Remote measurement of ELF/VLF radio emissions by lightning and ground-based transmitters

by

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Dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Department of Electrical and Computer Engineering in the Graduate School of Duke University
2017
ABSTRACT

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Abstract

Electromagnetic waves in the very low frequency (VLF, $3 - 30\, \text{kHz}$) and extremely low frequency (ELF, $3 - 3000\, \text{Hz}$) bands propagate extremely well in the cavity between the earth and the ionosphere with low attenuation. Because of this, radio waves emitted in this frequency range can be measured at extremely large distances (thousands of kilometers) from the sources of such emissions. Two main sources of signals at these frequencies are lightning events and VLF transmitters designed for communicating with submarines and other naval vessels. Measurement of the signals from both of these sources can be used to discover information about the source, in the case of lightning, or to measure the factors affecting propagation and other signal properties, as with VLF transmitter signals. This document provides a summary of the work undertaken to measure both of these signal sources and to outline goals and briefly outlines some objectives for future work.

A brief background on the atmospheric ELF and VLF environments is given in chapter 1, including a description of the conditions that allow for excellent propagation. A brief introduction to the lightning processes, as well as classification and measurement techniques is included as background information. Details describing current VLF transmitters examined in this work and basics of minimum-shift keying are also described.

Chapter 2 describes the design process and operating characteristics of a sensor designed for measuring magnetic fields in the ELF and VLF frequency ranges of interest in this work. This sensor system is robust and suitable for long-term deployment in thunderstorm environments. Chapter 3 details a method of measuring faint average signals generated by some lightning processes at large distances. Such an averaging process allows for the extraction of extremely small-magnitude processes that are otherwise not visible and enables the com-
parison of lightning on a larger scale. Averaged waveforms for four separate thunderstorms are compared and post-first stroke flash parameters are analyzed. Chapter 4 applies the averaging procedure to a specific type of lightning known as narrow bipolar events (NBEs). NBEs play an important role in the initiation of other types of lightning but not all NBEs initiate other lightning. This work divides positive NBEs according to whether they initiate other lightning events and examines the differences between them, helping to investigate the processes and conditions that give rise to lightning. Chapter 5 describes a method of unambiguously determining the position of a receiver through the measurement of terrestrial MSK-encoded VLF transmitters. Such a system has many advantages over other methods of navigation and simulated and field-tested capabilities and limitations are discussed, as well as factors affecting system accuracy. Finally, proposals and suggestions for future work are given in chapter 6.
To my parents,
Lyle and Sara,
for believing in me every step of the way,
even when I didn’t believe in myself.

*Ad astra per aspera.*
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Symbols

\[ \varepsilon_0 \quad \text{Permittivity of free space (} 8.85 \times 10^{-12} \text{ F/m)} \]
\[ \mu_0 \quad \text{Permeability of free space (} 4\pi \times 10^{-7} \text{ H/m)} \]

Abbreviations

AWGN Additive white Gaussian noise
CC Continuing current
CG Cloud-to-ground lightning event
CMC Charge moment change
DC Direct current
DEV Duke ELF/VLF sensor
DLF Duke LF sensor
DULF Duke ULF sensor
DVLF Duke VLF sensor
EIWG Earth-ionosphere waveguide
EM Electromagnetic
EMF Electromotive force
ELF Extremely low frequency (3–3000 Hz)
FFT Fast Fourier transform
FSK Frequency-shift keying
FDTD Finite-difference time-domain
FWHM Full width at half maximum
GPS  Global positioning system
IB  Initial breakdown
IC  In-cloud lightning event
LF  Low frequency (3–300 kHz)
LPF  Low-pass filter
MSK  Minimum-shift keying
NAA  Call sign for VLF transmitter located near Cutler, Maine
NAU  Call sign for VLF transmitter located near Aguado, Puerto Rico
NBE  Narrow bipolar event
NLDN  National Lightning Detection Network
NLK  Call sign for VLF transmitter located near Jim Creek, Wash.
NLM  Call sign for VLF transmitter located near LaMoure, N.D.
NNBE  Negative narrow bipolar event
NPM  Call sign for VLF transmitter located near Lualualei, Hawaii
PNBE  Positive polarity narrow bipolar event
PSD  Power spectral density
QFS  ELF/VLF sensor system manufactured by Quasar Federal Systems
RS  Return stroke
SNR  Signal-to-noise ratio
SR  Schumann resonance pulses
SS  Subsequent strokes
TIA  Transimpedance amplifier
UT  Universal time
ULF  Ultra low frequency (less than 3 Hz)
VHF  Very high frequency (30–300 MHz)
VLF  Very low frequency (3–30 kHz)
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1

Introduction

1.1 Atmospheric Electricity

Because the ionosphere layer of the atmosphere contains charged particles, it can be approximately modeled as a conductor. When combined with the conducting surface of the earth, these parallel conductors form a waveguide-like structure that allows signals in the ultra low frequency (ULF), extremely low frequency (ELF), and very low frequency (VLF) bands (see table 1.1) to propagate extremely well in the atmosphere. These signals propagate by using multiple reflections in the Earth-ionosphere waveguide (EIWG) the same way that electromagnetic waves propagate within a metal-wall waveguide [1].

The layer of the ionosphere most important for this process is the $D$-region, which spans approximately 60–90 km in altitude. Although the $D$-region is often approximated as a sharp conducting boundary for certain forms of analysis (such as ray theory), in reality the region’s complex boundary conditions can make it difficult to realistically model, requiring the use of advanced techniques such as waveguide mode theory [2] and finite-difference time-domain (FDTD) simulations [3].

Further complicating analysis of ionospheric effects is its variability. The ionization of the $D$-region of the ionosphere is primarily driven by the sun yielding fairly stable, consistent days and complicated, unpredictable night conditions [4]. Further adding to the unpredictability
are the sunrise and sunset transitions, as well as variability based on the solar cycle and even seasonal changes. Solar flares, which bathe Earth in ionizing X-ray emissions, can have a powerful effect on the state of the ionosphere [5], as can lightning activity [6].

Because VLF radio waves propagate extremely well within the atmosphere with very little loss (less than 2 dB per 1000 km for some frequencies [7]), emissions in this frequency range can be measured at extremely long distance. Although electromagnetic (EM) radiation of lightning spans the bandwidth from a few hertz to hundreds of megahertz, the VLF and ELF bands compose the majority of the radiated energy [8], meaning that measurements in these frequency ranges are particularly useful for observing and characterizing lightning.

While lightning is the primary source of atmospheric VLF emissions, many man-made transmitters also operate in the VLF band. Both of these sources of VLF emissions are examined in this work – lightning in chapters 3 and 4 and man-made VLF transmitters in chapter 5. Additionally, design and construction of a magnetic field sensor operating in the ELF/VLF frequency bands is described in chapter 2.

1.2 Lightning

From the beginning of recorded human history, lightning has featured prominently in the mythos and legends of many societies. In early Greek mythology, lightning was believed to be a weapon of Zeus, so any spot struck by lightning was considered sacred. Lightning is also said to be a tool of deities in the Bible, the Koran, Hindu mythology, Norse mythology, and Native American tradition. Even Santa Claus’s sleigh is said to be pulled by reindeer
Figure 1.1: Global lightning flash density in km$^{-2}$yr$^{-1}$, adapted from data collected by NASA Optical Transient Detector measurements [12].

named Donner (thunder) and Blitzen (lightning). Lightning and thunder were incorporated into the traditions and beliefs of every known ancient civilization.

But the importance of lightning is not exclusive to religion. Fulgurites are hollow glass tubes formed by lightning strikes in certain materials, and scientists have collected and studied fulgurites as old as 250 million years. Lightning is believed to have played an important part in the development of early life through its ability to enable the formation of organic compounds and amino acids from inorganic molecules [9]. Furthermore, lightning may also have contributed greatly to atmospheric conditions conducive to the formation of life [10]. Even today, lightning plays an important role in the processes of the climate system, producing nitrous oxide (NOx) and possibly even serving as a sort of slow negative feedback for anthropomorphic-induced climate change [11].

With more than a thousand thunderstorms taking place at any time, estimates of lightning occurrence as far back as 1925 place the global lightning flash rate at approximately 100 s$^{-1}$ [13]. Despite a relatively primitive method of calculation, this early prediction is within a factor of 2 of most surveys on the subject [14, 15, 16]. More recent estimates based on satellite observations place the value at approximately 65 s$^{-1}$, although that estimate is believed to be a lower bound due to poor detection efficiency of certain types of lightning events [17]. Despite these global averages, lightning incidence rates intuitively can
vary greatly. These rates can show large temporal variations on time scales ranging from hours (presence of local thunderstorms), days (time of day), months (local seasons), or years and decades (large-scale climate trends). Lightning flash rates can also vary spatially over a range of just a few kilometers (local topography) to continents (weather tendencies and latitude variance). Global lightning flash density based on data collected by NASA’s Optical Transient Detector satellite for April 1995 – March 2000 is shown in figure 1.1.

Despite its relatively common rate of incidence, much is still unknown about lightning processes and effects. This is partly due to the difficulty of measuring lightning, as well as its relatively unpredictable nature. Although research into the nature of lightning has been conducted for centuries, the modern era of lightning research truly began during the 1970s when equipment had advanced sufficiently to allow for measurement of electric and magnetic fields at the submicrosecond time scales [18].

1.2.1 Formation of lightning

The cumulonimbus is the type of cloud that is primarily responsible for producing lightning, although not all cumulonimbus formations produce lightning. Thunderclouds are those clouds that produce lightning, with thunderstorms typically being made up of several thunderclouds. Within this thundercloud, several relevant process are at work. Among these are mechanical processes (such as horizontal and vertical winds), condensate processes (such as rain and hail), and electrical processes (such as lightning). Thunderstorms typically comprise convective cloud systems with vertical extent between 3 and 20 km and horizontal dimensions that can stretch for hundreds of kilometers, divided into smaller convection cells, each of which have individually strong updrafts ($\gtrsim 10 \text{ m/s}$).

The details of the process that leads to the electrification of clouds are still not fully understood, but recent research indicates the process occurs primarily in the center area of the storm, where the strongest updrafts are present and temperatures range from $-25$ to $-15^\circ \text{C}$. In this region, the rapid air motion and cold temperatures combine to produce three types of precipitation — supercooled water droplets (small liquid water droplets below freezing),
small ice crystals, and graupel (otherwise known as soft hail). The strong updraft carries the supercooled droplets and small ice crystals upward, while the heavier graupel falls toward the earth or is suspended. When rising supercooled droplets or ice crystals collide with falling graupel, the graupel becomes negatively charged and the rising particles become positively charged. This process is believed to be primarily responsible for the electrical nature of thunderclouds and has been tested in laboratory conditions for a variety of parameters [19, 20, 21, 22].

Several models exist for the charge structure of electrified clouds, each with increasing complexity. The simplest model for an electrified cloud is that of a simple dipole structure, with a negative point charge on the order of about 40 C situated beneath an approximately equal magnitude positive point charge. This separation of charges (referred to as the main charges) creates a measurable electric field. This model is slightly increased in complexity and accuracy by the addition of an additional small positive charge (of about 3 C) below the negative main charge to create a tripole structure. This lower, screening charge is caused by corona from the ground and positive ions generated by cosmic rays which are attracted to the lower negative charge [23]. This tripole model (figure 1.2) is sufficient for most analysis of lightning formation and propagation, although there is evidence for a negative screening charge above the main positive charge [24], as well as more complicated layer structures that cannot be described by point charges, especially in the updraft portion of the cloud [25].
1.2.2 Classification of lightning

Lightning can be classified in a variety of ways. The first type of classification is the location of the destination of the transferred charge. Cloud-to-ground (CG) events are those that transfer charge from a location in the atmosphere to the ground, while in-cloud (IC) events are those that do not transfer charge to ground. The majority of lightning events that occur are of the IC type, with the ratio of IC to CG events typically being about 3 [17], although this value can vary greatly depending on storm type and stage, as well as latitude and other factors. The work described in this document involves investigation into both CG lightning (chapter 3) and IC lightning (chapter 4).

Lightning events can also be classified based on the polarity of the transferred charge. Positive events are those that transfer a net positive charge from the source to the terminating point, while negative events are those that transfer negative charge. For instance, positive cloud-to-ground (+CG) events transfer positive charge from the charged cloud to ground, with negative cloud-to-ground (–CG) events transferring net negative charge. For CG events, -CG flashes are much more common, by a factor of 20 [26] to 30 [27].

1.2.3 Cloud-to-ground lightning

The lightning process is capable of transferring charge in CG events in several different ways, the most prominent of which are visible in figure 1.3. The most visible lightning process is that of the leader and return stroke. In this process, a leader, whose current is
on the order of about a kiloamp, descends from the charge center within the cloud. As it travels, it creates a conductive path, depositing charge along this channel as it travels. This channel has a conductivity on the order of $10^4$ S/m, many orders of magnitude greater than that of the surrounding virgin air [28]. Once the channel reaches and attaches to the ground, a return stroke is initiated, traveling from the ground to the charge source within the cloud. This return stroke, which has a current magnitude ranging from a few kiloamps to several hundred kiloamps, neutralizes charge deposited in the channel and produces the bright flash typically associated with lightning. Many CG flashes contain multiple return strokes. After the conclusion of the initial return stroke, it is possible for subsequent strokes (SS) to propagate using the same conductive channel. These return strokes are delayed from previous strokes by anywhere from a few milliseconds to more than a hundred milliseconds [29]. A flash is considered to be the collection of an initial stroke along with any associated subsequent strokes.

Many CG flashes, especially +CG flashes, are followed by a continuing current (CC) on the order of a few hundred amps that can last hundreds of milliseconds after the conclusion of the return stroke. This continuing current, which flows in the same channel as the return stroke, does not occur in all CG flashes, but continuing current lasting more than 40 ms has been estimated to occur in the majority of positive flashes [30], but less than 10% of negative flashes [31].

1.2.4 In-cloud lightning

In-cloud (IC) lightning is a term which is used to encompass several main types of lightning. Intracloud lightning, that which occurs within a single thundercloud, is thought to be the most common type of in-cloud lightning [18]. It is contrasted with intercloud lightning (lightning discharges between two or more thunderclouds) and air discharges (those which occur between a thundercloud and the air).

Despite being more common than CG lightning, because of its location within the thundercloud, IC lightning is particularly difficult to measure. Because it is obscured by clouds,
it is difficult to visually observe lightning paths and channels. Furthermore, because it does not discharge to the earth, it cannot be measured directly with instrumented towers. Therefore, nearly all observation of IC lightning is done indirectly, using electric and magnetic field sensors. More recently, the study of IC lightning has expanded greatly with the introduction of interferometric systems [32, 33], time of arrival systems [34, 35], and hybrid systems that use both interferometric and time of arrival techniques [36, 37].

IC lightning typically consists of two main stages. The early stage is similar to that of the stepped leader of CG lightning flashes. In this stage, which can last some tens to hundreds of milliseconds [38, 39], a negatively charged conductive channel is extending bidirectionally from its origin (often the upper boundary of the main negative charge region). This channel, whose final length is on the order of a few kilometers, bridges both the main negative charge region and the main positive charge regions [34, 40].

The beginning of the late stage of the IC flash is thought to be caused by the cessation of extension of the upward-going negative leader channel. The late stage, which typically has a duration of a few hundred milliseconds [39], can be described as transporting negative charge from distant areas of the flash back to the origin [38].

Although this description presents a view of a “typical” IC lightning flash, IC lightning is much more varied than its CG counterpart. This difference is primarily due to the fact that IC discharges do not have well-defined electrodes, unlike CG flashes, in which the ground behaves like a good conducting electrode. Many IC flashes are also predominantly horizontal in orientation [32] or can result in hybrid IC-CG flashes of both polarities [41]. Overall, however, many similarities exist between IC and CG flashes, both during the stepped leader initiation and the late-stage processes present in both [18].

1.2.5 Measurement of lightning

Lightning can be measured in a variety of ways, the most accurate of which is through the use of instrumented towers [42, 43, 44, 45, 46, 47]. Instrumented towers have the benefit of providing extremely precise measurements, but suffer from relatively infrequent measure-
ments. Even the most commonly struck towers only receive several dozen strikes per year, meaning that they are only capable of measuring an extremely small number of events.

It is also possible to measure and characterize lightning by measuring the change in the electric field produced by the separation of charges within the thunderclouds (described above). For the simple dipole model (ignoring the lower positive charge), the electric field at a remote location can be expressed as

$$|E| = \frac{|Q| H}{2\pi \varepsilon_0 (H^2 + r^2)^{3/2}}$$

(1.1)

where $|Q|$ is the magnitude of the two main charges, $H$ is the average elevation of the point charges, $\varepsilon_0$ is the vacuum permittivity, and $r$ is the horizontal distance of the observer from the dipole structure [18]. As lightning rearranges charges within the dipole, it causes changes in the electric field, which can be measured, allowing observers to estimate the charge being transferred [23, 31, 48].

The third primary method of measuring lightning currents, and the one used in this work, is by measuring the magnetic fields produced by the electrical current, both within the channel and in other processes. For the approximation of current flowing in a wire (which is valid for this scenario), the magnetic field for a given current is

$$B = \frac{\mu_0 I}{2\pi r}$$

(1.2)

where $\mu_0$ is the permeability of free space, $I$ is the current within the channel, and $r$ is the distance from the lightning flash to the observer. By utilizing a simple magnetic loop antenna, it is possible to measure the characteristics of lightning in this manner [49, 50, 51]. For frequencies with wavelengths longer than lightning channels (VLF and lower), the measured EM radiation is from the current moment ($M_i(t)$), which is a function of the length of the lightning channel ($l$) and channel current ($i(t)$) and given by equation 1.3 [52].

$$M_i(t) = \int i(t) dl$$

(1.3)
Because the electric dipole field decays fairly quickly (at a rate of $1/r^3$ for $r >> H$), observations of electric fields are limited in practice to about 100 km. Even in well-instrumented areas, the majority of lightning flashes do not usually occur within 100 km of electric field sensors suitable for measuring lightning. This limits their usefulness to a minority of flashes. Because the magnetic field decays at a rate of $1/r$, long-range measurement and observation of lightning is often best accomplished through the use of magnetic field sensors, even at distances greater than 1000 km [53].

1.3 Radio Navigation

Navigational systems have been of particular interest to mankind since prehistoric times. Although navigation on pre-established stationary paths (such as roads) and near known landmarks (such as geographical features) has been relatively trivial for millennia, these navigational methods required the use of accurate maps, the creation of which relied upon many technological developments, such as the compass. Navigation and location-finding is a much more complicated process in areas with non-determined paths and no known visible landmarks, such as when sailing. Sailing across oceans was a particularly dangerous undertaking, as errors due to miscalculations or relying on dead reckoning could easily lead to course deviations and disaster.

Although the determination of latitude was relatively simple by observing the positions of the stars, the British Parliament as early as 1714 offered prizes of up to £20,000 (worth nearly $3.9 million in 2017 dollars [54]) for a proven method of accurately determining longitude [55]. Indeed, the chronometer design invented by John Harrison in the middle of the 18th century remained the standard timekeeping device until the invention of reliable electronic oscillator circuits near the end of World War I.

During the middle of the 20th century, two main factors led to the invention and proliferation of radio navigation systems – World War II and the availability of cheap and reproducible electronics. The extensive use of aircraft in World War II, particularly those that participated in missions at night or bad weather behind enemy lines, drove the development
of long-distance navigation and location-finding [56].

These radio systems mainly relied on principals of hyperbolic navigation [57]. Hyperbolic navigation systems rely on the difference in arrival time of signals from two physically separated transmitters. By converting these timing differences to physical separation and comparing to the known location of relevant transmitters, the receiver’s location can be determined to be somewhere on a hyperbolic curve between the two transmitters. By utilizing multiple pairs of transmitters, overlapping hyperbolas can yield the previously unknown location of the receiver. As distance from a pair of transmitters increases, however, accuracy also decreases, due to the geometry of intersecting hyperbolas [58].

Radio navigation systems were largely supplanted by satellite navigation systems, such as the global positioning system (GPS) which became available for civilian use in 1983 [59]. These satellite systems provided accuracy greater than those achievable using terrestrial-based transmitters, leading to their rapid adoption during the 1990s and beyond. Radio navigation are still of great interest in many areas, particularly those in which GPS signals might not be available.

1.3.1 Historical radio navigation systems

Although radar could conceivably be thought of as a radio positioning system, radar yields the location of an unknown object to an operator located at a known position, which is not helpful for ships or airplanes unaware of their current location. Furthermore, radar is a directional process, requiring rotating antennas or beam-forming and generally requires line-of-sight visibility of an object.

