88908354</td>
<td>0.840598484</td>
<td>0.840598484</td>
<td>0.840598484</td>
</tr>
<tr>
<td>UCD072013000035</td>
<td>20</td>
<td>317.7497</td>
<td>1.40</td>
<td>5.625</td>
<td>1.40975</td>
<td>1.88908354</td>
<td>0.741129198</td>
<td>0.741129198</td>
<td>0.741129198</td>
</tr>
<tr>
<td>UCD072013000031</td>
<td>27</td>
<td>302.2568</td>
<td>1.31</td>
<td>5.625</td>
<td>1.30975</td>
<td>1.88908354</td>
<td>0.522659007</td>
<td>0.522659007</td>
<td>0.522659007</td>
</tr>
<tr>
<td>UCD072013000044</td>
<td>48</td>
<td>112.6357</td>
<td>0.46</td>
<td>3.579</td>
<td>0.44975</td>
<td>0.374088486</td>
<td>0.334188767</td>
<td>0.334188767</td>
<td>0.334188767</td>
</tr>
<tr>
<td>UCD072013000047</td>
<td>50</td>
<td>115.3139</td>
<td>0.59</td>
<td>4.506</td>
<td>0.59975</td>
<td>0.754930354</td>
<td>0.680634721</td>
<td>0.680634721</td>
<td>0.680634721</td>
</tr>
<tr>
<td>UCD072013000051</td>
<td>54</td>
<td>110.4021</td>
<td>0.7</td>
<td>4.506</td>
<td>0.69975</td>
<td>0.754930354</td>
<td>0.520666657</td>
<td>0.520666657</td>
<td>0.520666657</td>
</tr>
</tbody>
</table>

Basic statistical analysis was tabulated in Table 4.3. Here we can compare the statistics for all four cases for corrected.
Table 4.3: Statistics of group delay for daytime short distances for VLF corrected data

<table>
<thead>
<tr>
<th></th>
<th>VLF site correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.787877783</td>
</tr>
<tr>
<td>Standard Error</td>
<td>0.04327414</td>
</tr>
<tr>
<td>Median</td>
<td>0.836889225</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.136844845</td>
</tr>
<tr>
<td>Sample Variance</td>
<td>0.018726512</td>
</tr>
<tr>
<td>Range</td>
<td>0.413057581</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.526107027</td>
</tr>
<tr>
<td>Maximum</td>
<td>0.939164607</td>
</tr>
<tr>
<td>Count</td>
<td>10</td>
</tr>
</tbody>
</table>

Statistics for the ELF data were also generated in the same fashion as the VLF data. This is found in Table 4.4.

Table 4.4: Statistics of group delay for daytime short distances for ELF corrected data

<table>
<thead>
<tr>
<th></th>
<th>ELF site correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.62497513</td>
</tr>
<tr>
<td>Standard Error</td>
<td>0.223432504</td>
</tr>
<tr>
<td>Median</td>
<td>0.567651923</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.706555617</td>
</tr>
<tr>
<td>Sample Variance</td>
<td>0.49922084</td>
</tr>
<tr>
<td>Range</td>
<td>2.644315513</td>
</tr>
<tr>
<td>Minimum</td>
<td>-1.007994886</td>
</tr>
<tr>
<td>Maximum</td>
<td>1.636320627</td>
</tr>
<tr>
<td>Sum</td>
<td>6.249751299</td>
</tr>
<tr>
<td>Count</td>
<td>10</td>
</tr>
</tbody>
</table>

The next set of tables presented are the remaining three classifications. Each classification will again have statistics for VLF and ELF data.
Table 4.5: Table of daytime long distances