The earliest developed hyperbolic radio navigation system was the Gee system, used by the British during World War II [60]. The Gee system utilized networks (called chains) of three transmitters, each operating in the high frequency (HF) bands (20–85 MHz) with an operating power of 300 kW [61]. A master transmitter transmitted an initiating pulse. The two secondary transmitters would detect the pulse from the master transmitter and then transmit their own pulses in a predetermined sequence. Bomber navigators would then use
standard oscilloscopes to estimate the difference in arrival time between the master pulse and each of the secondary signals. By finding the intersection of these hyperbolic curves on a map of precalculated curves, the navigator could then know the aircraft’s position. The Gee system worked better than expected, but location accuracy was limited by distance from the transmitters, with accuracy decreasing at the rate of the square of the distance. Short ranges allowed for accuracies of less than 200 meters, while longer ranges yielded accuracies of approximately ten kilometers, up to a maximum usable distance of approximately 600 km [60]. Gee began operation in 1941 and continued until the last station was shut down in 1970 [61].

The development of the Gee system in the United Kingdom directly inspired the creation of a similar system in the United State, called the LORAN, short for LOng Range Aid to Navigation. Deployed in mid-1942 and continuing into the 1980s, although LORAN had many common features with Gee (and in many cases, the same engineers worked on both systems), it also had several differences. Perhaps most significantly, these stations operated at lower frequencies (1.75–1.95 MHz). This lower frequency range allowed for better propagation in the atmosphere, meaning that signals could be received as far as 2500 km away from the transmitters at night or 1300 km during the day [62]. This longer distance reception was accompanied by the disadvantage of more complicated received signals, which were often distorted by the longer transit, requiring extensive training to decipher [61], but also meant that the system, while usable at longer distances than the Gee system, also yielded lower accuracies. Although the possible range of received signals was more than 2000 km, the average location error was found in practice to be about 2% of the range from transmitters, yielding an error of 45 km when the receiver was 2300 km from the transmitter [63]. By the end of World War II, more than 70 LORAN stations were in operation, and stations continued to be added over the following several decades to add coverage to the mid-Atlantic and southern Pacific [59].

The next major radio navigation network was the Decca Navigator System, which was deployed in the UK during World War II, then expanded during the 1950s to networks around
the world [64]. While the Gee and LORAN systems relied upon comparisons of the arrival times of pulses from multiple stations, the Decca network relied on transmitters transmitting continuous waves at different harmonic frequencies, all of which were in the low frequency (LF) range, operating at frequencies of 70–129 kHz [65]. By measuring the phase difference between two transmitters, it was possible to determine which hyperbolic curve the receiver was located on. Each Decca chain consisted of a master and three slaves, allowing positions to be triangulated according to associated maps and, later, calculated using microprocessors. Because the phase differences are all calculated modulo 360 degrees, the hyperbola for any pair of transmitters can also be only calculated modulo approximately 10.5 km. Careful constant monitoring of the phases was necessary to ensure that this uncertainty was taken into account [66]. The Decca networks were eventually taken out of service beginning in the late 1990s, with the last Decca chain ceasing operation in early 2001 [67]. Accuracy of the Decca system, like other hyperbolic navigation radio networks, was largely dependent on range, with accuracies as small as a few meters when on top of the network to several kilometers towards the limits of the range [68]. The range of a Decca chain was limited in practice to just a few hundred kilometers [67]. At night, the received signals were also more likely to be distorted during transit, sometimes leading the receiver to miscalculate the number of complete cycles observed, resulting in location errors of more than 10 km without the operator knowing [69].

The next major iteration of the LORAN network (called LORAN-C, with the older version being retroactively renamed LORAN-A) combined the non-ambiguous location-finding of pulse timing networks with the greater accuracy of the phase comparison techniques [70]. Operating in the LF frequency range (90–110 kHz), the system was in use in more than a dozen countries by 1962 [71], dominated the navigation system market in the 1980s and 1990s, and continued operation until the last networks were finally removed from service in 2015 [72]. The range of the LORAN-C system was significantly dependent on the power of the transmitting network, but ranges of 5000 km were achievable in some cases with sufficiently high-powered transmitters [73]. LORAN-C networks eventually covered most of
North America, Europe, and the Pacific Rim, with location accuracy typically being within half a kilometer [74].

The first truly global radio navigation system was the Omega network. Developed by the United States, it was operational between 1971 and 1997 and operated in the very low frequency range, with stations transmitting between 10 and 14 kHz [73]. Signals transmitted within the VLF range propagate extremely well in the atmosphere with little attenuation, due to the presence of the ionosphere. The boundary of the ionosphere, a collection of charged particles beginning at altitudes of about 60 km, and the earth form a waveguide-like structure, allowing signals below approximately 30 kHz to be detected at very long distances [75]. As these signals propagate long distances however, they reflect off of the ground and ionosphere before arriving at the receiver. Each additional hop adds additional distortion. Furthermore, as the ionosphere experiences diurnal changes, its state can significantly affect propagation properties [76]. Because of these factors, extracting precise timing information from a master signal can be difficult at large distances for signals that have undergone an unknown number of hops [77]. The introduction of atomic clocks allowed for the synchronization of multiple transmitters without having to rely on the master/slave relationship [78]. The Omega system took advantage of the accuracy of atomic clocks, with each station transmitting a unique time-synchronized pattern of pulses. By identifying the timing of individual pulses and comparing received phases, the Omega system allowed for worldwide location accuracy within about 7.5 km [61]. Because of the long-range abilities of a VLF-based system, worldwide coverage was achieved with only eight transmitters, operating around the world. Because of the long propagation distances, calculation of hyperbolic curves was non-trivial and varied depending on time of day and propagation paths [79].

1.3.2 Advantages and disadvantages of VLF navigation

As mentioned above, the ability of VLF waves to propagate extremely long distances makes this frequency range well-suited to its use for radio navigation purposes. Because VLF signals can propagate with less than 2 dB of loss per 1000 km [7], each transmitter has a much larger
area that it can service. In addition, each transmitter can operate at lower power. Omega transmitters, for example, operated at powers of just 10 kW [80], compared to 100 kW for long-distance LORAN-C networks [74].

Because of the long range of VLF transmitters, very few transmitters are required, especially when compared to higher frequencies. The Omega system, for example, achieved worldwide coverage with only eight transmitters [76]. The LORAN-C system, for comparison, required more than 120 transmitters and still only covered the continental United States, Europe, and portions of the Pacific Rim and mid-Atlantic ocean [74].

Compared to satellites, VLF transmitters, and terrestrial transmitters in general, have several advantages. Because even the remotest island is more easily accessible than the orbits used by GPS satellites, repairs are simpler and changes are easier to implement.

Location systems have also always been prone to interference and jamming. Development of the Decca system just a few years after the Gee system was significantly spurred by German jamming of the known capabilities of the Gee system [61]. By simply transmitting large-amplitude noise in the frequency bands, it is possible to overpower and disrupt the transmitter signals, which are often very faint by the time they arrive at a receiver of any navigation system. GPS systems, especially, are prone to jamming and interference, including poor weather, tall buildings, and GPS-specific jammers, which are relatively cheap and easy to construct [81].

VLF-based systems, however, are practically impervious to jamming. Because of the low frequency of the signals used, the wavelength of said signals is very long, approximately 30 km for a 10 kHz signal. Because antennas that are less than a quarter wavelength in length suffer from gross inefficiencies, antennas used to transmit VLF signals must necessarily either be very large, have high input power, or, preferably, both. The Omega transmitters were generally either radio masts about 400 meters in height or antennas consisting of many several-kilometer wires strung over a valley [80]. Because of the large size and power requirements of VLF transmitters, jamming VLF signals by transmitting in-band noise is an impractical task, a definite advantages over GPS and radio navigation networks operating
at higher frequencies.

Navigation networks operating in the VLF realm suffer from two main disadvantages: transmission and accuracy. While the requirement for very large antennas or high transmission powers prevents jamming, it also makes construction and operation of VLF transmitter towers both technically difficult and expensive. This makes VLF transmitters unappealing in many cases, particularly for organizations concerned with the cost of operation. Furthermore, VLF transmitters are certainly stationary and not able to be transported due to political or environmental concerns.

Accuracy of VLF-based systems is also lower than those of GPS or higher-frequency radio systems (such as LORAN-C). This is primarily a function of the large wavelength of VLF signals, which makes it difficult to instantaneously detect precise phases or the beginning of a pulse, both of which can be easily influenced by propagation. Without the ability to measure these values precisely, VLF systems are less accurate than those operating with shorter wavelengths [73].

1.3.3 Current terrestrial VLF MSK-encoded transmitters

Despite the relative cost and complexity of operating VLF transmitters, the benefits of their long-range transmission capabilities can often outweigh the cost. The National Institute of Standards and Technology (NIST), for example, broadcasts an atomic clock-derived time signal at 60 kHz from a station near Fort Collins, Colo. that is used to synchronize most consumer time-synchronized clocks in North America [82]. More commonly, VLF transmitters are operated by national militaries around the world for long-distance one-way communications with deployed assets, usually submarines. The long-range capabilities of VLF transmitters means that their messages can be heard around the world without the transmitter requiring knowledge of even the general location of the receiver. Furthermore, because of the long wavelength of VLF transmitters, VLF signals will penetrate several dozen meters into seawater, allowing for submerged submarines to receive messages without having to surface and reveal their position. The five transmitters discussed in this work are all operated by
Table 1.2: List of VLF transmitters examined in this work

<table>
<thead>
<tr>
<th>Call Sign</th>
<th>Location</th>
<th>Frequency (kHz)</th>
<th>Latitude (°N)</th>
<th>Longitude (°W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPM</td>
<td>Lualualei, Hawaii</td>
<td>21.4</td>
<td>21.420</td>
<td>158.154</td>
</tr>
<tr>
<td>NAA</td>
<td>Cutler, Maine</td>
<td>24.0</td>
<td>44.645</td>
<td>67.281</td>
</tr>
<tr>
<td>NLK</td>
<td>Jim Creek, Wash.</td>
<td>24.8</td>
<td>48.203</td>
<td>121.917</td>
</tr>
<tr>
<td>NLM</td>
<td>LaMoure, N.D.</td>
<td>25.2</td>
<td>46.366</td>
<td>98.336</td>
</tr>
<tr>
<td>NAU</td>
<td>Aguado, Puerto Rico</td>
<td>40.75</td>
<td>18.399</td>
<td>67.178</td>
</tr>
</tbody>
</table>

Because of the limited bandwidth of VLF transmissions, video or even voice communication is impossible. Instead, transmissions are limited to coded text transmission. Typically, VLF transmitters utilize frequency-shift keying (FSK) with the majority using a type of FSK called minimum-shift keying (MSK). MSK is particularly advantageous because of its phase continuity, compact spectrum, and higher data transmission rate than other types of FSK. Even so, MSK-encoded VLF transmitters are extremely limited in their data rate, with most systems in the world transmitting at a baud rate of 200 bits/second. This allows for 25 ASCII characters to be transmitted per second (or about 300 words/minute).
Details for the five American transmitters used here are given in table 1.2 and figure 1.4. It is interesting to note that two of the transmitters (NLM in LaMoure, North Dakota and NPM in Lualualei, Hawaii) both operated as transmitters for the Omega navigation system. Because the five transmitters here are spread around the periphery of the United States, they allow for good reception in the continental United States, particularly in the interior of the country. Although the work here focuses on VLF transmitters operated in the United States, transmitters operating in other countries (including Australia and Iceland) are detectable using the techniques described here. Furthermore, this technique could be extrapolated to utilize the dozens of VLF transmitters operated by countries around the world to allow for worldwide coverage.

1.3.4 Description of MSK-encoded signals

MSK encoding relies on two offset bit streams \( b_I \) and \( b_Q \), each of which has been encoded with a positive half-sinusoid for the 1 bit and a negative half-sinusoid for the 0 bit. These in-phase \( s_I(t) \) and quadrature \( s_Q(t) \) components are given in equations 1.4 and 1.5, with \( T_b \) being the bit time for a single bit in the overall signal (\( T_b = 5 \text{ ms} \) for the transmitters here).

\[
s_I(t) = b_I(t) \cos \left( \frac{\pi t}{2T_b} \right) \quad (1.4)
\]

\[
s_Q(t) = b_Q(t) \sin \left( \frac{\pi t}{2T_b} \right) \quad (1.5)
\]

\[
s(t) = A \left[ s_I(t) \cos (2\pi f_c t + \phi_c) + s_Q(t) \sin (2\pi f_c t + \phi_c) \right] \quad (1.6)
\]

As is visible in figure 1.5, these bit streams are each mixed with a carrier wave of frequency \( f_c \), with the in-phase sinusoid bit stream, \( s_I(t) \), being mixed with a cosine carrier, and the quadrature sinusoid bit stream, \( s_Q(t) \), being mixed with a sine carrier. After mixing, the two orthogonal components are summed to create the final MSK-encoded signal, \( s(t) \), as given
in equation 1.6, where $A$ is the transmitted amplitude and $\phi_c$ is the constant phase offset of the carrier. MSK is spectrally compact and has good error performance, allowing it to be used in a wide variety of circumstances, including satellite communications, Blu-ray discs, and the GSM cellular network [83].

1.4 Contributions

The following contributions are described in this dissertation:

- Design, construction, and testing of a magnetic field sensor operating in the ELF and VLF frequency ranges is described. Creation of a low-cost, repeatable magnetic field
sensor allows for the construction and deployment of many sensors at a much cheaper cost than comparable commercial systems. This sensor has a flat gain bandwidth of 2.1 Hz to 50 kHz and is capable of long-term outdoors deployment in adverse weather, making it well-suited for ongoing, continuous measurements of lightning and other ELF/VLF sources.

• Using this and similar sensors, tens of thousands of lightning events are analyzed using time-aligned epoch averaging. Through time-aligned averaging, sensor and environmental noise can be minimized, allowing for the characterization of lightning processes with extremely faint emissions to be measured at large distances (current moments smaller than 7.8 A km at 1000 km). Time-aligned averaging also allows for the investigation of similar types of lightning from a single sensor on much larger scales, allowing for much greater statistical power than examination of individual events. While some average flash parameters, such as total charge moment change, can be measured directly, others, such as post-first-stroke -CG distributions, are investigated using Monte Carlo simulations. Finally, the averaged cloud-to-ground lightning events from four storms were analyzed and compared.

• NBEs, a type of in-cloud lightning of which much is still not fully understood, are also good candidates for time-aligned averaging. While some NBEs develop into other types of lightning, including in-cloud and cloud-to-ground flashes, other NBEs do not. Through time-aligned averaging of multiple sensor systems, the link between initiator NBEs and those which occur in isolation is examined, yielding differences in initiator NBE pulse width. Pre-NBE conditions are also examined using sensors operating in a variety of frequency ranges.

• Man-made VLF transmitter signals also propagate well within the atmosphere. By examining the MSK-encoded signals, a method of determining the propagation distance from transmitter to receiver by comparing MSK sideband phases is developed and demonstrated. Using multiple transmitters allows for the localization of the receiver
within a few kilometers of the correct location. Capabilities and limitations of this localization technique were investigated through simulation, as well as tests in both good and non-ideal operating conditions, allowing for the determination of limiting factors in the accuracy of the system.
In this chapter, the design and testing of an ELF/VLF magnetic field receiver is described. This Duke ELF/VLF receiver, hereafter referred to as the “DEV” system, has many potential applications in measuring and monitoring sources of atmospheric electrical activity, including lightning and VLF transmitters.

2.1 Motivation of Sensor Design

As mentioned in section 1.2, currents flowing in lightning channels produce magnetic fields that are detectable at a considerable distance. Section 1.1 details why frequencies in the ELF and VLF ranges are of particular interest in lightning research. By measuring the magnetic fields in these frequency bands, it is possible to characterize and measure lightning remotely. Commercial systems are available, but typically cost several thousands of dollars. Furthermore, these systems are often available only in very limited quantities. Attempting to acquire several complete systems in a short time period is infeasible. Even more problematic, Schlumberger’s BF-4 sensor, a magnetic field sensor operating in the ULF frequency range commonly used for lightning research [84, 85, 86], is no longer manufactured or serviced.

An example of a commercial ELF/VLF receiver used for lightning research is the one manufactured by Quasar Federal Systems (QFS) [87, 88], which has a flat gain from 2.1 Hz
Figure 2.1: Circuit model of the magnetic search coil: \( L, R, C \) are parameters of the coil; \( R_0 \) and \( C_0 \) are the load resistance and capacitance of the preamplifier.

to 25 kHz. A low-cost sensor with similar performance specifications would allow for more widespread deployment and easier monitoring and measurement of lightning and other atmospheric electricity. Most lightning magnetic field sensors are induction magnetometers, and consist of two sections – a magnetic loop antenna (referred to in this work as the coil) and an amplifier circuit. The specific design of these components is detailed below.

2.2 Construction and Design of Sensor

A magnetic search coil is essentially a loop antenna whose circumference is much smaller than the wavelength of interest. This allows for a somewhat constant current to be produced on the coil as a result of Faraday’s law of induction, which states

\[
V = -\mu_c \cdot \mu_0 \cdot n \cdot A \cdot \frac{dH}{dt}
\]  

(2.1)

where \( V \) is the EMF induced on \( n \) coils of wire with area \( A \) surrounding a ferromagnetic material of effective relative permeability \( \mu_c \), by a changing magnetic field \( dH/dt \), with \( \mu_0 \) being the permeability of free space. Performance of a search coil depends on several factors. Increasing sensitivity to a given magnetic field can be accomplished by increasing the effective relative permeability \( (\mu_c) \), increasing the number of turns, or increasing the area of the loops.

The model of the search coil is given in figure 2.1. Assuming a low-impedance loading of the coil, the frequency response of the coil can be described using the three circuit ele-
ment parameters of the coil. For the coil design considered here, the frequency response is considered to be flat between the frequency \( f_l \) and the self-resonant frequency \( f_0 \). The coil frequency response exhibits peaking around \( f_0 \); because a large, flat bandwidth is desired, \( f_0 \) is designed to be as far above the frequency band of interest as possible in order to allow for sufficient filtering to limit the non-linear effects around \( f_0 \). \( f_l \) and \( f_0 \) are given by

\[
f_l = \frac{R}{2\pi L} \tag{2.2}
\]

\[
f_0 = \frac{1}{2\pi \sqrt{LC}} \tag{2.3}
\]

where \( R, L, \) and \( C \) are the equivalent parameters from figure 2.1. To achieve the best low-frequency response possible, \( L \) should be maximized. This, however, also decreases \( f_0 \), which is undesirable. To achieve the lowest \( f_l \) and highest \( f_0 \), \( R \) and \( C \) should both be minimized, respectively. \( R \) is a function of the wire used in the coil windings. A shorter length of wire results in a lower \( R \), but would yield fewer turns on the coil and decrease the \( L \) value. More turns result in higher values for both \( R \) and \( L \), so a balance must be achieved to maximize the ratio between the inductance and resistance gained for an increase in wire length. Figure 2.1 also shows the load capacitance and resistance, \( C_0 \) and \( R_0 \), respectively.

Coil capacitance comes from two main sources, which are referred to as intralayer and interlayer. In order to achieve a high number of turns, coils are typically wound with several
layers of coils, especially near the center of the core where the effective permeability is highest. Capacitance in the coil occurs when turns are in close proximity to each other. Interlayer capacitance is capacitance that occurs between different layers having a high amount of surface area in close contact. This type of capacitance occurs between turns of wire that are not adjacent. Intralayer capacitance occurs as a result of adjacent windings that are positioned in proximity to each other. Figure 2.2 demonstrates the two types of coil capacitance, with $C_L$ being interlayer capacitance and $C_W$ being intralayer capacitance.

Capacitance of the coil can be controlled in two main methods. First, the coil windings are often subdivided into smaller sections of close windings, with some distance between the sections. From a circuit-level perspective, this divides the single large capacitor of the unpartitioned coil into several smaller capacitors connected in series. Because of the nature of series capacitors, this yields a total capacitance much lower than that of a single-section coil. Second, the coil sections can be wound using certain winding schemes. Unlike winding methods that attempt to minimize horizontal space for a given number of turns (and therefore maximize surface area within and between layers), some winding schemes (such as basket winding or the Ayrton-Perry winding scheme) are designed to minimize capacitance by minimizing nearby surface area. In these, adjacent turns are more spread out and only cross each other at nearly right angles. However, both the basket winding and Ayrton-Perry schemes require complicated jigs and winding machines to achieve. To remedy this, a different scheme termed “scatter winding” was used for this work. In this scheme, turns were spread out at approximately random spacing with no attempt to form specific layers. This method was found to be sufficiently effective at reducing capacitance without the need for complicated equipment.

Coils were constructed using a ferrite core with $\mu_r = 2000$, $l = 28\text{ in}$, and $d = 0.845\text{ in}$. The core was coated in plastic for stability, bringing the total diameter to 1 inch and was wound with 24AWG magnet wire. Magnet wire has an enameled insulation, making it suitable for use in narrow confines such as search coil windings. To maximize inductance, sections closer to the middle of the core were given a greater number of turns than those
Search coil magnetometers produce an electric current as a function of their measured magnetic field. This current must be converted to a voltage before it can be amplified, transmitted, or recorded. In this work, this is accomplished through the use of a transimpedance amplifier (TIA) circuit, shown in figure 2.3. To limit common mode noise, the search coil is tapped in the middle, creating two oppositely oriented coils, each of which is half of the overall coil (figure 2.3(a)). Each half-coil is connected to its individual TIA (figure 2.3(b)), the outputs of which are connected to an instrumentation amplifier (figure 2.3(c)). After the instrumentation amplifier, the output signal passes through a passive single-pole low-pass filter (LPF), which helps limit the resonance of the coil and clean up the undesirable portion.
of the signal (figure 2.3(d)). This filter is set at $f_c \approx 48$ kHz but can be tuned depending on the characteristics of the coil and deployment site. Finally, the signal is conditioned using a unity-gain line driver which is capable of driving coaxial cable loads at distances of several hundred meters (figure 2.3(e)). An optional differential line driver is also installed for further limiting common-mode noise. This differential line driver also allows for the transmission of several sensor outputs and power connections over a single cable with multiple conductors.

2.3 Deployment and Test Conditions

As the DEV sensors are intended for long-term outdoors deployment, steps must be taken to ensure survival and continued operation of the sensors. Coils are housed in PVC pipes which have been attached to PVC boxes which contain the amplifier electronics. This enclosure (seen in figure 2.4) has been tested to be impact-resistant and waterproof to 1 m for 30 minutes, allowing it to withstand exposure to wind and rain. To provide an extra layer of protection, packaged sensors are placed inside additional weatherproof enclosures, which also make the sensors easier to transport, align, and set up in a minimum amount of time.

Initial gain and frequency response testing was performed in the laboratory, yielding the gain amplitude results for two of the constructed sensors shown in figure 2.5. After laboratory testing, sensors were deployed at the Duke Forest research site near Durham, N.C.
Figure 2.5: Gain of orthogonal channels of DEV system

(35.970° N, 79.094° W) which is permanently equipped with a variety of magnetic sensors, including the commercial QFS ELF/VLF system (2.1 Hz–25 kHz) and a Duke VLF (DVLF) system (100 Hz–12 kHz). All ELF/VLF systems, including DEV, DVLF, and QFS systems, were operated in continuous data collection mode and sampled at a rate of $f_s = 100$ Sa/s.

2.4 Sensor Testing

Although two DEV sensors are typically deployed in an orthogonal manner, for testing, all sensors were deployed in a north/south arrangement. As DEV coils are designed to emulate the nominal performance of the QFS coils, four DEV coils were tested in comparison to two identical QFS sensors, along with one DVLF sensor. Testing was conducted at the Duke Forest on 29 June 2015.

2.4.1 Bandwidth verification and comparison with similar sensors

For the purpose of quantifying the performance of the systems, five criteria were assigned weighted “point” values, based on subjective significance, for a maximum score of 100 points. One QFS system (denoted as QFS1) was chosen as the control system and assumed to be operating ideally. In addition to the four DEV and one DVLF sensors, another QFS system, denoted QFS2, was compared to QFS1 to see how similar performance was for two systems that should be nominally identical. The five criteria used for testing are as follows:
Schumann resonances (25 points) Power levels of the first two Schumann resonances (7.3 and 14.0 Hz) were compared, with the ratio of powers being the normalized value. These are the standing wave frequencies within the earth ionosphere waveguide (section 1.1) and are a valuable source of information about ionosphere and global lightning conditions.

VLF transmitter (25 points) Power levels were compared for three VLF transmitters (NAA, NLK, and NLM). Transmitters are described in section 1.3.3 and table 1.2). Scores for the three frequencies were summed and normalized.

Power line harmonics (10 points) Power levels for each 60-Hz harmonic from 60 Hz to 3 kHz were compared. Each increasing harmonic was weighted less than previous ones.

General lightning waveguide (10 points) Ratio of the background power level between 5 kHz and 11 kHz was compared. This band is dominated by distant lightning signals.

Transient lightning signals (30 points) CG events with $|I_{pk}| \geq 30$ kA between 300 km and 600 km from the test site were analyzed. The correlation coefficient of 25 ms windows was calculated, with the coefficients being summed and normalized.

To calculate the field bandwidth of the DEV sensors, 46 lightning CG events were analyzed for one DEV, DVLF, and QFS sensor. For each event, the fast Fourier transform (FFT) was calculated for a 400-millisecond window beginning a few milliseconds before the return stroke. For each event, the ratio between DEV and the other two systems was calculated at each frequency and averaged. By incorporating the known response of the DVLF and QFS systems, different potential frequency rolloffs for the DEV system can be calculated and compared with the measured results.

2.4.2 Results of testing and comparison with comparable sensors

During field testing on 29 June 2015, four DEV sensors (DEV1, DEV4, DEV5, and DEV7) were tested. An example of the calculated PSDs for the control sensor (QFS1) and DEV7,
as well as QFS2 and DVLF, can be seen in figure 2.6. The two Schumann resonances are marked in figure 2.6(a), while figures 2.6(b) and 2.6(c) show the power-line harmonics and the VLF transmitter frequencies, respectively. Figure 2.6(d) shows an example of the frequency spectrum band where lightning signal is expected to be the dominant contributor.

Figure 2.7 shows an example of a lightning event that was analyzed for the transient signal testing. The figure shows the return stroke of a CG event for two DEV and two QFS systems. The event had a peak current of $-43 \text{ kA}$ and occurred 432 km from the test site.

Table 2.1 shows the results of the normalized values for the Schumann resonances (SR), power line harmonics (PL), lightning band (LB), VLF transmitters (VLF), and lightning events (EV). Each of those normalized values is weighted according to the point values described in section 2.4.1, with the final value also listed on the table. As is readily visible, all DEV systems performed markedly better than the second QFS system, especially for the analyzed lightning events. This implies that the DEV systems are presumably more similar
Figure 2.7: Example of typical lightning example. This CG event had a peak current of −43 kA and was located 432 km from the Duke Forest. Signals are offset by 0.5 nT.

Table 2.1: DEV testing results using QFS1 as control sensor

<table>
<thead>
<tr>
<th>Name</th>
<th>SR (25)</th>
<th>PL (10)</th>
<th>LB (10)</th>
<th>VLF (25)</th>
<th>EV (30)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEV1</td>
<td>0.9685</td>
<td>0.7890</td>
<td>0.9783</td>
<td>0.8212</td>
<td>0.9925</td>
<td><strong>92.1925</strong></td>
</tr>
<tr>
<td>DEV4</td>
<td>0.9895</td>
<td>0.7388</td>
<td>0.9291</td>
<td>0.7913</td>
<td>0.9892</td>
<td><strong>90.8765</strong></td>
</tr>
<tr>
<td>DEV5</td>
<td>0.9591</td>
<td>0.7053</td>
<td>0.8394</td>
<td>0.8576</td>
<td>0.9920</td>
<td><strong>90.6244</strong></td>
</tr>
<tr>
<td>DEV7</td>
<td>0.9710</td>
<td>0.6940</td>
<td>0.7885</td>
<td>0.8470</td>
<td>0.9939</td>
<td><strong>90.0926</strong></td>
</tr>
<tr>
<td>QFS1</td>
<td>1.0000</td>
<td>1.0000</td>
<td>1.0000</td>
<td>1.0000</td>
<td>1.0000</td>
<td><strong>100.0000</strong></td>
</tr>
<tr>
<td>QFS2</td>
<td>0.9105</td>
<td>0.8555</td>
<td>0.8441</td>
<td>0.6225</td>
<td>0.9570</td>
<td><strong>84.0310</strong></td>
</tr>
<tr>
<td>DVLF</td>
<td>0.6461</td>
<td>0.3457</td>
<td>0.3005</td>
<td>0.2280</td>
<td>0.5427</td>
<td><strong>44.5957</strong></td>
</tr>
</tbody>
</table>

and performing better than two nominally identical QFS systems operating in the field.

To verify the similarity of the DEV systems, the analysis was performed again, this time using DEV1 as the “control” sensor to which the other sensors were compared. By using the DEV system as the base system for comparison, the DEV systems are measured to be much more consistent (all scores greater than 90 points) than the identical QFS systems were (score of 84.031 points in table 2.1), thus confirming our assessment of the DEV systems as sufficiently repeatable.

The field bandwidth measurements (given in figure 2.8), confirm the lab bandwidth measurements. Figure 2.8(a) shows the ratio at each frequency between the DEV1 and DVLF systems. The black dashed line assumes that the DVLF bandwidth is flat for the same bandwidth as the DEV sensor, while the red dashed line has been adjusted for the known
frequency rolloff of the DVLF system starting at 12 kHz. The filters required to achieve this fit are two low-pass filters with cutoffs of 50 and 80 kHz. These are explained by the design of the sensor, with the 50 kHz LPF being due to the passive low-pass filter in the amplifier and the 80 kHz LPF being due to the natural rolloff of the coil (section 2.2). Figure 2.8(b) shows that the frequency response of the DEV system is the same at the low end as that of the QFS sensor down to at least 1.2 Hz. Therefore, the bandwidth of the DEV sensor is flat between 2.1 Hz and 50 kHz.

2.5 Conclusions

The work presented in this chapter details the design and testing of a new Duke ELF/VLF (DEV) magnetic field receiver. This new DEV system functions better and is more consistent than commercial systems, but costs a fraction of the price. This lower price point, as well as complete control over the design and manufacturing process, allows for more extensive use
and deployment for a variety of purposes. The work detailed in this chapter will allow for many long- and short-term applications, such as measuring signals produced by lightning (such as an application similar to chapters 3 and 4), as well as measuring and characterizing the signals emitted by transmitters in the VLF frequency range (section 5).
In this chapter, a method of measuring and characterizing large numbers of lightning flashes at particularly long distances (greater than 1000 km) for storms that span large geographic areas is described. This method is capable of extracting and measuring average signals that are below the noise floor for individual events, but are visible when utilizing the averaging technique here. By averaging thousands of +CG and tens of thousands of -CG events, the averaged noise level is low enough to allow for the measurement of low magnitude processes, such as pre-stroke leader and post-stroke continuing current.

3.1 Background and Motivation of Epoch Averaging

As discussed in section 1.2, lightning is a common process that happens frequently, but can be difficult to measure. Lightning strikes of instrumented towers, although allowing for very accurate measurement, are limited in number. The electric dipole is a simple method of performing measurements, but decays quickly with distance from the storm, at the rate of $1/r^3$ (with $r$ being the distance from lightning to receiver), limiting effectiveness to about a hundred kilometers. Magnetic fields decay more slowly, at the rate of $1/r$, allowing measurement and characterization of lightning parameters to be accomplished at large distances, most significantly charge moment change [52, 89]. In some cases, exceptionally large con-
continuing current can be measured using this method [53]. However the applicability of these measurement techniques to typical individual events at larger distances is limited, as the signal low-magnitude processes is easily obscured by both sensor and environmental noise.

There is also usefulness in being able to perform measurements over larger geographical areas. Because thunderstorms are not typically stationary, the time in which they remain over heavily instrumented areas cannot be easily predicted or controlled. Reducing the effective noise levels of measurement equipment would enable the study of lightning events at much farther distances than would normally be useful, thus allowing for the study of much larger numbers of lightning events than have been conducted previously. Studies of long continuing current, for example, have mostly been conducted in geographically constrained areas, meaning that most statistical knowledge of this important lightning process has come from measurements involving just tens to hundreds of strokes [29, 31, 48, 90, 91, 92]. Knowledge and understanding of continuing current and other important lightning processes that produce weak electromagnetic field signatures could be dramatically improved with long-distance measurements.

3.2 Materials, Data, and Epoch Averaging Procedure

3.2.1 Sensors

As this work is primarily interested in the charge transfer over long time scales (greater than 1 ms), the primary frequency range of interest is frequencies less than 500 Hz. Therefore, the primary sensor system used in this work is an orthogonal pair of EMI BF-4 magnetic field sensors with a flat frequency response between 0.3 and 500 Hz. In this analysis, we compensate for the single pole roll-off below 0.3 Hz and thus are able to examine time scales as long as several seconds. The system is located at the Duke Forest research station near Durham, N.C. (35.970° N, 79.094° W) and is sampled at a rate of \( f_s = 2.5 \, \text{kSa/s} \).
Although individual events may possess continuing current or pre-stroke activity, such small
signals are often not visible above the noise floor for the sensors. Noise sources at individual
frequencies (such as 60 Hz power line harmonics) can be effectively removed from individual
signals using a variety of techniques [93, 94, 95]. Broadband noise (such as most environmen-
tal or sensor noise) is more difficult to remove from individual events without compromising
the integrity of the individual measurements. Because such noise is broadband, however, by
averaging signals together, the effective noise level of the system can be reduced by a factor
of $1/\sqrt{n}$, where $n$ is the number of events being averaged, given that the desired signals can
be time-aligned and added coherently [96]. This noise reduction comes at the cost of losing
any ability to remark specifically about any of the individual events of interest.

For each section of this work, identical lightning events (such as +CG or -CG first return
strokes) are selected from each storm by examining data from Vaisalas National Lightning
Detection Network (NLDN) [97]. The NLDN is a network of more than a hundred magnetic
and electric field sensors operating in the VLF and LF frequency ranges. By using multiple
stations, the NLDN has an approximately 90%–95% detection rate for lightning in the United
States [98], with peak current estimates with median error within 15% [97]. To ensure
maximum alignment, analyses in this work include a basic peak-search algorithm. This
search locates the moment of the largest magnetic field magnitude (defined here as $t = 0$),
assumed to be the center of the return stroke, which contains the highest current magnitude
and longest conducting channel.

An example of this averaging process can be seen in figure 3.1. In figure 3.1(a), the ULF
signal from a single time-aligned event is shown. The background noise level is roughly 10 pT,
and signals from return strokes in other storms are a major noise source. By aligning and
averaging 100 events from the same storm (figure 3.1(b)), coherent features of the stroke are
enhanced and the weak signal from post-return processes begins to emerge. After averaging
10,000 events (figure 3.1(c)) sensor noise and non-coherent events are low enough to allow for
the emergence of very low-amplitude features (hundreds of femtotesla), including apparent leader initiation (figure 3.1(d)) and the around-the-world Schumann resonance pulses (SR) (figure 3.1(e)). These SR pulses are the lightning return stroke signals signal arriving at the receiver after traveling around the world once or more in the direction opposite from the shortest path. Because of their much longer propagation distance, these pulses are much smaller than the return stroke signal arriving directly and are superimposed on the shorter path post-return stroke signal, produced by the sum of continuing current and the average of many subsequent strokes which produces the DC offset in the figure. This small-magnitude SR signal is not visible beneath the noise floor of any individual events, but is easily visible using the averaging technique described here.

For this work, in addition to the simple averaging procedure, a boxcar filter was applied to sections of the averaged waveform in which the signal of interest was significantly slower.
Figure 3.2: Effect of increasing number of events on averaged noise level

than the width of the boxcar. This further reduces the noise in parts of the signal where we know that the highest frequencies are pure noise. Areas of fast signal change, such as the time period around the return stroke, did not have the boxcar filter applied.

After time adjustment, events are averaged without any normalization of values. To quantify the effect of averaging on the noise level of the signal, the standard deviation of the one-second window between $-3 \, s < t < -2 \, s$ (well before the lightning events of interest) is used as a figure of merit for the noise level of the overall signal. By averaging many similar events, the system noise (standard deviation) can be seen in figure 3.2 to reduce through averaging alone at a rate that follows the expected $1/\sqrt{n}$ reduction in broadband noise levels, dropping to roughly $\sigma = 200 \, $fT for $n = 10,000$. In this work, $n$ rises as high as 23,826 for -CG first strokes during one storm and the broadband noise level drops as low as $\sigma = 151.7 \, $fT with averaging alone. Through appropriate use of the boxcar filter, the broadband noise level is decreased further to 28.4 fT.

We can compute an initial estimate of the measurement sensitivity that can be achieved with this approach. Long-duration continuing lightning currents, which are of particular interest in this work, can be modeled as near-DC electrical currents flowing in a vertical channel. The magnetic field of such a quasi-static arrangement can be described by the equation
\[ B_\phi = \left( \frac{\mu_0}{2\pi r} \right) \left( \frac{h_s}{h_i} \right) I \] (3.1)

where \( r \) is the distance from source to receiver, and \( h_s \) and \( h_i \) are the length of the lightning channel and ionosphere height, respectively \([52]\). In this equation, at large receiver distances \((r \gtrsim h_i)\), the field polarity does not change and scales linearly with current magnitude and inversely with receiver distance. By this analysis, achieving an effective sensor noise level of 28.4 fT as described above allows for the measurement of quasi-continuous current moments as small as 7.8 A km, and thus a continuing current of just 1 to 2 A, at a measurement distance of 1000 km, assuming a sharp ionospheric height of 55 km.

### 3.2.3 Limits of signal averaging

For the aligning and averaging process to coherently reinforce the desired signal, it is essential that the signals that are combined do not partially cancel. If all of the signals to be averaged originated in a narrow window in time and space, then we can assume that each was produced by exactly the same propagation characteristics or impulse response. Linearity of the convolution operator then says that the average of the signals is the same as the convolution of the average source with the single impulse response.

However, in order to capture many events in our analysis, we are interested in averaging signals over a range of propagation distances and a range of origination times, and thus we cannot assume that the propagation impulse response is the same for all events. This would cause a major problem, for example, in averaging VLF waveforms over a range of propagation distances because the highly oscillatory VLF impulse response from different distances will partially cancel.

We specifically target ULF/ELF averaging because the propagation impulse responses in this bandwidth are not oscillatory and, as we show here, do not suffer from partial cancellation. To investigate the impact and limits of averaging, we examine the propagation impulse responses for different distances, calculated using finite-difference time-domain simu-
Figure 3.3: Comparison of simulated impulse responses for several distances

Simulations (see section 3.5) and filtered to the 0–500 Hz bandwidth of the magnetic field sensors used in this work. Figure 3.3 shows the ULF/ELF propagation impulse responses (after peak time-alignment) across the propagation distance range of 750 to 1250 km, typical of the storms analyzed in this work. The impulse responses are not equal in magnitude due to distance-dependent attenuation and spreading, but at the two limits the shapes are nearly identical. Figure 3.3 also shows that the average of the two limiting impulse responses (750 and 1250 km) is very close to the impulse response at the average propagation distance of 1000 km (with 1.1% rms error). This means that the impulse responses across this entire distance range are simply amplitude scaled versions of each other. If we account for the amplitude scaling in our analysis (which we do), then we can meaningfully extract an average source current moment waveform from the average signal. This may not necessarily be true for signals across a wider distance range, but it is for the storms analyzed here.

3.2.4 Storm and event selection

For this work, CG events were selected from four candidate storms. Storms were selected that were approximately 900 km from the Duke Forest station. This distance allows for return stroke peaks to be visible in ULF frequency range, but renders small-magnitude signals (such as continuing current) below the noise floor. Selected storms, which occurred during 2013 and 2014, took place at the desired distance, but also during a time when little other lightning activity was occurring (other than the storms of interest) within range of the
Figure 3.4: (Top) Storm extent for selected storms. Red ‘X’ indicates location of the Duke Forest observation site. Concentric circles are separated by 200 km. (Bottom) Distance distribution for selected -CGs (blue) and +CGs (yellow) with 25 km bins for four storms.

<table>
<thead>
<tr>
<th>Storm</th>
<th>Storm Start (UT)</th>
<th>Storm End (UT)</th>
<th>Distance to Receiver (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8/06</td>
<td>6 Aug 2013 15:00</td>
<td>7 Aug 2013 05:00</td>
<td>650-1000</td>
</tr>
<tr>
<td>8/08</td>
<td>8 Aug 2013 15:00</td>
<td>9 Aug 2013 01:00</td>
<td>500-950</td>
</tr>
<tr>
<td>9/24</td>
<td>24 Sep 2013 10:00</td>
<td>25 Sep 2013 10:00</td>
<td>750-1250</td>
</tr>
<tr>
<td>8/17</td>
<td>17 Aug 2014 17:00</td>
<td>18 Aug 2014 02:00</td>
<td>500-1500</td>
</tr>
</tbody>
</table>

sensors.