<table>
<thead>
<tr>
<th>Band</th>
<th>Index</th>
<th>Distance km</th>
<th>UT time of arrival</th>
<th>UT time of arrival</th>
<th>UT site correction</th>
<th>Group Delay</th>
<th>Group Delay site correction</th>
<th>Group Delay</th>
<th>Group Delay site correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>LC63702702131843</td>
<td>626</td>
<td>1471.134</td>
<td>5.85</td>
<td>11.34</td>
<td>5.28978</td>
<td>7.80989</td>
<td>0.9801342</td>
<td>0.9683267</td>
<td>0.9365551</td>
</tr>
<tr>
<td>LC63702702090832</td>
<td>58</td>
<td>2827.299</td>
<td>9.06</td>
<td>13.53</td>
<td>0.76985</td>
<td>9.78388</td>
<td>0.9835102</td>
<td>0.9621721</td>
<td>0.9401252</td>
</tr>
<tr>
<td>LC63702702060064</td>
<td>104</td>
<td>2702.157</td>
<td>9.30</td>
<td>14.46</td>
<td>6.32987</td>
<td>15.08991</td>
<td>0.9904867</td>
<td>0.9742446</td>
<td>0.9514767</td>
</tr>
<tr>
<td>LC63702702090864</td>
<td>217</td>
<td>1006.229</td>
<td>11.24</td>
<td>14.06</td>
<td>10.28093</td>
<td>10.28093</td>
<td>0.9188007</td>
<td>0.9188007</td>
<td>0.9188007</td>
</tr>
<tr>
<td>LC63702702060064</td>
<td>236</td>
<td>526.83</td>
<td>7.02</td>
<td>11.34</td>
<td>7.32697</td>
<td>7.32697</td>
<td>0.9904867</td>
<td>0.9904867</td>
<td>0.9904867</td>
</tr>
<tr>
<td>LC63702702060064</td>
<td>236</td>
<td>2827.299</td>
<td>9.06</td>
<td>13.53</td>
<td>0.76985</td>
<td>9.78388</td>
<td>0.9835102</td>
<td>0.9621721</td>
<td>0.9401252</td>
</tr>
<tr>
<td>LC63702702090864</td>
<td>223</td>
<td>1903.446</td>
<td>6.06</td>
<td>11.26</td>
<td>6.40979</td>
<td>7.50881</td>
<td>0.9188007</td>
<td>0.9188007</td>
<td>0.9188007</td>
</tr>
<tr>
<td>LC63702702090864</td>
<td>223</td>
<td>1903.446</td>
<td>6.06</td>
<td>11.26</td>
<td>6.40979</td>
<td>7.50881</td>
<td>0.9188007</td>
<td>0.9188007</td>
<td>0.9188007</td>
</tr>
<tr>
<td>LC63702702131843</td>
<td>101</td>
<td>1958.772</td>
<td>6.64</td>
<td>11.34</td>
<td>6.89979</td>
<td>7.50881</td>
<td>0.9188007</td>
<td>0.9188007</td>
<td>0.9188007</td>
</tr>
</tbody>
</table>

Table 4.6: Statistics of group delay for daytime long distances for VLF corrected data

<table>
<thead>
<tr>
<th>VLF site correction</th>
<th>Mean</th>
<th>Standard Error</th>
<th>Median</th>
<th>Standard Deviation</th>
<th>Sample Variance</th>
<th>Range</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Sum</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.960850111</td>
<td>0.005841504</td>
<td>0.96199207</td>
<td>0.018472456</td>
<td>0.000341232</td>
<td>0.06554613</td>
<td>0.918658033</td>
<td>0.984204163</td>
<td>9.608501106</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 4.7: Statistics of group delay for daytime long distances for ELF corrected data

<table>
<thead>
<tr>
<th>ELF site correction</th>
<th>Mean</th>
<th>Standard Error</th>
<th>Median</th>
<th>Standard Deviation</th>
<th>Sample Variance</th>
<th>Range</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.89790404</td>
<td>0.030070482</td>
<td>0.896213774</td>
<td>0.095091215</td>
<td>0.009042339</td>
<td>0.316466029</td>
<td>0.74236999</td>
<td>1.058833028</td>
<td>10</td>
</tr>
</tbody>
</table>
Table 4.8: Table of nighttime short distances