Figure 3.4 (top) shows the range of the four storms chosen for analysis. For example, the first storm occurred on 6-7 August 2013. The storms footprint was greater than the area of Alabama, making it difficult to perform electrostatic field measurements of lightning from the entire storm without an extensive network of sensors. By contrast, the method of analysis described here is able to perform large-scale analysis of the entire storm with a single magnetic field sensor located many hundreds of kilometers away. Figure 3.4 (bottom) also shows the distance distribution of the selected events for the analyzed storms.
Table 3.2: Event counts for analyzed storms

<table>
<thead>
<tr>
<th>Storm</th>
<th>8/06</th>
<th>8/08</th>
<th>9/24</th>
<th>8/17</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>NLDN +CG Strokes (≥ 20 kA)</strong></td>
<td>1,348</td>
<td>673</td>
<td>3,208</td>
<td>2,132</td>
</tr>
<tr>
<td>First +CG Strokes</td>
<td>1,317</td>
<td>659</td>
<td>3,124</td>
<td>2,076</td>
</tr>
<tr>
<td>Subsequent +CG Strokes</td>
<td>31</td>
<td>14</td>
<td>84</td>
<td>56</td>
</tr>
<tr>
<td><strong>First -CG Strokes (≥ 20 kA)</strong></td>
<td>35,165</td>
<td>19,703</td>
<td>60,201</td>
<td>48,473</td>
</tr>
<tr>
<td>First -CG Strokes</td>
<td>17,157</td>
<td>10,242</td>
<td>23,826</td>
<td>22,987</td>
</tr>
<tr>
<td>Subsequent -CG Strokes</td>
<td>18,008</td>
<td>9,461</td>
<td>36,375</td>
<td>25,486</td>
</tr>
</tbody>
</table>

To ensure received individual signals would be sufficiently large for peak-detection algorithms, selected events were required to have a peak current magnitude greater than 20 kA. Because different types of lightning activity occur at different times during the flash (e.g. only the first return stroke is preceded by a stepped leader, but subsequent strokes may be preceded by continuing current), we average a flash based on the first return stroke in a given CG flash. CG strokes were defined to be those that occurred within 10 km and 500 ms of a previous ground stroke [91]. Geographic information on the selected storms can be found in table 3.1, with the number of eligible events in table 3.2.

### 3.3 Characterization of Averaged -CG Waveforms

Averaged events are divided for further examination according to polarity. These groups are analyzed during several distinct time periods (visible in figure 3.5(a)). For this work, the pre-stroke period is that for which $t < -2\text{ms}$ (which includes pre-stroke and leader activities), with the return stroke (RS) period being $-2\text{ms} < t < 4\text{ms}$. The post-stroke is that for which $t > 4\text{ms}$. Because of the averaging procedure, all post-stroke processes are superposed into a smooth signal during this time period, which includes processes like subsequent strokes, continuing current, M-components, and J- and K- processes. The first group of events to be examined is -CG events. For ease of analysis, the pre-stroke and post-stroke periods from a single storm (24 September 13) will be discussed in detail, then compared to other analyzed storms.
3.3.1 Features of -CG pre-stroke activity

The average -CG pre-stroke waveforms for the analyzed storms are given in figure 3.5(b). The 24 September 13 storm is plotted as the blue waveform. The values of reported initial breakdown processes in -CGs is typically at most 100 ms [33, 99] Some researchers, however, have reported observing storms with a significant percentage of flashes with initial breakdown periods in excess of 100 ms (with periods as long as 178 ms being observed) [100].

The averaged -CG pre-stroke waveforms are given in figure 3.5(b), with the 24 September 13 storm plotted as the blue waveform. The averaged signal shows activity clearly beginning ~500 ms before the return stroke (and may be as much as 800 ms before). This is much longer than previously observed, but signal magnitude is very small, reaching a maximum value of $|B_\phi| = 121 \text{ fT}$ and does not exceed a magnitude greater than 50 fT (corresponding with a current moment of 13.75 A·km at 1000 km) until less than 400 ms before
the return stroke. This duration of pre-leader activity is significantly greater that by other researchers for -CG flashes, which has been reported as 100 ms [99], most of which consisted of horizontal streamers within the cloud. Marshall et al. observed -CG flashes with initial breakdown (IB) pulses occurring up to 178 ms prior to the return stroke [100], much shorter than the averaged values here.

As with all averaged measurements, it is again significant to note that this measurement does not indicate that all (or even most) -CGs exhibit pre-leader activity this early. Rather, this indicates only that either a sufficiently high number of events exhibit faint activity or a small minority of events possesses large-magnitude activity significantly prior to the leader and return stroke. We think the former scenario is more likely, with a small fraction of the CG flashes containing activity this early. This early signal could be explained by large-magnitude hybrid IC-CG events and bolts-from-the-blue (BFBs), such as those described by Lu et al. in 2012 [41]. Both of these types of flash initially develop as positive IC events (with an upward negative leader) before transitioning much later into negative CG flashes. These hybrid IC-NCG and BFB events are typically extremely powerful and are responsible for the majority of -CG flashes with extremely large impulse charge moments (greater than $\sim 200 \, \text{C} \cdot \text{km}$), but are recorded by NLDN based on the return stroke time, meaning that any IC activity would occur at $t < 0$ after time-alignment. Marshall et al. observed a handful of hybrid IC-NCG flashes at distances of less than 50 km, some with activity occurring more than 500 ms prior to the first return stroke [100].

3.3.2 Features of -CG post-stroke activity

Waveforms for the post-stroke period are given in figures 3.5(a) and 3.5(c). This time period exhibits two particularly notable features. The first is a set of Schumann resonance signals, visible and labeled in figure 3.5(c). These are the pulses from the radiated energy that has traveled around the world one or more times. Because the source to receiver distance of 750 to 1250 km is short compared to the 40 Mm circumference of Earth, the energy that travels the long way around Earth arrives delayed (at $t \approx 155 \, \text{ms}$) and significantly smaller in
Figure 3.6: (a) Full waveform and (b) pre-stroke time period for average waveforms of -CG flashes from 24 September 13 storm with averaging based on subsequent strokes (blue) compared with averaging based on first strokes only (red).

magnitude (approximately 1 pT). The noise reduction via averaging even allows the energy that travels twice around Earth to be seen in a second pulse at approximately $t \approx 325 \text{ ms}$.

Because of the lack of continuing current, the overshoot exhibited as a result of filtering and hardware limitations is significant. After this point, the long-time scale waveform magnitude is measurable, with a peak value of $|B_\phi| = 0.4 \text{ pT}$.

The second major feature is a smooth and slowly-varying tail of several pT amplitude that decays over several hundred milliseconds, particularly visible in figure 3.5(a). This slow post-stroke signal is the average of all the downward negative charge motion that occurs after the first return stroke in the flash, primarily long continuing current and subsequent return strokes, all of which becomes a smoothly varying waveform after averaging tens of thousands of flashes. Although this signal is detectable all the way out to $t = 3 \text{s}$, the undershoot is produced by the frequency response of the sensor itself. The duration of the actual average flash current is approximately 1.5 seconds, as shown in section 3.5 where we extract in detail the quantitative current waveform responsible for the average signal.

To examine the relative contribution of subsequent strokes and continuing current on the post-stroke time period, the averaging process was also performed based on time-aligned
subsequent strokes only. For subsequent strokes, each included event would necessarily
include one or more previous return strokes at \( t < 0 \). Any signal before \( t = 0 \) is due to
both return strokes and interstroke continuing current, much like the signal for \( t > 0 \). The
resulting averaged waveforms for the 24 September 13 storm are given in figure 3.6, where
significant signal is present prior to \( t = 0 \). Because 95\% of subsequent strokes exhibit an
interstroke period greater than 7 ms [29] and a mean leader duration less than 2 ms [90], any
signal during the time period a few milliseconds before \( t = 0 \) is expected to primarily be
due to continuing current. This time period (which will be examined in greater detail in
section 3.5) is visible in figure 3.6(b), where the signal is, indeed, non-zero.

3.3.3 Comparison of -CG flashes between storms

We now turn to a comparison of the waveforms for the four observed storms, where many
similarities between storms emerge. All storms show faint activity beginning at \( t \approx -500 \text{ ms} \)
that is similar in polarity, which then transitions to a positive slope at \( t \approx -250 \text{ ms} \). The
waveforms of all storms are similar, although the positive-slope section from \( t \approx -800 \text{ ms} \) to
\( t \approx -500 \text{ ms} \) is more significant in the 8 August 13 and 17 August 14 storms than for the
24 September 13 storm. If an offset is added to the 24 September 13 storm to compensate
for this period, the resulting signals (from \( t \approx -500 \text{ ms} \) onwards) are nearly identical for the
four storms.

As seen in figures 3.5(a) and 3.5(c), the post-stroke time period for -CG events from
the selected storms appears to be nearly identical, both in magnitude and duration. The
Schumann resonances are visible at the same times as those in the single previously analyzed
storm, with the second resonance again being visible as a small dip at about \( t \approx 325 \text{ ms} \).

3.4 Characterization of Averaged +CG Waveforms

Averaged +CG events are now examined using the same procedure and time windows as
described for -CGs in section 3.3. The noise levels for +CGs in a given storm are higher
than those of the averaged -CGs. This is because the number of eligible -CG events for each
storm is significantly greater than the number of corresponding +CG events (table 3.2).

3.4.1 Features of +CG pre-stroke activity

The averaged pre-stroke waveforms for +CG events during the selected storms are given in figure 3.7(b), with the 24 September 13 storm plotted as the bold, blue waveform. One of the most noticeable features of this time period is measurable activity beginning at \( t \approx -1 \text{s} \). While this activity is longer than pre-stroke activity reported by previous researchers, this long measured pre-stroke period does not indicate that all, or even most, of the recorded events possess such extensive pre-stroke activity, only that the average stroke does.

Other researchers have also observed significant activity preceding many +CG flashes (see, for example \[101\]). Fuquay reported pre-stroke durations with \( \mu = 130 \text{ ms} \) and \( \sigma = 36 \text{ ms} \) for \( N = 75 \) \[27\], with Rust and MacGown reporting \( \mu = 241 \text{ ms} \) for \( N = 25 \) \[30\]. However, some flashes exhibit much longer pre-stroke activity with Rust and MacGorman...
also reporting +CG flashes with pre-stroke durations as long as 800 ms [30] and Kong et al. measuring +CG flashes with pre-stroke durations greater than 600 ms [102]. Although our averaged flash signal has pre-stroke durations greater than these values, because of the nature of averaging, reported values should be considered more approximate of the upper limit of such values than the mean, as only a few long-duration events will be visible with a low enough noise floor. Observation of pre-stroke activity to this point has been heavily dependent on the use of electric-field sensors located within a few kilometers of the flash. Because of this distance limitation, few +CG flashes have been analyzed accurately enough to extensively characterize pre-stroke duration, a problem addressed by the technique described here.

Pre-leader activity is also much more significant than -CG events, as expected. Although the pre-leader -CG activity had a maximum magnitude of $|B_\phi| \approx 121 \text{ fT}$, +CG pre-stroke activity is significantly greater than this, achieving a maximum pre-leader magnitude of $|B_\phi| \approx 3.3 \text{ pT}$, corresponding with a maximum pre-leader current moment of 907 A·km at a distance of 1000 km. One pre-leader feature of interest, visible in figure 3.7(b), is the slope reversal present at $t \approx -100 \text{ ms}$. This slope reversal in the magnetic field is consistent with the +CG flash waveforms described by Fuquay [27], Rust and MacGorman [30], Rust et al. [101], and Kong et al. [102], providing validation that the averaged +CG waveforms are consistent with observed single-flash properties.

3.4.2 Features of +CG post-stroke activity

The post-stroke average waveforms are given in figure 3.7(c). The overshoot observed due to filtering and hardware is, as expected, less significant and occurs later than that of the -CG case. This is primarily due to the increased occurrence rate of continuing current in +CG flashes, when compared with their -CG counterparts (see section 3.3.2 and section 3.5). After the initial overshoot, the +CG waveform has maximum magnitudes of $|B_\phi| = 1 \text{ pT}$, compared to a peak value of $|B_\phi| = 0.4 \text{ pT}$ in the -CG case.

Much like the -CG case, the Schumann Resonance pulse at $t \approx 157 \text{ ms}$ is visible (fig-
ure 3.7(c)). The second Schumann Resonance pulse is visible in -CG case but not the +CG case because of the greater number of -CG events used for averaging. There is also clearly some continuing signal (with $|B_\phi| > 13 \text{pT}$) immediately after the return stroke. As some continuing current is relatively common in +CG flashes, it is safe to assume that most post-stroke activity can be attributed to continuing current, as opposed to subsequent strokes. This assumption is not valid for -CG strokes, as was seen in section 3.3.2.

3.4.3 Comparison of +CG flashes between storms

All storms show significant activity beginning around the same time during the development of the flash ($t \approx -1 \text{s}$). Similarly, the positive strokes all demonstrate the same positive slope, although this positive slope begins at $t \approx -130 \text{ms}$ for one storm (17 August 14) but $t \approx -100 \text{ms}$ for the other three storms (see figure 3.7(b)). The rest of the pre-stroke activity, although similar in time scale, varies noticeably in magnitude.

The measurements show an average continuing current signal of $|B_\phi| > 13 \text{pT}$ for three of the storms (including the 24 September 13 storm), with the final storm (17 August 14) still possessing continuing $|B_\phi| > 10 \text{pT}$. Overall, the four storms show noticeable differences in both duration and magnitude during the post-stroke activity.

On the whole, +CG events appear to be much less similar across storms than -CG flashes. To examine the different waveforms, the cross-correlation value for the four storms was calculated and then normalized using the product of the Euclidean norm of both waveforms, resulting in a perfectly-matched value of unity, independent of signal magnitude. The mean normalized cross-correlation value for -CG flashes between storms is $0.9937 (\sigma = 0.0025)$, while the mean normalized cross-correlation value for +CG for different storms is $0.9787 (\sigma = 0.0062)$. It is clear that +CG events show much greater variance than -CG events across storms, even when normalizing for signal magnitudes and distances.
3.5 Extraction of Source Current Moments from Averaged Waveforms

Because the noise levels of signals achieved in previous sections is sufficiently low, it is possible to simulate the source current that produces the given average waveforms. From this source current, it is then possible to characterize many parameters of the average waveforms, such as total charge transferred by the flash or by the storm. In addition, the extracted source waveforms can be divided based on different processes associated with the lightning flash.

3.5.1 Source extraction procedure

The procedure here builds on the procedure outlined by Cummer and Inan [94] and utilizes a propagation model described by Hu and Cummer [103], who performed finite difference time domain (FDTD) simulations for lightning sferic propagations within the atmosphere and ionosphere. Their model takes into account the dispersive and anisotropic effects of the ionosphere through the use of a nearly perfectly matched layer model [104], as well as Earth curvature and surface inhomogeneity. Based on this model, one can calculate the magnetic fields produced at an arbitrary distance from an impulsive current moment. Because the simulated field from the impulsive source, \( h(t) \), includes propagation effects, different source current moments, \( M_i(t) \), can be analyzed through the use of the convolution operation, \( B(t) = \int_{-\infty}^{\infty} M_i(\tau) h(t - \tau) \, d\tau \), and compared to the measured averaged magnetic fields, \( f(t) \).

After convolution and filtering, the simulated waveforms are passed through the same peak-detection algorithms as those used on measured data. Because the storms analyzed in this work cover a relatively large geographic area, the distance between an analyzed lightning flash and the receiver can vary considerably, even within a single storm. To mitigate this issue, a composite simulated waveform was calculated using weighted average of simulated waveforms for the range of the storm in question and used as the representative simulated waveform for the entire storm.
3.5.2 Extracted source waveforms

To model the current of the source waveforms, the signal was divided into three sections. A double exponential equation was chosen to represent the return stroke, an equation with three exponential terms was chosen for subsequent stroke/continuing current sections, with a more complicated waveform being chosen for the pre-stroke/leader section of the waveform.

\[
i_1(t) = I_1 \left( e^{\tau_1 t} - e^{\tau_2 t} \right)
\]  
\[
i_2(t) = I_2 \left( e^{\tau_3 t} + e^{\tau_4 t} - 2 \cdot e^{\tau_5 t} \right)
\]
\[
i_3(t) = I_3 \left( e^{\tau_6 t} + e^{\tau_7 t} \right) + \Lambda(t)
\]

The double exponential equation, described by Bruce and Golde [105], has since been supplanted as the most physically accurate model of ground currents in lightning flashes, but remains one of the simplest models available, useful for first-order approximations. The basic model, given in equation 3.2 describes the return stroke ground current using a constant current multiplier, \(I_1\), and two time decay coefficients — \(\tau_1\), which controls the decay of the current waveform, and \(\tau_2\), which controls the parameters of the rising wavefront.

To model the post-stroke activity (equation 3.3), two time constants were used to describe the decaying current due to subsequent strokes (\(\tau_3\)) and continuing current (\(\tau_4\)), with one time constant (\(\tau_5\)) describing the increasing current associated with the post-stroke time period. The last exponential term is doubled, so as to provide for zero current at \(t = 0\).

For the pre-stroke time period (equation 3.4), two exponential terms are added together, one of which represents in-cloud pre-stroke activity (\(\tau_6\)), with the other representing the leader current (\(\tau_7\)). To account for more complicated pre-stroke activity, such as that in sections 3.3.1 and 3.4.1, some small-scale (<10 A) transient corrections are included (\(\Lambda(t)\)). Parameters were adjusted and judged based on the maximum normalized cross-correlation factor. All storm simulations achieved a normalized cross-correlation of greater than 0.995.
Figure 3.8: Source current magnitudes from 24 September 13 storm for (a) averaged first -CG and +CG waveforms (b) averaged subsequent -CG strokes. Blue waveform is subsequent strokes with continuing current, red is continuing current only, green is subsequent strokes only.

The source current magnitudes for both for +CG and -CG cases for the 24 September 13 storm are given in figure 3.8(a). Consistent with the results described in section 3.3 and section 3.4, the +CG case shows more significant activity both before and after the return stroke. Bandwidth-adjusted simulated signals are shown in comparison with the measured averaged waveforms in figure 3.9.

Flash duration, defined here as a current moment greater than 200 A km, was 720 ms for -CGs. Ogawa reported ground flash durations ranging from 10 ms to 2 s with a typical value of 300 ms [106], comparable to the value of the average flash reported here. Flash duration for +CGs was found here to be 1550 ms. This is longer than the mean value of 520 ms for \( N = 31 \) reported by Rust [30], but is comparable with the longest flash durations of 1200 ms reported in the same study. As with all averaged measurements, this represents the time period over which any activity was measured, so it is probable that a few powerful long-lasting events are mainly responsible for the long time durations calculated here.

To verify the methodology used in this work, the same source current was simulated with the bandwidth for a second sensor system, also operating at the same Duke Forest. This ELF/VLF system, the basis of development of the DEV system described in chapter 2, was
Figure 3.9: Comparison between simulated and measured ULF waveforms for (a) -CG pre-
and post-stroke, (b) +CG pre- and post-stroke, (c) -CG return stroke, and (d) +CG return
stroke from 24 September 13 storm. Pre- and post-stroke simulated waveforms are offset by
1 pT, return stroke simulated waveforms offset by 100 pT.

Manufactured by Quasar Federal Systems (QFS). The system had a natural lower-frequency
cutoff of approximately 2.1 Hz and was filtered with a high-frequency cutoff of 500 Hz to
approximate the rolloff of the BF-4 system. After applying these filter parameters, the same
source waveforms as described previously were simulated and compared to measurements
taken by the QFS sensors from the 24 September 13 storm. As with the BF-4 system, the

Figure 3.10: Comparison between simulated and measured ELF/VLF waveforms for (a)
-CG pre- and post-stroke, (b) +CG pre- and post-stroke, (c) -CG return stroke, and (d)
+CG return stroke from 24 September 13 storm. Pre- and post-stroke simulated waveforms
are offset by 1 pT, return stroke simulated waveforms offset by 100 pT.

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agreement between the filtered simulated and measured waveforms was very good for both the +CG and -CG cases, seen in figure 3.10. The high agreement for the source waveform with a second, independent system substantiates the accuracy of the source waveform.

3.5.3 Calculation of average -CG post-stroke parameters

Performing the same source extraction process on the waveform obtained by averaging subsequent strokes (see section 3.3.2 and figure 3.6) yields the source channel current magnitude given in figure 3.8(b). As mentioned previously, the time periods for $-7 \text{ ms} < t < -2 \text{ ms}$ and $2 \text{ ms} < t < 7 \text{ ms}$ are likely to be free of both other return strokes and of leader activity, so any source current during this time is likely to be due primarily to interstroke and continuing current. Indeed, in this simulation, we see minimum current values at $t = -3.4 \text{ ms}$ and $t = 3.6 \text{ ms}$. The channel current at both of these times is $|I| \approx 28.3 \text{ A}$, assuming a channel length of 7 km.

By subtracting out the magnitude of the near-DC continuing current, it is also possible to calculate the average current magnitude of the subsequent strokes alone (with no continuing current) during the post-stroke time period for the waveform produced by averaging first strokes. Because each impulsive subsequent stroke will be a narrow pulse in the time domain, when averaged together, the average subsequent stroke current can also be regarded as a proxy for the timing of the subsequent strokes.

3.5.4 Monte Carlo analysis of -CG post-stroke activity

To verify the accuracy of the previous continuing current magnitude calculation, a Monte Carlo analysis was also performed using parameters typical of -CG flashes described in [29] and [31]. After generating high-bandwidth ground current waveforms for 25,000 -CG flashes, the noiseless magnetic fields for the waveforms were calculated for the same distance distribution as was present for events in the 24 September 13 storm. After filtering, downsampling, and averaging appropriately to imitate the sensor system utilized here, the continuing current magnitude was adjusted and compared with the measured waveform. The maximum normal-
Figure 3.11: (a) Comparison of noise levels during post-stroke period between Monte Carlo simulation and ideal case (b) Effect of excluding subsequent strokes (SS) and continuing current (CC) on averaged simulated waveform

ized cross-correlation value occurred for an average flash continuing current of $|I| = 27.3$ A, which validates the previously calculated value of $|I| \approx 28.3$ A.

The average noise level for an increasing number of Monte Carlo trials was also calculated for the post-stroke period. For this case, additive white Gaussian noise is included to model the natural and electronics noise observed by the system. The level of noise was scaled to the noise levels observed during the 24 September 13 storm. A comparison of the noise level of the Monte Carlo simulation, along with the observed noise levels and the ideal noise levels is given in figure 3.11(a). The noise level observed during the post-stroke is seen to scale well with the ideal case. This trial serves to verify the procedure described above as an effective method of simulating lightning signals.

The Monte Carlo averaging technique can also be a useful tool for examining the effect of different flash parameters on the overall averaged received waveform. For instance, figure 3.11(b) shows the difference in received waveforms when subsequent strokes are eliminated, when continuing current is eliminated, as well as when both elements are included with their normal likelihood. As expected, for time more than about 30 milliseconds after the return stroke, the magnetic field is dominated by the contribution from the subsequent strokes, while before this point, the continuing current, although rare for -CGs, is the dom-
Figure 3.12: Comparison between calculated and measured post-stroke time period based on changing (a) stroke multiplicity distribution (b) interstroke interval geometric mean and (c) interstroke interval geometric standard deviation.

iant factor. This is consistent with the current contributions found in section 3.5.2 and evidenced in figure 3.11(b), and serves as a confirmation that both the previously described methodology and the Monte Carlo simulations are functioning correctly.

To determine the distribution of subsequent strokes, three distribution parameters were examined – stroke multiplicity, interstroke interval geometric mean, and interstroke interval geometric standard deviation. Stroke multiplicity was assumed to have a geometric distribution of the form $\Pr(n) = p(1-p)^n$, where $\Pr(n)$ is the probability of a flash having $n$ subsequent strokes, given the corresponding probability, $p$. Furthermore, interstroke delay was assumed to be of a log-normal distribution. Both of these assumptions are heavily suggested by the data reported by Rakov and Uman [90] and Kitagawa et al. [48] for sample sizes of 76 and 83 flashes, respectively.

To analyze the distribution of subsequent strokes, the stroke multiplicity probability, $p$, as well as the geometric mean and standard deviation of the interstroke interval were adjusted. For each combination of three values, timing data for half a million flashes were generated. The times of each subsequent stroke were then binned with millisecond precision and quantitatively compared to the measured post-stroke waveform for the 24 September 13 storm using the normalized cross-correlation.

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The best fit for stroke multiplicity probability was found to have $p = 0.16$. The best fit log-normal interstroke interval distribution had a geometric mean of 60.9 ms and a geometric standard deviation of 1.90. This geometric mean interstroke interval for the observed storm compares favorably with reported values of 60 ms for $N = 270$ by Rakov and Uman [92], 56–58 ms for $N = 53443$ by Diendorfer et al. [107], and 61 ms for $N = 186$ by Saba et al. [108].

3.5.5 Analysis of flash and storm charge moment change

Further analysis can now be performed on the source current waveforms. One particular value of interest is the total charge moment change (CMC), which is the integration of the current moment (itself the integration of the channel current over the length of the channel) over time (section 1.2). The CMC over the flash duration for the analyzed events from the 24 September 13 storm is visible in figure 3.13, where it is clear that this value is the integral of the source current moment waveform (figure 3.8). The CMC values for the four storms are given in table 3.3 (-CG) and table 3.4 (+CG), subdivided into pre-stroke, return stroke, and post-stroke time periods.

Analyzed CG flashes had an average CMC of $256.9–310.6\, \text{C km}$ over the entire flash. This was significantly greater than the value of $52.5\, \text{C km}$ reported by Berger (sample size $N = 94$)
Table 3.3: Charge moment change (CMC) values for -CGs for four analyzed storms

<table>
<thead>
<tr>
<th>Storm</th>
<th>Pre-stroke (C·km)</th>
<th>Return Stroke (C·km)</th>
<th>Post-stroke (C·km)</th>
<th>Total (C·km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8/06</td>
<td>24.5</td>
<td>22.4</td>
<td>233.8</td>
<td>280.7</td>
</tr>
<tr>
<td>8/08</td>
<td>28.9</td>
<td>23.6</td>
<td>204.35</td>
<td>256.9</td>
</tr>
<tr>
<td>9/24</td>
<td>12.41</td>
<td>27.63</td>
<td>233.86</td>
<td>273.9</td>
</tr>
<tr>
<td>8/17</td>
<td>52.31</td>
<td>24.43</td>
<td>233.86</td>
<td>310.6</td>
</tr>
</tbody>
</table>

Table 3.4: Charge moment change (CMC) values for +CGs for four analyzed storms

<table>
<thead>
<tr>
<th>Storm</th>
<th>Pre-stroke (C·km)</th>
<th>Return Stroke (C·km)</th>
<th>Post-stroke (C·km)</th>
<th>Total (C·km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8/6</td>
<td>365.1</td>
<td>44.5</td>
<td>315.1</td>
<td>624.7</td>
</tr>
<tr>
<td>8/8</td>
<td>189.5</td>
<td>38.2</td>
<td>301.8</td>
<td>529.5</td>
</tr>
<tr>
<td>9/24</td>
<td>245.5</td>
<td>43.6</td>
<td>594.6</td>
<td>883.7</td>
</tr>
<tr>
<td>8/17</td>
<td>142.3</td>
<td>29.5</td>
<td>348.1</td>
<td>519.9</td>
</tr>
</tbody>
</table>

[29], assuming a channel length of 7 km. However, the impulse charge moment change value calculated here of 22.4–27.63 C·km compares favorably with the median value reported in the same work of 31.5 C·km (N = 90). Bergers reported values were for all observed CG flashes, regardless of peak current magnitude. This difference in methodology may partially explain the difference in calculated CMC values.

If it is assumed that the -CG post-stroke period contains a continuing current with magnitude |I| = 28 A and an overall flash duration of t = 700 ms, this continuing current accounts for approximately 140 C·km of the post-stroke CMC, with the remaining 65–95 C·km being attributable to subsequent strokes. This ratio is greater than reported previously for a small number of events [29]. By the measurements presented here, although continuing current is seen as relatively rare for -CG flashes, it still accounts for the majority of charge transferred to ground, especially during the post-stroke time period.

For +CG flashes, the average calculated CMC was 883.7 C·km, compared to 560 C·km reported by Berger (N = 26). However, much of the CMC calculated here is due to pre-stroke activity within the cloud that, while not significant in magnitude, has a very long duration. Possibly as a result, the calculated impulse charge moment change found here is
only 43.6 C km, compared to 102 C km reported by Berger for \( N = 24 \).

For CGs of both polarities, the majority of the CMC took place during the post-stroke time period, with most of the CMC from that time period being the result of continuing current. Despite this fact, the CMC from negative continuing current is less than half that of the continuing current CMC for +CGs.

With the calculated CMC for each polarity, it is now possible to track the progress of the charge transferred for an entire storm over the duration of the storm. Figure 3.14 shows the charge transferred by the four storms as a function of time, assuming a channel length of 7 km for all events. Even though +CGs transfer a much greater amount of charge per flash, the greater number of -CG events mean that the net charge transferred during the storm is negative. Over the length of the 24 September 13 storm, +CGs resulted in a positive total CMC of 2433.5 kC km, yielding an average of 113.9 kC km/hr. -CGs accounted for a total CMC of −6552.7 kC km (−273 kC km/hr), yielding a net CMC for the storm of
−3819.2 kC km (−159.1 kC km/hr). As is intuitively apparent (and confirmed by figure 3.14), different storms produce lightning at extremely different rates and in different ratios of polarity, resulting in widely varying total CMC and CMC rates. Total CMC rates ranged from −159.1 kC km/hr (for the 24 September 13 storm) to −603.4 kC km/hr (17 August 14).

3.6 Conclusions

This work presented a technique for averaging many time-aligned CG lightning magnetic field signals to reduce the overall noise level of the system. This averaging allows for the measurement and calculation of very small-magnitude average magnetic field signals (on the order of tens of femtotesla) at distances greater than a thousand kilometers for storms which span tens of thousands of square kilometers. By investigating low-noise ULF/ELF waveforms, we have shown that average waveforms for CGs have pre-leader activity beginning as early as 500 ms before the first return stroke for -CGs and 1000 ms before the first return stroke for +CGs.

Due to the reduced noise levels of these averaged signals, lightning channel current moments as small as 7.8 A km can be extracted at ranges greater than 1000 km. Utilizing this technique, this work has demonstrated that the average continuing current of -CG flashes is approximately 28.3 A, while -CG subsequent stroke interstroke delays were distributed with a geometric mean of 60.9 ms. Analysis of several different storms demonstrates that average -CG flashes are notably more consistent from storm to storm than +CG lightning events.

Extraction of the source current allows for measurement of the average charge moment change (256.9 to 310.6 C km -CGs and 529.5 to 883.7 C km +CGs from the analyzed storms), as well as the division of total CMC into different lightning processes for each storm. The scale of analyzed events also allowed for the characterization of the charge transferred over the entire duration and geographic extent of the analyzed storms.
In this chapter, we describe the averaging of dozens of in-cloud lightning events known as narrow bipolar events. These events are characterized by their extremely short duration and spatial extent and are believed to play an important role in the initiation of other lightning process. In this work, we separately average narrow bipolar events that initiate other lightning flashes and those that do not. Doing so allows us to examine the environment that may give rise to initiator narrow bipolar events as well as characterize the average source currents for both types of narrow bipolar events, as well as the average source current for observed flashes initiated by narrow bipolar events. By combining the measurements from several sensors operating in a variety of frequency ranges, we can examine these processes over frequencies ranging from sub-hertz to hundreds of kilohertz.

4.1 Background and Motivation for Averaging Narrow Bipolar Events

Narrow bipolar events (NBE) are an uncommon type of IC lightning event which were identified by their strong electromagnetic waveforms beginning in the 1980s [109, 110]. NBEs are characterized by their narrow electromagnetic waveforms (typically 10–20μs), measured in the VLF and LF frequency ranges, but also by their exceptionally powerful very high
frequency (VHF) emissions [109, 111]. Along with their brief duration and relatively small magnitude of charge moment change (less than 1 C km), NBEs are also characterized by extremely short channel lengths, typically between 200 and 1000 m [110, 113, 114], and high propagation velocities, on the order of $10^7$–$10^8$ m/s [110, 112]. Due to this short channel length, NBEs are sometimes referred to as compact intracloud discharges (CIDs).

Although NBEs necessarily include powerful VHF radiation, events with NBE-like waveforms can be categorized using LF waveforms alone, using pulse width and signal-to-noise ratio (SNR) [115, 116, 117]. Figure 4.1 gives an example of normalized LF measurements of a positive NBE-like event, as well as examples of typical +IC and +CG events for comparison. Because of the strength of NBE emissions, LF observations of NBEs can be performed at a distance of several hundred kilometers [118, 119].

Despite observation of NBEs for multiple decades, many open questions still remain about their origin and the role that they play in the overall lightning and thunderstorm process. Although NBEs were originally thought to occur as distinct lightning processes, temporally separated from other lightning events [109, 110, 111, 120], more recent research has shown numerous examples of NBEs occurring in conjunction with other lightning activities, includ-
ing both IC and CG events [34, 115]. Indeed, some recent publications have suggested that NBEs may play a role in the initiation of all IC and CG lightning events [118]. Despite this fact, it is clear that a sizable percentage of, if not most, NBEs are temporally isolated from other lightning events and do not develop into more typical IC or CG flashes [121]. It is currently unknown what differences exist between initiator NBEs (those that lead to other lightning processes) and normal NBEs (those that do not) or under what conditions these different types of NBEs are produced.

Time-aligned averaging could allow for the investigation of NBEs, particularly their initiation within the thundercloud. Averaging these events in different frequency bands would reveal the presence of any discernible charge motion within the cloud preceding the average NBE-like event. Through careful selection of candidate NBE-like events, averaging can further be performed individually on isolated events or that which lead to other lightning processes.

As demonstrated in chapter 3, time-aligned averaging of lightning signals can be a powerful tool for the analysis of lightning events, especially those with faint processes that fall below the noise floor of the sensors. Furthermore, in addition to allowing for the measurement of faint processes, averaging also increases the statistical power of such inferences, as the measurements are performed on a larger group of signals than through individual inspection targeting single events.

4.2 Time-Aligned Averaging of Narrow Bipolar Events

4.2.1 Sensors

The work demonstrated in chapter 3 demonstrates the principles of the averaging procedure, primarily through the use of sensors operating in the ULF/ELF frequency band. Although the technique was also verified for sensors operating in the ELF/VLF frequency bands, that work was mainly reliant almost exclusively on ULF/ELF sensors. Expanding this averaging to other frequency bands would allow for the investigation of lightning features on much faster time scales than are capable with the sensors ULF/ELF sensors from chapter 3.
Researchers have previously used averaging for waveform comparison in limited extents, such as Zoghzoghy et al., who investigated -CG waveforms using averaging in the VLF frequency range [122].

Three sensors with overlapping coverage were used in this work. The frequency responses for the utilized sensors are given in figure 4.2. In order to identify the fast signals of the NBE processes, a sensor with a high frequency of operation is required. To this end, potential events were first examined using sensors operating in the LF frequency range, referred to as the Duke LF (DLF) sensors. These sensors, which are operated as a pair of orthogonal magnetic search coils, have a flat frequency response between approximately 100 and 200 kHz, but have a linearly proportional frequency response from 1 to 100 kHz. The system was sampled at a rate of $f_s = 1$ MSa/s.

The second set of sensors utilized was the Duke VLF (DLVF) sensor system, briefly described in chapter 2. These sensors have a flat frequency response between 100 Hz and 12 kHz. Like the DLF sensors, the DVLF sensors are orthogonal magnetic search coils, however the DVLF sensors are air-core, while the DLF sensors are ferrite-core. The DVLF system was sampled at a rate of $f_s = 100$ kSa/s. A 6-pole anti-aliasing filter with $f_c = 25$ kHz was included to prevent aliasing of higher-frequency components.

The final set of magnetic field sensors is the same as the primary set of sensors utilized
in chapter 3, referred to as the Duke ULF (DULF) system. These sensors are a pair of EMI
BF-4 magnetic field sensors, also operated in an orthogonal fashion. These sensors have
a flat frequency response between 0.3 and 500 hertz. The system was sampled at a rate of
\( f_s = 2.5 \text{ kSa/s} \), with an anti-aliasing filter at \( f_c = 600 \text{ Hz} \).

All three systems were operated simultaneously at the Duke Forest research station,
located near Durham, N.C. (35.970° N, 79.094° W) and sampled continuously, using GPS-
disciplined sampling clocks. Although collected data consist of orthogonal channels, pro-
cessed and averaged waveforms have been converted to azimuthal/radial fields for ease of
analysis.

4.2.2 Time-alignment process

While an NBE-like event is identified using the DLF sensor, we still wish to examine time-
aligned information in the DVLF and DULF systems. Despite the fact that all sensor
systems utilized here are time-synchronized, there still exists some uncertainty in the timing
of events due to factors such as GPS clock error and hardware delays. As a result, special
care must be given to synchronize lightning events for maximum alignment between systems.
Although the three sensor systems operate in distinctly different frequency bands, correct
time-alignment can be ensured by examining and shifting measured waveforms from separate
sensor systems, particularly after digitally filtering to maximize the overlapping frequency
ranges.

An example of this time alignment process can be seen in figure 4.3. After identification
of the NBE-like event (along with its associated time-alignment information) with the DLF
sensor, we use this time-alignment to synchronize the DVLF measurements. Because the
DLF frequency response is linearly proportional below about 100 kHz, the sensor functions
approximately like a \( dB/dt \) sensor at these frequencies. We can compensate for the hard-
ware roll-off by integrating and filtering the measured signal in post-processing. By using a
passband with a bandwidth of 1 to 12 kHz, we can then compare the DLF signal with the
waveform from the DVLF system filtered to the same passband and determine the time delay
and offset of the DVLF system relative to the now time-aligned DLF signal. This process is demonstrated in figures 4.3(a) and 4.3(b).

Next, by low-pass filtering the DVLF signal ($f_c = 500$ Hz) and high-pass filtering the DULF signal ($f_c = 100$ Hz), we can use the time-aligned DVLF signal to achieve synchronization for the DULF measurements as well. Because the NBE process does not radiate strongly in the ULF frequency range, this alignment process typically relies on other lightning events that radiate more strongly in this frequency band (such as those initiated by the NBEs). This process can be seen in figures 4.3(c) and 4.3(d). At this point, the signals from all three sensors systems have been correctly aligned in time and are suitable for analysis.
via averaging with other signals from the same sensors.

4.2.3 Automatic identification of NBEs

As mentioned previously, for an event to be positively classified as an NBE, it must include high emissions in the VHF spectrum. Therefore, the use of VHF detectors is necessary to definitively state whether a particular lightning event is an NBE. It is possible, however, to identify NBE-like events based on the electric or magnetic field change produced by the event. This method has proven effective, with greater than 95% of candidate NBEs identified by magnetic or electric waveform inspection being confirmed as actual NBEs (F. Lu, personal communication).

As discussed previously, most automatic identification methodologies rely on two main waveform characteristics – pulse width and waveform SNR [115, 116]. Many methods exist of quickly calculating these parameters based on the waveforms in question, so many researchers calculate these parameters in different ways and focus on different parameters, such as, for example, Wu et al., who focused exclusively on main pulse width and post-event SNR [117].

In all cases involving automatic identification, individual factors must be individually weighted, depending on the sensors used and the method of operation. For our work, we focus on five separate parameters, each of which has been weighted to achieve a total possible score of 100 points:

Rise time $\leq 4 \mu s$ (20 points) The 10-90% rise time of the initial peak.

Full width at half maximum $\leq 5 \mu s$ (15 points) FWHM of the initial peak.

Total duration $\leq 30 \mu s$ (15 points) Duration from 10% of the initial peak until the value falls below 10% of the overshoot peak.

Pre-pulse SNR $\geq 28 \text{ dB}$ (30 points) Pre-pulse time period defined to be 4–300$\mu$s before the peak of the initial pulse
Post-pulse SNR $\geq 18$ dB (20 points) Post-pulse time period defined to be 30–800 µs after the peak of the initial pulse

The SNR metrics were weighted particularly heavily to ensure that waveforms identified were most likely to reject normal IC lightning events. Events were considered potentially NBE-like if they achieved a score of 75 points or greater according to the above metrics. After automatic identification, events were individually verified to ensure that measured DLF magnetic fields were sufficiently large and that no misidentification had taken place. Henceforth in this work, NBE-like events identified through this methodology will be referred to as NBEs. After this selection process, the largest value for the initial peak of the DLF magnetic field was defined to be $t = 0$ for the sake of average, similar to the procedure of chapter 3.