<table>
<thead>
<tr>
<th>Event</th>
<th>Index</th>
<th>Distance km</th>
<th>DT time of arrival</th>
<th>DT site corrected</th>
<th>ELF site correction</th>
<th>Group delay VLF</th>
<th>Group delay VLF corrected</th>
<th>Group delay ELF</th>
<th>Group delay ELF corrected</th>
</tr>
</thead>
<tbody>
<tr>
<td>EV001</td>
<td>10101</td>
<td>1.67</td>
<td>4.186</td>
<td>1.59797</td>
<td>0.759182</td>
<td>0.749067</td>
<td>0.749067</td>
<td>0.749067</td>
<td>0.749067</td>
</tr>
<tr>
<td>EV002</td>
<td>10102</td>
<td>1.67</td>
<td>4.186</td>
<td>1.59797</td>
<td>0.759182</td>
<td>0.749067</td>
<td>0.749067</td>
<td>0.749067</td>
<td>0.749067</td>
</tr>
</tbody>
</table>

Table 4.9: Statistics of group delay for nighttime short distances for VLF corrected data

<table>
<thead>
<tr>
<th>VLF site correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>Standard Error</td>
</tr>
<tr>
<td>Median</td>
</tr>
<tr>
<td>Standard Deviation</td>
</tr>
<tr>
<td>Sample Variance</td>
</tr>
<tr>
<td>Range</td>
</tr>
<tr>
<td>Minimum</td>
</tr>
<tr>
<td>Maximum</td>
</tr>
<tr>
<td>Count</td>
</tr>
</tbody>
</table>

Table 4.10: Statistics of group delay for nighttime short distances for ELF corrected data

<table>
<thead>
<tr>
<th>ELF site correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>Standard Error</td>
</tr>
<tr>
<td>Median</td>
</tr>
<tr>
<td>Standard Deviation</td>
</tr>
<tr>
<td>Sample Variance</td>
</tr>
<tr>
<td>Range</td>
</tr>
<tr>
<td>Minimum</td>
</tr>
<tr>
<td>Maximum</td>
</tr>
<tr>
<td>Count</td>
</tr>
</tbody>
</table>
Table 4.11: Table of nighttime long distances

<table>
<thead>
<tr>
<th>Event</th>
<th>Index</th>
<th>Distance km</th>
<th>VLF site correction</th>
<th>ELF site correction</th>
<th>Group Delay VLF</th>
<th>Group Delay ELF</th>
<th>Group Delay VLF correction</th>
<th>Group Delay ELF correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Event 1</td>
<td>Index 1</td>
<td>Distance 1</td>
<td>VLF site correction 1</td>
<td>ELF site correction 1</td>
<td>Group Delay VLF 1</td>
<td>Group Delay ELF 1</td>
<td>Group Delay VLF correction 1</td>
<td>Group Delay ELF correction 1</td>
</tr>
<tr>
<td>Event 2</td>
<td>Index 2</td>
<td>Distance 2</td>
<td>VLF site correction 2</td>
<td>ELF site correction 2</td>
<td>Group Delay VLF 2</td>
<td>Group Delay ELF 2</td>
<td>Group Delay VLF correction 2</td>
<td>Group Delay ELF correction 2</td>
</tr>
<tr>
<td>Event 3</td>
<td>Index 3</td>
<td>Distance 3</td>
<td>VLF site correction 3</td>
<td>ELF site correction 3</td>
<td>Group Delay VLF 3</td>
<td>Group Delay ELF 3</td>
<td>Group Delay VLF correction 3</td>
<td>Group Delay ELF correction 3</td>
</tr>
</tbody>
</table>

Table 4.12: Statistics of group delay for nighttime long distances for VLF corrected data

<table>
<thead>
<tr>
<th>VLF site correction</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.956118863</td>
</tr>
<tr>
<td>Standard Error</td>
<td>0.006897614</td>
</tr>
<tr>
<td>Median</td>
<td>0.952702009</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.02181217</td>
</tr>
<tr>
<td>Sample Variance</td>
<td>0.000475771</td>
</tr>
<tr>
<td>Range</td>
<td>0.055057962</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.928788105</td>
</tr>
<tr>
<td>Maximum</td>
<td>0.983846067</td>
</tr>
<tr>
<td>Count</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 4.13: Statistics of group delay for nighttime long distances for ELF corrected data

<table>
<thead>
<tr>
<th>ELF site correction</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.959895073</td>
</tr>
<tr>
<td>Standard Error</td>
<td>0.043848338</td>
</tr>
<tr>
<td>Median</td>
<td>0.964907502</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.138660761</td>
</tr>
<tr>
<td>Sample Variance</td>
<td>0.019226807</td>
</tr>
<tr>
<td>Range</td>
<td>0.475414058</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.671533189</td>
</tr>
<tr>
<td>Maximum</td>
<td>1.146947247</td>
</tr>
<tr>
<td>Count</td>
<td>10</td>
</tr>
</tbody>
</table>

Histograms were generated for both daytime and nighttime. This highlights distributions of the classifications as well as determine out liars. Daytime histogram
can be found in figure

![Histogram of group velocities](image)

Figure 4.5: Histogram of group velocities

A powerful statistical tool that employed here is the two-sample Kolmogorov-Smirnov test, which provides a probability if two sample sets are from the same distribution. In this test a null hypothesis is proposed that the two sample sets come from the same distribution. A p-value is then calculated. A p-value below 0.05 is taken to mean that the two sample sets are from different distributions and the null hypothesis should be rejected. For the four classifications presented in this work, the two-sample Kolmogorov-Smirnov test was conducted between each set to determine how related one set is to another. This is presented in Table 4.14.

Table 4.14: Kolmogorov-Smirnov test for all four cases compared to one another

<table>
<thead>
<tr>
<th>Test cases</th>
<th>Mean</th>
<th>Rejected</th>
<th>p</th>
<th>k</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daytime short VLF vs. Nighttime short VLF</td>
<td>0.7878, 0.7182</td>
<td>0</td>
<td>0.6751</td>
<td>0.3</td>
</tr>
<tr>
<td>Daytime long VLF vs. Nighttime long VLF</td>
<td>0.9608, 0.9561</td>
<td>0</td>
<td>3.13E-01</td>
<td>0.4</td>
</tr>
<tr>
<td>Daytime short ELF vs. Nighttime short ELF</td>
<td>0.6249, 0.7692</td>
<td>0</td>
<td>3.13E-01</td>
<td>0.4</td>
</tr>
<tr>
<td>Daytime long ELF vs. Nighttime long ELF</td>
<td>0.8979, 0.9599</td>
<td>1</td>
<td>0.031</td>
<td>0.6</td>
</tr>
</tbody>
</table>
In Chapter four, data was presented in the form of tables. These tables included statistics of group delay of daytime short distances, daytime long distances, nighttime short distances, and nighttime long distances. The Kolmogorov-Smirnov test was then presented to quantify the relationship of the data sets compared to each other. In this chapter, an in depth analysis will be conducted to see how Chapter 3.3 methodology compares to theoretical results presented in Chapter 2. In Chapter 5.1, results from Chapter 4.1 will be examined. In Chapter 5.2, a brief conclusion will be presented to highlight how the experiment presented in this thesis contributes to knowledge of the plasma physics in the ionosphere.

5.1 Analysis

Referencing Table 4.2 or any of the ELF columns it can be observed that the group delays can at times be inaccurate. For example, in the first column of 4.2, the ELF group delay was calculated to be 160 % faster than the speed of light. Physically this is impossible. However, the sampling frequency of the ELF receiver as mentioned in Chapter 3.2.1 is 888 Hz. This means the resolution is significantly lower than that of the VLF receiver. This is why all the ELF data looks courser. The arrival time (indicated by the first peak) might be off by a sample. This means the arrival time could be off by as much as 1 ms. For short distances, this was clearly an issue since the arrival time of the sferic traveling at the speed of light was a fraction of a ms. This is why some of the data, especially subtracting the site correction indicates that the wave is traveling faster than the speed of light. However, this was consistently calculated so the distributions of the data sets were to some degree accurate and therefore tests such as Kolmogorov-Smirnov were valid.