4.2.4 Summary of selected NBE events

As identification of NBEs requires data collected by the DLF system, this work focuses on events that were captured in 2015 through continuous operation. Although the Cummer Lab group operates sensors identical to the DLF system at several locations throughout the United States, only data collected at the Duke Forest location was considered, as the time-alignment process outlined in section 4.2.2 requires collocated sensor systems. Data from the DLF system are not typically retained unless deemed to have notable thunderstorm activity or for testing purposes. As a result, examined data, which were collected during 2015 and retained, included approximately 133 hours of time-stamped DLF data.

Much like typical IC lightning events, NBEs can be of two polarities – positive NBEs (PNBEs) or negative NBEs (NNBEs). PNBEs are overwhelmingly more common than NNBEs [120, 123] and occur at lower altitude. As initiator NBEs occur at even lower altitudes [121], the link between initiator NBEs and PNBEs is thought to be stronger than the link between initiator NBEs and NNBEs. Therefore, in this work, we focus on the averaging of PNBEs.

Based on the time periods of retained data, a search was conducted using the National
Lightning Detection Network (NLDN) [97]. The NLDN is capable of identifying lightning type (IC or CG), peak current magnitude, and location. As we are interested in PNBEs, we examined events identified by the NLDN as positive ICs with peak current magnitudes greater than 20 kA, as these events were more likely to be NBEs and were expected to produce large magnetic field signals at the receiver. To avoid the possible distortion of ionospheric reflections on the received signal, events close enough to have distinct ground and sky wave divisions were desired, although in many cases, the fields produced by these events may be sufficiently strong to saturate the data acquisition system. Therefore, our search focused on events located 200–400 km from the Duke Forest research site.

After identification as NBEs based on the DLF magnetic field waveform, an event was classified as initiator PNBEs if an NLDN-reported event (including both ICs and CGs of any magnitude) occurred within 10 km and 50 ms of the NBE. This spatial extent was chosen to be large enough to eliminate NLDN location uncertainty as a source of potential error while still allowing for horizontal in-cloud development. The temporal cutoff was chosen based on the work of Wu et al., who found no upward leaders following NBEs lasting longer than 42.3 ms [121].
The selected PNBE events are shown in figure 4.4 and described in table 4.1. Nearly all analyzed PNBE events took place from late June to mid-August, with a handful of events occurring in September and October. This does not necessarily indicate any temporal preferences conducive to the creation of NBEs, but is instead significantly related to the limited availability of retained data. There does not appear to be a location bias for initiator PNBEs compared to normal PNBEs, with nearly all events taking place in the coastal regions of North and South Carolina.

Our analysis identified 56 initiator PNBEs, compared with 210 normal PNBEs. This compares favorably with the ratios observed by researchers using a broadband 3-D lightning location network to track entire in-cloud flash progressions [121, 124]. Within these events, the distribution of peak currents was nearly identical, as was the distribution of distances from event to receiver. Additionally, we identified 12 initiator PNBEs and 58 normal PNBEs with large unrelated events located in the 100 ms time period prior to the NBE itself. As we are interested in any activity during this time period, we excluded these from analysis to avoid the inclusion of known other lightning events that could alter the averaged waveform. One possible source of error in this study is that it exclusively utilized data retained due to the existing presence of lightning. It is possible that these conditions may be either more or less likely to produce NBEs that are initiator or normal type, a factor that is not examined using the data here.

In order to investigate the relative NLDN timing of events analyzed here, NLDN-identified events close to the reported NBE location (within 10 km) were plotted with respect to time in figure 4.5. Only events within 10 km of the selected NBE are plotted here, as events at

<table>
<thead>
<tr>
<th>N</th>
<th>NLDN Peak Current (kA)</th>
<th>Distance to Receiver (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Standard Deviation</td>
</tr>
<tr>
<td><strong>Initiator PNBEs</strong></td>
<td>56</td>
<td>29.9</td>
</tr>
<tr>
<td><strong>Normal PNBEs</strong></td>
<td>210</td>
<td>30.8</td>
</tr>
<tr>
<td><strong>Total PNBEs</strong></td>
<td>266</td>
<td>30.6</td>
</tr>
</tbody>
</table>
Figure 4.5: Timing and peak current magnitude of other NLDN-reported events in comparison to (a) normal PNBEs and (b) initiator PNBEs.

Larger distances than this are considered to be unrelated to the NBE process and should therefore provide a constant background level of activity after averaging.

As mentioned previously, any PNBEs with events in the 100 ms time window prior to the NBE itself were excluded from analysis. There are no NLDN-reported events between $t = 0$ and $t = 50$ ms for the normal PNBEs, as any events during this time period would have caused the NBE to be classified as an initiator PNBE. After $t = 50$ ms, the number of reported NLDN events for normal PNBEs has returned to approximately the background level (the level prior to $t = -100$ ms).

After $t = 0$ (the aligned NBE time), there is an immediate surge in NLDN-reported events associated with the initiator PNBEs. Indeed, the increased rate of these events continues well past the 50 ms cutoff used to determine whether a PNBE is an initiator. This implies that most of those later events are related to initiated lightning events between $t = 0$ and $t = 50$ ms. While it is somewhat curious that all three initiated +CGs occurred within 2 ms,
while +ICs and -CG were spread out over a much longer time period, this difference is not examined in this work.

4.3 Averaged Narrow Bipolar Event Waveforms

4.3.1 Measured average initiator and normal PNBE waveforms

The averaged waveforms for initiator and normal PNBEs are given in figure 4.6. While the actual NBE pulse is essentially identical for both types of PNBEs, the overshoot peaks begin to noticeably differ. While this difference is particularly obvious on the overshoot magnitude, the post-NBE timing of the slower tail is also different for the two types. This post-NBE difference will be examined in greater detail in section 4.3.2.

We are able to measure some characteristics of the averaged waveform. The first pulses for both types of signals are nearly identical, with rise times of 2.53 µs and FWHM values of 2.74 µs. These values compare favorably with the mean first pulse measurements reported by Smith et al. for $N = 24$ of 2.3 µs ($\sigma = 0.8$ µs) and 4.7 µs ($\sigma = 1.3$ µs) for rise time and FWHM, respectively [110]. The averaged signals measured here, however exhibited full pulse durations of 14.72 µs, compared to 25.8 µs ($\sigma = 4.9$ µs) by Smith et al. Furthermore, the ratio of the initial peak to the overshoot peak measured here was 1.34 and 1.61 for initiator and normal PNBEs, respectively, compared to 2.7 by Smith et al.

These discrepancies can be potentially explained by the selection process for NBEs used.
in this work. Although all events that met the points criteria were flagged as potential NBEs (and before identification as initiator or normal PNBEs), the visual inspection process used here was potentially more discerning, particularly in the requirement of an abrupt transition at the beginning of the pulse. This was primarily to ensure that all averaged signals were definitively NBEs, as opposed to normal initial breakdown pulses [121], however it may have yielded NBEs that were particularly short or had especially narrow initial pulses, at the exclusion of longer events that were NBEs nonetheless. It is also worth noting that all of the NBEs observed by Smith et al. were to have occurred in complete isolation from all other lightning processes.

Figure 4.7: (a) Comparison of averaged DVLF waveforms for initiator and normal PNBEs with 3σ levels (b) Averaged waveform for all investigated PNBEs with 3σ levels.

We are particularly interested in investigating the pre-NBE time period to examine whether any activity takes place prior to either initiator or normal PNBEs that would account for the difference in the post-NBE activity and flash development. We first focus on the millisecond or so prior to the NBE itself. This time duration and frequency range is well-suited to investigation with data collected from the DVLF waveforms. To determine whether any signal is present prior to the NBE itself, we define any activity greater than three standard deviations of the quiet time period ($-750\,\text{ms} < t < -250\,\text{ms}$ for DVLF) to
be sufficient evidence of specific activity and not merely due to random noise.

The averaged pre-NBE waveforms for initiator and normal PNBEs are given in figure 4.7(a). Also included are the accompanying levels corresponding with three standard deviations of the “quiet” time period for the signal. As we are particularly interested in slower activity which might precede NBEs, a boxcar filter with a width of 100µs has been applied to further decrease the noise level, although the NBE itself (−100µs < t < 1 ms) has been excluded from this boxcar filtering. Neither the normal nor the initiator PNBEs exhibit activity exceeding the 3σ threshold until the NBE itself (t ≈ 0). Due to complicated propagation effects of electromagnetic signals in the VLF frequency range, the magnitude of a received signal is heavily dependent on the ionospheric conditions, as well as the frequency content of the source signal itself. With the sensor system used here, assuming a specific ionospheric profile, we can examine different minimum source current moment magnitudes for a given source pulse shape. Assuming a Gaussian shaped source current moment with a FWHM of 70µs, the 3σ level for the initiator and normal PNBEs corresponds with peak current moments at a range of 320 km of approximately 308.7 A km and 220.5 A km, respectively. Any average activity taking place prior to the NBE itself would have to be smaller than this value to remain below the 3σ level.

To examine the pre-NBE time period for the maximum number of events, both initiator and normal PNBEs are averaged together, giving the waveform shown in figure 4.7(b). Even with the further decreased 3σ level, the combined waveform does not exhibit any detectable pre-NBE activity. The threshold current moment for detection for the combined PNBEs, assuming the same pulse shape as before, is approximately 187.4 A km.

To examine longer time periods prior to the NBE themselves, we now analyze the DULF waveforms. The averaged time-aligned DULF waveforms of initiator and normal PNBEs are shown in figure 4.8. Much like the DVLF case, neither initiator nor normal PNBEs showed pre-NBE activity exceeding the 3σ threshold. Using the equation given in equation 3.1, we can calculate the threshold quasi-static current moments to be approximately 35 A km and 51 A km for normal and initiator PNBEs, respectively. Equation 3.1 is valid in this
Figure 4.8: (a) Comparison of averaged DULF waveforms for initiator and normal PNBEs. (b) Inset of (a) demonstrating the lack of pre-NBE activity for initiator PNBEs.

case because the we are interested in the quasi-static magnetic fields (those longer than approximately ten milliseconds) that are particularly strong in measurements made with the DULF system.

While normal PNBEs showed no measurable post-NBE signal in this frequency band, even after averaging, initiator PNBE-initiated flashes can be examined through the averaged waveform. Although all post-NBE IC and CG are averaged together into a relatively smooth waveform in this time period (much like chapter 3), the average waveform can still be a useful metric for examining several flash parameters. The peak seen between $t = 0$ and $t = 25$ ms is likely a combination of both upward leaders and IC and CG lightning events initiated by the NBE. After this point, the post-NBE time period is dominated by subsequent events and processes in the same flash, such as the late stage of IC events. Because of the sometimes extremely short delay between initiator PNBE, we cannot separate the initiated flashes from the upward-moving leader began by the PNBE.
4.3.2 Extracted source current waveforms

In order to calculate the source currents for the measured averaged waveforms, magnetic fields for a given current were modeled using the equation for current flowing a vertical channel given by Thottappillil et al. [125].

\[
B_\phi (r, t) = \frac{\mu_0}{2\pi r} \left[ \frac{H_m}{\sqrt{H_m^2 + r^2}} - \frac{H_m - \lambda}{\sqrt{(H_m - \lambda)^2 + r^2}} \right] I(t) \quad (4.1)
\]

In this equation \(\mu_0\) is the permeability of free space, \(r\) is the horizontal distance from the event to the receiver, \(H_m\) is the top of the NBE channel, \(r\), and \(\lambda\) is the NBE channel length. We are able to use this equation because we are interested in modeling only the ground wave, as opposed to the sky waves, which require more complicated ionospheric conditions and simulations to replicate. For this work, we assume a channel length of \(\lambda = 500\) m, a typical value for NBE length estimates [110, 113]. For our current source waveforms, we use the equation form described by Karunarathne et al. [114], who themselves used a modification of the NBE current waveform described by Watson and Marshall [126]. Karunarathne et al. utilized a double exponential model with an additional small-magnitude, linearly decreasing parameter included. Utilizing this model provided a good fit for the measured DLF signals of the averaged PNBEs.

The simulated magnetic fields waveforms are compared with the averaged observed waveforms in figure 4.9. The fit for both initiator and normal PNBEs is quite good, particularly for the initial and overshoot peaks. The source current waveforms are given in figure 4.10. Although the 10-90 rise times of both sources is identical (2.33 \(\mu s\)), the normal PNBE current source has a much wider FWHM (6.92 \(\mu s\)) than the initiator PNBE (5.41 \(\mu s\)).

Furthermore, and more notably, the initiator source current has a noticeable continuing current that lasts for at several hundred microseconds, much longer than the complete normal PNBE source or initiator pulse. This continuing current is probably the beginnings of the negative breakdown process of the impending IC or CG, a fact well-observed by Rison et al.
and supported by Karunarathne et al. [114]. This negative breakdown is only present in the PNBEs that will go on to initiate IC or CG lightning flashes. It is clear that this initial breakdown process (IBP) is begun by the presence of the initiator PNBE, a fact confirmed by observation by Rison et al. [118].

Based on these sources, we can also draw some conclusions about the charge transferred
Figure 4.11: Comparison of measured and simulated average (a) initiator and (b) normal PNBEs

by the PNBE currents. The charge transferred by the average PNBEs is calculated to be 0.13 C, in line with the values reported for individual PNBEs by Eack of 0.3, 0.16, 0.17, and 0.12 C [112]. For the average initiator PNBEs, the pulse itself transfers 0.10 C, which compares favorably with the values from Eack, while the overall average initiator PNBE source transfers 1.05 C, which compares well with the estimates by Rison et al., who observed several initiator NBES, all of which contained negative breakdown [118]. The final value for charge transferred listed here for initiator PNBEs is likely to be a lower limit of that actual value, as the duration of post-pulse current was as small as possible without decreasing the quality of the fit with measured data. Meanwhile, modeling longer duration values of post-pulse current did not decrease the quality of the overall fit with the measured waveform.

Unlike the DLF case, when we wish to characterize the entire PNBE-initiated flash, we cannot rely on equation 4.1, as this does not take into account ionospheric factors. Therefore, we rely on a process similar to the one outlined in section 3.5 to extract the source waveforms that produce the observed averaged DULF measurements. In this case, we only need to extract the source current for initiator PNBEs, as the normal PNBEs did not have significant emissions in the ULF/ELF frequency range (figure 4.8).

The simulated ULF/ELF magnetic field for the selected source current is shown in figure 4.11. As is visible in the figure, the simulated field agrees well with the measured average waveform for nearly the entire time window. The source current and charge moments
for this field are given in figure 4.12. These values assume a channel length of 3 km, a typical value for a IC flash [127]. Overall, the average flash has a charge moment of 87.9 C km, a value on par with those reported by several researchers, who found typical values of 90 to 96 C km for an assumed 3 km channel [39, 128, 129]. Some of those same researchers also found average flash durations of 420 to 500 ms, which compares well with the flash duration found here of 445 ms.

4.4 Conclusions

This work described the averaging of many time-aligned positive narrow bipolar events. This averaging process reduces the effective noise level of the measurement system to significantly lower levels than are achievable for a single lightning event. Furthermore, it allows for investigations of average lightning signals to have a greater statistical power than investigation of individual lightning events. Through the use of several collocated sensor systems, each covering a different frequency range, we can investigate lightning processes across an extremely wide bandwidth.

By investigating positive NBEs that initiate other lightning processes separately from isolated, normal PNBEs, we can contrast their formation and magnetic field waveforms. With sufficiently low noise levels, we can then calculate the source current that generated

![Figure 4.12: Source (a) current and (b) charge moments for flashes initiated by PNBEs.](image-url)
the measured distant waveform. Through averaging, we observe that the current required to match the averaged initiator PNBE (FWHM of 5.41µs) was noticeably shorter than that for normal PNBEs (6.92µs). We are also able to observe the negative breakdown of initiator PNBEs. The average normal PNBE transfers 0.13 C of charge, while the initiator PNBE transfers 0.10 C during the pulse itself and an additional 0.95 C during the negative breakdown process.

The average charge moment for a PNBE-initiated flash is 86.4 C km and the duration of the initiated flash was 445 ms. As expected, neither initiator nor normal PNBEs exhibited pre-NBE activity in the ULF/ELF frequency range.
In this chapter, a method of determining the phase of a carrier signal emitted by terrestrial VLF transmitters is detailed. Analyzing the carrier phase of a given transmitter allows for the determination of the pseudorange from the receiver to the transmitter. Through the combination of distance information from multiple transmitters, it is possible to determine the location of the receiver, subject to some limitations.

5.1 Principles of MSK Sideband Comparison Navigation

5.1.1 Conversion of MSK to Sunde’s FSK

As discussed in section 1.3.4, MSK, like all FSK-encoded signals, utilizes one transmission frequency for 1 bits (the mark frequency) and another transmission frequency for 0 bits (the space frequency). MSK is defined to be FSK encoding with the smallest possible modulation index, \( m = \frac{1}{2} \). This means that the difference between the mark and space frequencies is equal to half the overall bit rate, centered about the carrier frequency \( f_c \pm 50 \text{ Hz} \) for the transmitters here). However, due to MSK’s adherence to phase continuity, which is ensured by the possibility of a 180° phase difference from the base functions of the individual frequencies, there are no discrete frequency components to easily monitor, as there are for FSK signals with higher modulation indices.
Through clever processing, however, it is possible to convert MSK-encoded signals with a modulation index of \( m = \frac{1}{2} \) into a type of FSK encoding with \( m = 1 \), known as Sunde’s FSK. With the higher modulation index, phase continuity is automatically enforced without the need for additional phase corrections.

\[
s(t) = \sqrt{\frac{2E_b}{T_b}} \cos \left[ 2\pi f_c t + \Theta(t) \right]
\]  \(5.1\)

\[
\Theta(t) = \Theta(0) + \frac{\pi m}{T_b} \int_0^t b(t) \, dt
\]  \(5.2\)

FSK signals have the form given in equations 5.1 and 5.2. \( E_b \) is defined as the energy per bit and merely scales the amplitude of the signal. \( T_b, f_c, \) and \( m \) are the bit time, carrier frequency, and modulation index, as described previously. \( \Theta(0) \) is the phase of the system at \( t = 0 \), which is assumed to be the start of the observation period. \( b(t) \in \{ \pm 1 \} \) is the waveform representing the bit stream to be transmitted, with -1 and +1 representing binary 0 and 1, respectively. Bit transitions occur at \( t = n \cdot T_b \) for \( n \in \mathbb{Z} \). As each bit changes the phase by \( m \) radians, \( \Theta(0) \) is dependent on all previous bits of the signal and will be an integer multiple of \( m\pi \). Because \( m = \frac{1}{2} \) for MSK, we know that \( \Theta(0) = n \cdot \frac{\pi}{2} \).
The baseband power spectral density (PSD) of an MSK-encoded signal is given by equation 5.3 [83]. This represents a PSD that is smooth, with no discrete spectral components (shown in figure 5.1(a)), despite the two distinct transmission frequencies. This is due to the fact that MSK utilizes both in-phase and anti-phase signals at the two frequencies. Taking the MSK form of equation 5.1 and letting $\omega_c = 2\pi f_c$, we get the generalized MSK equation given in equation 5.4.

$$s(t) = \sqrt{\frac{2E_b}{T_b}} \cos \left[ \omega_c t + \frac{\pi}{2T_b} \int_0^t b(t) \, dt + \Theta(0) \right]$$ (5.4)

Squaring equation 5.4 yields the result given in equation 5.5. Using the trigonometric identity $\cos^2(x) = 1 + \cos(2x)$, we can simplify this equation to the form shown in equations 5.6 and 5.7.

$$s^2(t) = \frac{2E_b}{T_b} \cos^2 \left[ \omega_c t + \frac{\pi}{2T_b} \int_0^t b(t) \, dt + \Theta(0) \right]$$ (5.5)

$$s^2(t) = \frac{2E_b}{T_b} \left( 1 + \cos \left[ 2 \left( \omega_c t + \frac{\pi}{2T_b} \int_0^t b(t) \, dt + \Theta(0) \right) \right] \right)$$ (5.6)

$$s^2(t) = \frac{2E_b}{T_b} + \frac{2E_b}{T_b} \cos \left[ 2\omega_c t + \frac{\pi}{T_b} \int_0^t b(t) \, dt + 2\Theta(0) \right]$$ (5.7)

We can now examine the terms of equation 5.7 terms individually. The first term $\left( \frac{2E_b}{T_b} \right)$ is a DC offset that is a result of the squaring operation. The amplitude of the sinusoidal signal $\left( \frac{2E_b}{T_b} \right)$ is the square of the amplitude of the normal MSK signal (equation 5.4). Within the cosine term, the $2\omega_c t$ term denotes that the carrier frequency is now double that of the normal MSK signal.
The $\frac{\pi}{T_b} \int_0^t b(t) \, dt$ term shows that while the bitstream ($\int_0^t b(t) \, dt$) is the same as the base MSK form, the scaling value outside the integral is now doubled. If we go back to equation 5.1, we can compare this to the generalized FSK form and see that $\frac{\pi m}{T_b} = \frac{\pi}{T_b}$, indicating that the modulation index, $m$, is 1 in this case. Based on our allowable initial conditions for MSK, two possible situations emerge -- $2\Theta(0) = 0$ (for $\Theta(0) = 0, \pi$) or $2\Theta(0) = \pi$ (for $\Theta(0) = \frac{\pi}{2}, \frac{3\pi}{2}$).