In Mackay’s work [1], it was proposed that during the day, slowtails are very weak and sometimes non existent. This meant that the ELF content was significantly
reduced compared to nighttime. This was due to the ionospheric height as discussed in Chapter 1.2.2. To see this effect, refer to Figure 5.1

![Figure 5.1: Time domain of two sferics at equal distances, one at night and during the day [1]](image)

The Kolmogorov-Smirnov test can support these results simply by looking at Daytime long ELF vs. Nighttime long ELF in Table 4.14. It was shown that the null hypothesis was rejected, thus meaning that there is a significant difference between ELF propagation velocity day vs. night for a significance level of 5 percent.

For the VLF data sets, it was shown that the null hypothesis was supported for Daytime long VLF vs. Nighttime long VLF. This could only mean that VLF signals generated from sferics are supported during both at night and day. ELF signals however, act differently due to the rising ionospheric height given the cutoff frequency and modes presented in chapter 1.

Furthermore, these results can be further proven by looking at the statistical analysis in Chapter 4.2. The averaged group delay for ELF daytime long was computed to be 89.7 % that of the speed of light as shown in table 4.7. Compared to nighttime long distances the average group delay was computed to be 95.9 % of the speed of light in Table 4.13. This validates that at nighttime, ELF signals act like VLF signals as shown in Table 4.12 which computes the averaged group delay to be 95.6 % of speed of light.
5.2 Conclusion

In this work an experiment was carried out to observe the difference in sferic group velocity between the ELF and VLF bands for nighttime and daytime ionospheric conditions. The experiment involved two co-located receivers recording over a 24 hour period. A power supply using a solar panel and battery bank was deployed to allow the VLF system to operate off the power grid. Global Lightning Detection Network (GLD360) lightning location data was used to make time of arrival observations of sferics on both systems. For both systems the time of the first peak was used as the arrival time. The group delay through the ELF receiver was estimated using nearby sferics and assuming direct path propagation to the receiver. A Kolmogorov-Smirnov statistical test was used to evaluate differences in observations over day vs night conditions. Results show agreement with theory that ELF propagation velocity is strongly affected by the ionospheric height that changes for day vs. night. The results show that it is possible to use ELF sferic arrival time as a potential ionospheric diagnostics. Noise and uncertainty in the results was caused by the lack of precision sampling synchronization in the ELF system and the low sampling rate of 888 HZ, which could yield errors on the order of a N 0.5 ms. Suggestions for future work include averaging over a larger number of events and using a more sophisticated method of determining arrival time than the first peak observation used here. In this context we note that the GLD360 network utilized a canonical waveform bank to get precision time of arrival for sferic from VLF observations. Such a wavebank for ELF sferic observations could also be developed.
APPENDIX A. Daytime Short Distances

Figure A.1:

Figure A.2:
Figure A.3:

Figure A.4:
Figure A.9:

![Figure A.9](image)

Figure A.10:

![Figure A.10](image)
Figure A.11:

Figure A.12:
Figure A.13:

Figure A.14:
Figure A.17:

Figure A.18:
Figure A.19:

Figure A.20:
APPENDIX B. Daytime Long Distances

Figure B.1:

Figure B.2:
Figure B.3:

Figure B.4:
Figure B.5:

Figure B.6:
Figure B.7:

Figure B.8:
Figure B.9:

Figure B.10:
Figure B.11:

Figure B.12:
Figure B.13:

Figure B.14:
Figure B.15:

Figure B.16:
Figure B.17:

Figure B.18:
Figure B.19:

Figure B.20:
APPENDIX C. Nighttime Short Distances

Figure C.1:

Figure C.2:
Figure C.3:

Figure C.4:
Figure C.5:

Figure C.6:
Figure C.7:

Figure C.8:
Figure C.9:

Figure C.10:
Figure C.11:

Figure C.12:
Figure C.13:

Figure C.14:
Figure C.15:

Figure C.16:
Figure C.17:

Figure C.18:
Figure C.19:

Figure C.20:
APPENDIX D. Nighttime Long Distances

Figure D.1:

Figure D.2:
Figure D.3:

Figure D.4:
Figure D.7:

Figure D.8:
Figure D.9:

Figure D.10:
Figure D.11:

Figure D.12:
Figure D.13:

Figure D.14:
Figure D.15:

Figure D.16:
Figure D.17:

Figure D.18:
Figure D.19:

Figure D.20:
REFERENCES