Because these two initial phase conditions (0 and $\pi$) are the allowable initial phases for Sunde’s FSK and our modulation index is now 1, we have successfully converted the MSK signal to Sunde’s FSK at twice the carrier frequency of our original signal. This is useful, as Sunde’s FSK has a baseband PSD described by equation 5.8 [130].

$$S(f) = \frac{1}{4} \left[ \delta \left( f - \frac{1}{2T_b} \right) + \delta \left( f + \frac{1}{2T_b} \right) + \frac{4T_b}{\pi^2} \left( \cos \left( \frac{\pi f T_b}{2} \right) \right)^2 \right]$$  \hspace{1cm} (5.8)

This PSD exhibits discrete spectral components (underlined in equation 5.8) located at $f = \pm \frac{1}{2T_b}$, as seen in figure 5.1(b). We can therefore examine these spectral components (which, because $m = 1$ after squaring, occur at $2f_c \pm \frac{f_b}{2}$, with $f_b = \frac{1}{T_b}$) as proxies for the original signals with ambiguous $\pi$ phase offsets. A verification of this conversion between MSK and Sunde’s FSK can be seen in figure 5.2.

Paschal noted that this conversion could be done through a simple frequency doubler [131], a technique which was furthered and implemented in hardware by Wolf [132]. Wolf also implemented a phase-locked loop (PLL) to further filter and average each frequency. This PLL additionally helped maintain phase coherence when the received signal was transmitting on the opposite frequency. Shafer implemented a processing method which decoded the received signal and then calculated a reconstruction of the original transmitted signal based on the decoded bits. This reconstructed signal was compared to the received signal and, after taking into account the ionospheric transfer function, yielded the amplitude and phase of the received signal [133].

Each of these techniques possesses different advantages and similar techniques have been
integrated into a variety of research and monitoring equipment including the ELF/VLF Radiometer project [134] and the AWESOME project [135], as well as the OmniPAL system [136], the SuperSID system [137], and the open-source VLF Receiver Software Toolkit [138].

5.1.2 Conversion of discrete sideband spectral components to propagation distances

Because the two discrete spectral components necessarily occur at different frequencies, their wavelengths are also different. This is significant, as it means that the phase difference between them is not constant with distance from the transmitter. As the propagation distance increases, the phase of higher frequency spectral component (referred to here as phase $\phi_H$ of frequency $f_H$) will advance faster than that of the lower frequency component ($\phi_L$ and $f_L$).

This difference in frequencies can be quantified in the same way as offset acoustic waves which produce a beat frequency. Although our extracted Sunde’s FSK components occur at
for MSK-encoded signals. Therefore, although the separation between the extracted signals from the squared MSK is 200 Hz for 200 baud transmissions (figure 5.1(b)), the actual physical separation between them is only 100 Hz. Therefore we expect our measured beat frequency to be 100 Hz.

We can therefore convert the phases of the two spectral components to distances by calculating the wavelength of the beat frequency, given by:

\[
\lambda = \frac{c}{f_H - f_L} = \frac{c}{100 \text{ Hz}} = 2997.9 \text{ km}
\]  

(5.9)

We can then convert a measured phase difference to a distance by calculating first the slope of the phase change with respect to distance (equation 5.10), then converting it to a linear form, given in equation 5.11.

\[
k = \frac{2997.9 \text{ km}}{360^\circ} = 8.3275 \text{ km/}^\circ
\]

(5.10)

\[
d = k \Delta \phi + \phi_0 = -(8.3275 \text{ km/}^\circ) \Delta \phi + \phi_0
\]

(5.11)

In these equations, \(k\) is the calculated slope, \(\Delta \phi\) is the difference in sideband phases, and \(\phi_0\) is a constant that is different for each transmitter and determined from observation. The negative sign in equation 5.11 is chosen because we define sideband phase difference to be \(\Delta \phi = \phi_H - \phi_L\).

Sideband differences for simulated signals are given in figure 5.3. Generated MSK signals were propagated using finite difference time domain (FDTD) simulations to the desired distances. The simulated slope is found to be \(k = 8.2508 \text{ km/}^\circ\). While this value differs slightly from the calculated value, this simulated value takes into account ionospheric effects and the curvature of the earth, so is therefore considered to be more accurate.
Figure 5.3: Simulated sideband phase differences for different ionospheric profiles. (a) $h' = 72$ km (b) $h' = 74$ km (c) Difference in simulated sideband phase over distance for different ionospheric profiles.

5.1.3 Measurement and extraction of discrete sideband spectral components

In order to measure and characterize real VLF signals, two separate magnetic field search coil sensor systems are utilized at various times during this work. Both sets of sensors are operated with two orthogonal search coils, allowing signals to be measured in all directions regardless of orientation.

The first set of sensors is the DEV system, which possesses a flat frequency response between 2.1 Hz and 50 kHz, as described in chapter 2. Because of the low noise and ideal bandwidth of the DEV system, the system is considered well-suited for the measurement of VLF transmitter signals.

The second set of sensors, referred to as the Duke LF sensors (DLF, also described in
Figure 5.4: MSK sideband phase difference extraction used in this work. This procedure (other than data storage) was performed separately for each transmitter analyzed.

Chapter 4), have a linearly proportional response to frequency between 1 kHz and 200 kHz and a flat response between 200 kHz and 300 kHz. Although VLF transmitters are outside of the primary frequency of operation for the DLF sensors, the VLF signals are still clearly detectable and easy to characterize. The DLF sensors have the advantage of being significantly smaller and easier to deploy than the DEV sensors.

All data acquisition in this work is GPS-synchronized, allowing for clock alignment on the order of a few tens of nanoseconds at geographically separated locations. The GPS timing receiver also provides a pulse at the beginning of each second (referred to as the PPS pulse). Data collection at all locations is initiated at the beginning of a second. DLF sensors are sampled at a rate of 1 MSa/s, while the DEV sensors are either sampled at 1 MSa/s without anti-aliasing filters, or 100 kSa/s with 6-pole anti-aliasing filters at 35 kHz.

The process used in this work is shown in figure 5.4. Received data are sampled according to GPS timing and stored for future analysis. Real-time processing is possible for power enough computers. The captured signal is divided into 1-second time windows, then
for each transmitter frequency, the signal is bandpass filtered with a filter bandwidth of 2 kHz. To eliminate the effect of large lightning signals which present as noise in the system, momentarily large signals are clipped, and then the entire signal is mixed into the baseband using a complex exponential. By using a complex exponential, the data are separated into the in-phase (real) and quadrature (imaginary) components.

After down mixing, the baseband signal is filtered once again using a low-pass filter to eliminate any aliased signals, then self-mixed, converting the signal to Sunde’s FSK. At this point, the two orthogonal channels may either be calculated independently or, more commonly, added together to create a signal with an even greater signal to noise (SNR) ratio.

The Goertzel algorithm is used to quickly calculate the phase of the two spectral components, now located at $\pm 100$ Hz. The difference in phase of the two spectral components is found through subtraction, and then converted to a distance value. After calculating the distance measurements to several transmitters, it is possible, then, to localize the receiver through the process of trilateration.

There exists one major limitation to the distance calculation for individual transmitters, however. Because of the squaring process, all measured phases are modulo 180 degrees. Therefore, we can also only calculate phase distances modulo 180 degrees, meaning that calculated distances are modulo 1485.1 km. With a single transmitter, we have no way of knowing from sideband phase difference alone the actual distance from transmitter to receiver. With multiple transmitters, however, it quickly becomes clear what the correct values are for each transmitter, based on the intersection of small circle distances from multiple transmitters.

Before calculating the distance for unknown locations, we must determine $\phi_0$ from equation 5.11 for each transmitter. This is a matter of plotting the measured sideband phase differences for a variety of distances and then finding the best fit using the known slope. An example of this process is shown in figure 5.5 for the NAA transmitter. A mix of DLF (blue) and DEV (red) measurements were utilized, along with measurements taken by a
collaborator’s system (ARGON) located close to the transmitter. The collaborator’s system had a flat bandwidth between 2 Hz and 25 kHz.

These measurements consisted of approximately 20-minute readings, the timing of which was scattered over the course of more than a year. Because sideband phase differences are calculated for each second, the value shown in figure 5.5 is the mean value for the measurement window, with the error bar being the standard deviation for the phase difference over the same time period.

The Cummer Lab operates several systems identical to the DLF system around the country on a continuous basis, which yielded the points for $d > 2000$ km. Because Duke University is approximately 1380 km from the NAA transmitter, this distance allows for many measurements with both sensor systems. The inset shows the distance between 1280 and 1420 km. The fit at nearly all points is within one standard deviation of the mean. The transmitter phase offset for NAA is calculated to be $\phi_0 = 62.55^\circ$, while the process for other transmitters is similar.
5.2 Measured MSK Sideband Comparison Capabilities

5.2.1 Measured accuracy of MSK sideband comparison

To examine the effectiveness of the MSK sideband navigation process in different environments, two primary tests were conducted, one utilizing DEV sensors in a low-noise environment, the other using DLF sensors in an urban setting. Both test sites were located in northern Kansas. Northern Kansas is an ideal location for localization measurements, as it is fairly rural and sites can be located in areas with very little interference. More significantly, northern Kansas is located at a distance from each transmitter that allows for received signals from all five transmitters to be comparatively strong.

For each site, data sampled at 1 MSa/s were acquired for at least 20 hours and both processed in real time and saved for later analysis. Signal problems due to modulo 180° errors were corrected, as were times when the received signals were not detectable. This can be caused when ionospheric conditions are not favorable for long-distance transmission and when VLF transmitters are occasionally taken offline for maintenance. During periods when sideband phases were not measurable for a given transmitter, that transmitter was not used in location-finding analysis and the procedure continued with fewer utilized transmitter distances.

For each transmitter, locations were determined based on the phase difference of the two sidebands as described in section 5.1.2 and equation 5.11. To determine the matched location for the given number of transmitters with measurable phase differences, calculated distances were compared to a 2° x 2° latitude/longitude grid (approximately 225 km x 175 km) with 0.001° grid spacing (approximately 100 m). For each point on the grid, actual distances to the transmitters were known for each transmitter based on computation. The matched location for the measured distances was defined to be the location where the Euclidean norm of the total difference between known and measured distances for all transmitters was lowest. Transmitters utilized for location-finding were not weighted.

Because measured signal sideband phase differences are not precisely constant and sub-
ject to noise and interference, different integration windows were also examined. During initial processing, signals were processed using 1-second windows. For larger integration windows, the phase differences of multiple 1-second windows were averaged to achieve the mean sideband phase difference for the window. Because all of the signal phases for each 1-second window were coherent, the averaging of the phase differences of multiple windows is the same as computing the phase of the entire window [139]. For particularly long windows, a given transmitter’s sideband phase difference may be detectable for part of the window, but not all. In this case, a transmitter’s phase difference was considered to be valid if it was measurable for at least half the window.

Low-noise DEV test

In order to measure signals in as close to an ideal situation as possible, testing was conducted during March 2017 at a field location north of Simpson, Kansas (39.4375° N, 97.9248° W). Visible in figure 5.6, this location was selected as it was well-removed from possible interfering signals or sources of electromagnetic noise, such as power lines and heavy machinery. The closest power lines were located approximately 1.75 km from the test location and no heavy machinery was located within 3 km of the test site. Although the test site was accessible via gravel roads, no vehicle traffic passed within 400 meters during the test.

Testing was conducted using orthogonal DEV sensors. For the test, a consumer generator
was used to provide power for the sensors. Although the generator is a small source of electromagnetic interference, its effects on the measurements were mitigated by keeping AC power cables short and placing the generator behind shielding structures. Data collection equipment was housed during the test in an unpowered portable trailer, while the sensors were located approximately 30 meters away from the trailer, as shown in figure 5.6.

Mapped results for the low-noise DEV test are shown in figure 5.7. The test ran for approximately 42 hours, so integration windows were varied between 1 second and approximately 21 hours (half the data). Overall results were quite good, with nearly all results being within 10 km of the correct location regardless of integration window size. Results were found to be distributed evenly around the correct location, marked by the black triangle. While, generally, longer integration windows produced more accurate location fixes, the effect for this test when increasing the integration window size from 30 seconds to 5 minutes is not significant (see section 5.2.2 and figure 5.16(a)).
Table 5.1: Transmitter error mean and standard deviation for low-noise DEV test

<table>
<thead>
<tr>
<th>Transmitter</th>
<th>Error Mean (km)</th>
<th>Error Standard Deviation (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPM</td>
<td>-0.215</td>
<td>8.607</td>
</tr>
<tr>
<td>NAA</td>
<td>-0.133</td>
<td>5.592</td>
</tr>
<tr>
<td>NLK</td>
<td>-0.417</td>
<td>4.414</td>
</tr>
<tr>
<td>NLM</td>
<td>0.0952</td>
<td>3.111</td>
</tr>
<tr>
<td>NAU</td>
<td>-0.946</td>
<td>6.711</td>
</tr>
</tbody>
</table>

The error for each transmitter for 10-second integration windows is shown in figure 5.8, divided into 2 km bins centered at 0 km, and table 5.1. Certain transmitters (NLK and NLM) showed very little variation, with standard deviations of 3.111 km (NLM) or 4.414 km (NLK). Other transmitters, however, such as NPM and NAU were much more widely varied in their error (standard deviations of 8.607 km and 6.711 km, respectively). Although the values are not as precise as those of NLK and NLM, almost all of the measured distances are within ±20 km of the correct value.

It is important to note that the combined number of counts of all bins is not equal for all five transmitters. This is because some transmitters had many more windows with detectable and measurable sideband phases. NLM, for example is taken offline for eight hours every Tuesday for maintenance, which is included in this test.
The fact that the mean error for all transmitters is non-zero (and nearly 1 km for NAU) speaks to several possibilities. It is possible that the calculated $\phi_0$ from equation 5.11 is not precisely correct. This would yield a systemic error in either the positive or negative direction for all distances. Second, it is possible that the propagation characteristics at long distances are not as simple as those calculated in section 5.1.2. This would give errors at long distances from the transmitter while being more accurate at short distances.

Finally, propagation characteristics change with respect to time on a diurnal cycle. As the sun is the primary driver of the ionization process in the ionosphere, daytime ionospheric characteristics differ significantly from those at night. These changes could be leading to errors in the calculated distances based on the time of day and sunlight exposure over the propagation paths.

One curious result is that the distance error for NPM appears to be bimodal, with peaks at +7 km and -9 km. The complete cause of this distribution is unknown and it does not appear in the other transmitters or in the urban DLF test (figure 5.11, table 5.2), although it could potentially be related to diurnal variations in the ionosphere.

**Urban DLF Testing**

To characterize the system under non-ideal situations, analysis was performed on data collected in June 2016 at a preexisting sensor location also in northern Kansas. Unlike the field test location for the low-noise DEV test, the sensors for this system were located in the middle of Manhattan, Kansas, on the campus of Kansas State University (39.1902° N, 96.5845° W). The test location was on the roof of the Durland Hall engineering building in the center of campus. As visible in figure 5.9, the roof is also home to other communications equipment, as well as HVAC systems.

For this test, orthogonal DLF sensors were utilized. This test was analyzed because it used the DLF sensors, which are less well-suited (but still effective) for operating in the VLF frequency range of interest compared to the DEV sensors, and took place in an environment with much higher electromagnetic noise and interference. While the sensors were located on
Table 5.2: Transmitter error mean and standard deviation for urban DLF test

<table>
<thead>
<tr>
<th>Transmitter</th>
<th>Error Mean (km)</th>
<th>Error Standard Deviation (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPM</td>
<td>0.322</td>
<td>22.714</td>
</tr>
<tr>
<td>NAA</td>
<td>-0.515</td>
<td>12.348</td>
</tr>
<tr>
<td>NLK</td>
<td>-1.532</td>
<td>16.460</td>
</tr>
<tr>
<td>NLM</td>
<td>1.190</td>
<td>10.937</td>
</tr>
<tr>
<td>NAU</td>
<td>-0.5473</td>
<td>19.830</td>
</tr>
</tbody>
</table>

the roof of the building, data acquisition equipment was located inside the building, on a lower floor.

Mapped results for the urban DLF test are given in figure 5.10. Data from approximately 24 hours were analyzed and integration windows varied between 1 second and the full data period. Data were much more inconsistent than the low-noise DEV test (figure 5.7). Nearly all the mapped results were within 35 km of the correct location, compared to 10 km for the low-noise DEV test. Much like the low-noise DEV test, results did not appear to be directionally biased. Unlike the low-noise DEV test, however, significant improvements in the location error were seen when increasing the data integration window from 30 seconds to 5 minutes and beyond.
The distance error for 10-second integration windows during the urban DLF test for each transmitter is given in figure 5.11 and table 5.2. Once again, the error bins are 2 km wide, centered at 0 km. The error for all systems is significantly higher for all transmitters than that of the low-noise DEV test (figure 5.8, table 5.1). Error standard deviations were higher for the DLF test, meaning that phase measurements taken in this environment were much less consistent than those taken during the DEV test. While NLM is the most consistent (smallest standard deviation) for both tests, the NLK transmitter measurements differed significantly between the two tests. Unlike the DEV test, the NPM transmitter was not bimodal.

A comparison of the distributions of the mean distance error for both the low-noise DEV and urban DLF tests is given in figure 5.12, along with the mean errors for both tests. As is visible in figure 5.12(a), no locations were matched that were greater than 15 km from the correct position, with the mean error being 5.36 km. This contrasts with the urban DLF test in figure 5.12(b), in which a handful of locations had errors of 40 km or greater. The DLF
Figure 5.11: Distance error histograms with 2 km bins for measured VLF transmitters for 10-second integration length during the urban DLF test.

Figure 5.12: Location error histogram for (a) low-noise DEV test and (b) urban DLF test. Bin widths are 1 km and integration window was 30 s.

test had a mean error of 14.04 km, more than double the low-noise DEV test.

5.2.2 Factors influencing localization accuracy

During the localization process, several factors were found to influence the accuracy of transmitter distances and, thus, the accuracy of the overall location. While a location can be determined even in non-ideal situations, it is important to understand factors influencing the quality of the location fix to recognize the limitations of this process.

Phase difference signal examples for the five different transmitters are shown in fig-
Figure 5.13: Example transmitter signals from low-noise DEV test over 30 minute span with 1-second integration window length.

Figure 5.13. These examples were taken from a half hour during the low-noise DEV test when all five transmitters were visible and sideband phases were measurable. The data shown in figure 5.13 have been standardized by subtracting the mean of the measured signal so that the change from the mean is more visible. The consistency of the measured sideband phase difference has a direct impact on the quality of the distance calculation for that transmitter, especially for short integration windows. For measurements in which the sideband phase difference variation is small (such as NLM in the above figure), distance calculations will be relatively constant. Assuming a correct implementation of equation 5.11, this will yield the correct or nearly correct distance regardless of which measurement window is used. However, for very noisy signals (such as NAU in the above figure), the sideband phase difference can vary significantly from second to second, meaning that a distance calculation that is accurate in one second may be completely wrong if the data from the following second are analyzed.

When discussing the quality of signals, we can characterize the quality and consistency of the signal by measuring the standard deviation of the measured 1-second windows for the entire period of data collection. While this doesn’t differentiate between second-to-second variations (like those visible in NAU) and longer-scale variations (such as NLM), it is a useful metric for characterizing how consistent and reliable the measurements are.
One of the factors that have a significant impact on the quality of the measurements is the signal-to-noise ratio (SNR). Using the same method of simulated signal propagation described in section 5.1.2 and figure 5.3, we can also manually incorporate additive white Gaussian noise (AWGN) to the received signal to achieve a desired SNR. As visible in figure 5.14(a), increasing SNR decreases the distance error for 30-second windows as a result of noise when compared to the noiseless case. This increase in accuracy is consistent for increasing SNR values, but the mean error for $SNR = 20$ dB is only approximately 100 meters, which is the same as the grid size used to determine location (section 5.2.1), meaning that further increases in SNR are not likely to tangibly increase location accuracy.

Furthermore, increasing the SNR also decreases the standard deviation, but only for SNR values below 15 dB (figure 5.14(b)). Increasing transmitter SNR above this level does not appear to decrease the standard deviation further, meaning that signal levels are high enough that the measurement system can lock onto the transmitter signal without being influenced by the noise on a second-to-second basis. For $SNR > 15$ dB, the simulated phase difference is relatively consistent from window to window.

To test the relationship between SNR and measurement error in the field, both DEV and DLF sensors were operated in several environments with a variety of ambient electromagnetic noise levels. An example of the power spectral density (PSD) of a test of simultaneously
operated DEV and DLF sensors can be seen in figure 5.15(a), along with the transmission bands of several VLF transmitters identified. Both systems are calibrated, allowing their power levels to be compared between systems.

As can be seen in figure 5.15(a), the background noise level in this frequency range is approximately the same for both systems. This background noise can be due to environmental noise, sensor electronics noise, or data acquisition noise. However, the measured signal power for each of the transmitters is much higher for the DEV system than for the DLF system, typically by an order of magnitude or more. This is due to the bandwidth of the DEV sensor being more appropriate for measurement in the VLF frequency range. There is some additional noise between 25 and 26 kHz in the DEV system, which is not present in the DLF system.

The relationship between measured SNR and calculated phase difference standard deviation is visible in figure 5.15(b). To calculate SNR, the transmitter power level was compared to the measured VLF non-transmitter power level (22–23 kHz) of 30-minute data collection periods at several with a variety of noise levels. In measured tests, all transmitters with extractable sideband phases (i.e. in operation and detectable) had SNRs greater than 4 dB. As expected based on simulation, increasing SNR decreases the phase difference standard deviation.
deviation. Further consistent with the simulated case is the flattening out of the effect at higher SNR values. While the simulated case showed that increasing SNR above approximately 15 dB did not yield further decreases in standard deviation, this value for observations occurs at approximately 13 dB.

Based on these measurements, it is clear that higher SNR yields more precise and consistent data for both DEV and DLF sensors and local noise levels play an important role in the accuracy of the system. To increase the SNR, one must either increase the signal power or decrease the noise level. Because the noise level is often a function of the environment, it can be more prudent to increase the signal level through more appropriate sensors or ones that have been optimized for VLF measurement. Hardware filtering of non-VLF background noise levels is possible, but care must be taken to ensure a constant phase response for all VLF frequencies. Even a phase difference of a degree or two over the transmission band of a given transmitter can yield position errors of a dozen kilometers or more.

An additional factor that can influence the quality of the measured data is the integration window used to calculate the length sideband phase difference. The relationships between integration window length and mean position error for both the low-noise DEV and urban DLF tests are shown in figure 5.16(a). For rapid variations in distance measurements, av-

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure5_16}
\caption{Location error as a function of (a) receiver integration window length and (b) number of transmitters used for location determination using 10-second integration windows.}
\end{figure}
Averaging multiple windows can effectively remove some of the uncertainty due to poor SNR. For sufficiently long windows, it is possible to also remove some of the variations caused by changes in propagation.

However, as is visible in the figure, this tactic is not overly effective in all situations. For example, while increasing the integration window from 1 second to 1800 seconds (30 minutes) reduces the mean error of the urban DLF test from 25.36 km to 9.83 km (a reduction of 61.2%), the same increase in integration window size for the low-noise DEV test only decreases error from 5.47 km to 4.91 km (10.2%). Although the effect is not always extreme, increasing the integration window nearly always reduces location error (the only exceptions being windows longer than 3 hours for the DLF test). This implies that for a transmitter with a sufficiently high SNR (such as the low-noise DEV test), the main source of error is due to changes in the ionosphere, which cause changes in the propagation path. For measurements with large local noise (such as the urban DLF test), the main source of error is the measurement noise, which can be mitigated by using longer integration windows.

An additional factor affecting the accuracy of the measured location is the number of transmitters used for calculation. As two transmitters can yield two ambiguous small circle intersections that separated by large distances, a minimum of three transmitters is required for triangulation. The mean location error as a function of the number of transmitters with measurable phases is shown in figure 5.16(b), which assumes 10-second integration windows. While increasing the number of transmitters decreases location error for the low-noise DEV test, the opposite is true for the DLF test — increasing the number of transmitters increases the mean error. As low-SNR transmitters are likely to lose phase tracking, these are the transmitters that are most commonly eliminated. As they are also low-SNR, they have a tendency to yield the most incorrect distance calculations, which lead to location error. Therefore, as long as three transmitters are detectable, increasing the number of low-SNR transmitters does not help the overall location accuracy, whereas high-SNR transmitters do improve performance.
5.2.3 Advantages of MSK sideband comparison navigation

MSK sideband navigation has several advantages over other existing navigation systems. The advantages described in section 1.3.2 are equally valid for MSK sideband navigation. Among these advantages is the fact that good propagation characteristics for VLF waves allows for worldwide coverage with relatively few transmitters. Because these transmitters are terrestrially based, they are often simpler to operate than the relatively complex GPS satellite network. In addition, MSK sideband navigation possesses the distinct advantage of being essentially unjammable, unlike GPS and other navigation systems operating at higher frequencies.

The method described here also has several advantages over other navigation systems, including other VLF navigation networks. One major advantage is that MSK sideband navigation described here utilizes transmitters already operated around the world for alternative purposes. Because communications with submarines are a necessity for many militaries, it is highly likely that these transmitters will continue to be operated into the future. Furthermore, as the transmitters are operated by dozens of countries, this method is not reliant on any one country’s commitment to maintaining its transmitters.

Furthermore, the signal processing method described here is not dependent on any of the information encoded within the VLF MSK transmissions, but only on the physics of the propagation themselves. Therefore, it is unimportant what message is being transmitted and whether such a message is being transmitted as plaintext or has been cryptographically scrambled. As long as the transmitters continue to operate, the signal propagation characteristics are impervious to changes in message and are available even without the consent or decoding cipher of the transmitting entity.

The method of processing described here is also easily repeatable without the need for sophisticated, custom-built hardware. Measurements described in this work were performed using magnetic field sensors built and optimized for broadband measurements. Even so, processing for five transmitters is nearly real-time using a consumer-level laptop computer.
This processing assumes that no optimization has been performed in hardware. Even slight hardware specializations, such as bandpass filtering of transmitter frequencies or more powerful computing resources, would improve the processing speed even further, allowing for utilization of additional transmitters and better location accuracy.

5.2.4 Limitations of MSK sideband comparison navigation

There are some limitations of MSK sideband navigation, however. Primary among these limitations is the requirement for an extremely stable clock. This method of processing requires precise knowledge of the beginning of each second in order to begin data processing. For this work, timing information was provided by the GPS satellite network, using a commercial GPS location and timing receiver. As this method of location-finding is motivated towards situations where GPS information is unavailable, a free-running clock is highly-preferred, which introduces increased clock biases and error.

While the MSK processing system is more tolerant of mean-zero sampling period clock jitter, clock drift presents error in the processed phase differences. To determine the effect of clock drift, a single set of sensors was measured with two computers, each of which was con-
nected to a separate GPS. After approximately one day of operation, one of the GPS units was unplugged and data were collected while one system was GPS-synchronized and one system coasting (that is, without GPS-synchronization). These experimental tests of GPS receiver clock stability showed clock stability of $1 \times 10^{-8}$ was achievable using undisciplined consumer-level timing sources. This small amount of drift translated to an individual transmitter distance error rate of 12.051 km per hour of operation, shown in figure 5.17. For short distances of a few minutes or less, this error should not be significant enough to noticeably affect operation, however for independent operation on the time scale of days or weeks, this is clearly impractical. For a sufficiently high number of homogenously-distributed transmitters, this error should average out during processing. In reality, however, transmitters are not homogenously-distributed, so distance errors of this magnitude at a single transmitter can have significant effect on final calculated position.

The second major limitation on MSK sideband navigation is location accuracy. Even under the best of conditions (such as the low-noise DEV test), location accuracy for reasonable integration windows is typically only within 5 km or so. While this accuracy is too low for most consumer applications, it is still useful for many applications where a rough approximation of position is sufficient, such as transoceanic shipping or long-distance airplane navigation.

Much of the location error in MSK sideband navigation is due to local SNR, as evidenced by the urban DLF test. While some of this error could be mitigated through clever use of sensor bandwidth and hardware filtering and processing, much of the error present in the localization method described here is due to ionospheric uncertainty. As described in sections 1.3.1, 5.2.1, and 5.2.2, diurnal variations of the ionosphere can sufficiently affect the propagation distance of the VLF signal to alter the location precision. Calibration of transmitter $\phi_0$ for converting phase differences to distance can be performed while the ionosphere is very stable (daytime) or averaged over longer time periods (such as an entire day) to encompass both stable conditions and the turbulent nighttime state. Particularly at night, the condition of the ionosphere can be difficult to predict.
transmitter SNR is sufficiently high, ionospheric uncertainty can be the most significant contributor to final location error.

5.3 Conclusion

In this work, we have demonstrated a novel method of processing MSK-encoded VLF signals to determine distance between the transmitter and receiver. Because VLF signals propagate well in the earth-ionosphere waveguide, these signals can be measured at large distances with little attenuation. Worldwide coverage is attainable using few transmitters, including those already being operated by a variety of countries for communication purposes. To convert these transmitted signals into propagation distances, the MSK-encoded signals are mixed into the baseband and self-mixed to convert them to Sunde’s FSK signals, from which distinct spectral components can be extracted and measured.

Because sideband frequencies have different wavelengths, phase differences between sideband components can be converted to propagation distance from the transmitter. By utilizing multiple transmitters and their associate propagation distances, localization of the receiver can be performed in near real-time. Under good measurement scenarios, accuracy for short measurement windows is typically within 5.5 km.

Although this location finding method is limited by ionospheric effects, local noise levels, and clock accuracy, it is advantageous over existing navigation systems in that it is essentially unjammable by malicious forces. Furthermore, measurements can be performed easily using low-cost measurement hardware. Hardware optimizations could further increase the location accuracy and enable the system to be operated on moving vehicles.
6

Summary and Future Work

6.1 Summary

Effective measurements of atmospheric electricity in the ELF and VLF frequency ranges require the use of both specialized equipment and specialized processing techniques. Study of these frequencies can be extremely fruitful, as the structure of the earth and ionosphere allow for signals in these frequency bands to propagate large distances with little attenuation. Investigation of signals in this frequency band can be useful for the study of natural processes, including lightning, and man-made transmitters. The goals of this work were to describe and demonstrate several tools for the investigation of these signals, as well as to use these procedures to examine several types of signals in the frequency range of interest.

We began by first examining the difficulties of building magnetic field sensors capable of measurement in the ELF and VLF frequency ranges, called the Duke ELF/VLF (DEV) sensor (chapter 2). Because of the limited availability of commercial options, a rugged, low-cost sensor that is also reproducible would be of great assistance in studies of the ELF/VLF frequency ranges. The designed sensor was built around the principles of a ferrite-core magnetic search coil. The design and construction parameters of the search coil itself were described, as were the details of the pre-amplifier and associated housing. This system was
found to have good performance comparable to commercial systems, with a flat frequency response from 2.1 Hz to 50 kHz, making it well-suited to investigations in the ELF and VLF frequency bands.

After the design and construction of the DEV sensor system, we then turned to the averaging of the magnetic field waveforms for high numbers of similar lightning signals. In order to extract usable information about the measured waveforms, the lightning signals must be time-aligned to ensure that features add constructively instead of destructively. After time-aligning, which we performed based on the peak magnetic field waveform, lightning features are reinforced while the incoherent broadband noise is largely canceled, drastically increasing the SNR of the averaged waveform and allowing for the measurement and extraction of extremely faint lightning processes (and their corresponding source lightning currents), such as the stepped leader and continuing current. The averaging process is also useful because it allows for the characterization of many lightning flashes using a receiver at a distance of more than a thousand kilometers from the storm under observation. Storms of great geographic size can therefore be characterized using a single sensor. Averaging of many lightning emissions allows for the measurement of extremely faint average signals, but it does so by removing any specificity from the averaged waveforms. Any extracted parameters of the averaged waveform may not apply to any of the individual events measured, but will possess great statistical power due to the extremely large number of events characterized.

We performed this averaging process on four storms to investigate cloud-to-ground (CG) lightning events (chapter 3). Through the averaging of tens of thousands of similar polarity events, the noise level is sufficiently low to investigate pre-flash development of CG flashes, as well as to quantify the averaging continuing current of -CG flashes. Because of the low level of noise in the averaged waveforms, we can extract the source current moment waveform for the entire flash and examine the contribution of various processes to the average charge moment change for the flash. We also investigate some of the statistical properties of lightning flashes, including the distribution of flash multiplicity and interstroke timing of subsequent strokes. The averaging process also allows us to compare average lightning flashes between storms,
and to estimate the total charge moment change for entire storms.

We also applied this averaging process to a certain type of in-cloud (IC) lightning known as narrow bipolar events (NBE) in chapter 4. NBEs are known for their short spatial extent and duration, but may play a pivotal role in the initiation of other lightning processes, including IC and CG flashes. By using collocated sensor systems, we are able to time-align data from multiple sensors, including those covering the ULF, ELF, VLF, and LF frequency ranges. Doing so allowed us to investigate the difference between NBEs that initiate other lightning flashes and those that occur in isolation and gain insight into the conditions that give rise to lightning flashes.

Finally, we discussed in chapter 5 a method of measuring the sideband phases for man-made terrestrial VLF transmitters encoded using minimum-shift keying (MSK). Because the phases of the sideband components advance at different rates, it is possible to measure the distance of propagation by comparing the phases of the two sideband components. Performing this analysis first requires doubling the modulation index of the MSK-encoded signal, which we accomplish by self-mixing the received complex signal. After determining the pseudodistances to several transmitters, we can then calculate the receiver position to within a handful of kilometers. We also investigated the limitations of such position-finding system under both ideal and contested conditions.

The work in this document has illustrated a hardware sensor system capable of measurement in the frequency range of interest. We apply this sensor, along with others, to investigate lightning on large scales through the use of averaging. Furthermore, we showed that through the use of multiple MSK-encoded man-made VLF transmitters, we can determine the receiver location in a variety of conditions.

6.2 Suggestions for Future Work

6.2.1 Averaging of lightning

The results described in this work naturally lead to investigation on a variety of fronts. For example, the events selected in chapter 4 merit further investigation. The most apparent
future direction for expanding the results from this chapter is the expansion of the number of analyzed NBEs and the removal of biases of analyzed data. While the data examined are data that have been marked for long-term retention from 2015, the Cummer lab has comparable quantities of retained data for each year from 2011 to the present time. Expanding the quantity of data examined would improve the quality and statistical power of averaged results. Furthermore, as mentioned in the chapter, retained data are chosen based on the presence of other interesting or powerful lightning activity. This may unintentionally introduce a bias into the types of NBEs present or the conditions that lead to initiation.

As discussed previously, the overwhelming majority of investigated NBE events, both initiator and normal, occurred in coastal regions near North Carolina and South Carolina. While this geographic bias is primarily due to the availability of retained data, future investigations should expand the geographic area of examined signals to ensure that lightning from all areas is adequately represented. Many of these potential sources of bias should be investigated and could be mitigated by implementing near real-time processing on continuous collected data even before the data have been flagged for long-term retention. This would serve to help eliminate (or clarify) the geographic bias, as well as greatly increase the number of events suitable for averaging.

Furthermore, the NBE-initiated events involved in this study revealed that all of the initiated +CGs occurred within 2 ms of the initiating NBE, while the initiated -CGs and +ICs were spread more equally over the time window examined. This difference is intriguing, but, like previous investigations into initiator NBEs, the number of initiated +CGs is a very small fraction of the overall number of initiated events.

Finally, this averaging process could be expanded to other types of lightning events, such as terrestrial gamma-ray flashes (TGFs), a type of lightning process that emits gamma ray photons after powerful lightning flashes, such as certain types of ICs [140, 141]. These TGFs also emit a very distinctive magnetic waveform [142]. Averaging of additional lightning processes, such as TGFs, could yield additional insight into these types of lightning events.
6.2.2 MSK sideband comparison navigation

Future work on the navigation method described in chapter 5 should take several approaches. First, location error should be more fully understood so that it can be mitigated. As ionospheric changes are the main driver of error for measurements made in good conditions, efforts to understand and mitigate errors introduced by ionospheric conditions should be a top priority. Fully understanding and potentially predicting and compensating for these changes could lead to greatly improved location finding precision. Because the processing method used here requires knowledge of the local time and yields (at worst) a rough location estimate, it may be possible to take into account the predicted state of the ionosphere (daytime, nighttime, or in transition) for the propagation path of each individual transmitters after finding an initial location fix. By knowing the status of the propagation path, it may be possible to account for ionospheric changes to some degree. After the primary, rough, position determination, this would allow for subsequent location calculations to be more accurate. Alternatively, the system could allow for some warm-starting, with initial rough location being an input to the software processing. In this way, stable propagation paths (that is, those taking place entirely in sunlight) could be weighted more heavily than those with day/night or solely nighttime propagation paths.

Many methods also exist for potentially improving the location accuracy. Among these is the possibility of weighting of individual transmitters based on several factors, such as calculated distance or measured transmitter SNR. For some conditions with poor SNRs, the location fix may be improved by not including specific transmitters in the location-finding procedure. This weighting would require testing in a wider range of circumstances to investigate whether the weighting process improves the accuracy and under what conditions. Another method of improving the location accuracy could include the use of a Kalman filter. Because all measurements contain statistical noise, a Kalman filter integrates previous measurements, as well as new data points to drastically improve the accuracy of a variety of systems, including GPS. Implementing a Kalman filter in the location-finding technique
detailed here would improve the accuracy, particularly over longer test periods.

Next, although this timing was provided by the GPS network in this work, this is not realistic for a system that is designed to operate independently in situations where GPS signals are not available. The system as described in this work requires the use of a clock for precise accurate timing information with very little clock drift. Further development of a drift-tolerant processing system or the ability to determine timing information based on VLF transmitter signals would be extremely useful in extending the usefulness of the overall navigation system without being limited by the requirement for GPS-disciplined timing information.

Finally, the current processing systems are impractical for use in moving vehicles. For low-noise systems (such as the DEV sensors), the vibration of moving vehicles in the earth's static magnetic field is sufficient to saturate the sensors. Adjustment of the sensor bandwidth and clever bandpass filtering of known transmitter frequencies should be effective at limiting the effect of vehicle vibrations, most of which take place at frequencies of a few kilohertz or lower [143]. Further optimization of sensor hardware bandwidths would be also effective at limiting non-transmitter noise (thus improving transmitter SNR), further increasing the accuracy of individual transmitter measurements.
Bibliography


Joel Lyle Weinert was born in Wichita, Kansas on February 12, 1988. He received his B.S. in Electrical and Computer Engineering from Baylor University in May 2011, his M.S. in Electrical and Computer Engineering from Duke University in December 2014, and his Ph.D. in Electrical and Computer Engineering from Duke University in September 2017. He graduated magna cum laude in Electrical and Computer Engineering from Baylor University. He was awarded a student travel fellowship for the UNSC-URSI National Radio Science Meeting in January 2014, held in Boulder, Colorado. Joel is a member of IEEE and AGU. Below is a list of his publications and presentations, both published and in preparation.

- **Joel L. Weinert** and Steven A. Cummer. “*Sensitive measurements of lightning current and charge motion from coherently averaged low frequency magnetic field observations.*” Proceedings American Geophysical Union Fall Meeting, San Francisco CA (2013).

- **Joel L. Weinert** and Steven A. Cummer. “*Sensitive measurement of lightning current and charge motion using coherent averaging of low frequency magnetic field observations.*” Proceedings International Lightning Detection Conference, Tucson, AZ (2014).


- **Joel L. Weinert** and Steven A. Cummer. “*Measurement of sensitive current and
charge motion using coherent averaging of remote low frequency magnetic field observations.” Proceedings USNC-URSI NRSM, Boulder, CO (2014).


- **Joel L. Weinert** and Steven A. Cummer. “Superposed epoch averaging of ELF and ULF long-distance magnetic field observations of CG lightning events.” (in preparation).