MIDLATITUDE D REGION VARIATIONS
MEASURED FROM BROADBAND RADIO ATMOSPHERICS

by

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Department of Electrical and Computer Engineering
Duke University

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Thomas P. Witelski

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
2011
Abstract

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Abstract

The high power, broadband very low frequency (VLF, 3–30 kHz) and extremely low frequency (ELF, 3–3000 Hz) electromagnetic waves generated by lightning discharges and propagating in the Earth-ionosphere waveguide can be used to measure the average electron density profile of the lower ionosphere (D region) across the wave propagation path due to several reflections by the upper boundary (lower ionosphere) of the waveguide. This capability makes it possible to frequently and even continuously monitor the D region electron density profile variations over geographically large regions, which are measurements that are essentially impossible by other means. These guided waves, usually called atmospherics (or sferics for short), are recorded by our sensors located near Duke University. The purpose of this work is to develop and implement algorithms to derive the variations of D region electron density profile which is modeled by two parameters (one is height and another is sharpness), by comparing the recorded sferic spectra to a series of model simulated sferic spectra from using a finite difference time domain (FDTD) code.

In order to understand the time scales, magnitudes and sources for the midlatitude nighttime D region variations, we analyzed the sferic data of July and August 2005, and extracted both the height and sharpness of the D region electron density profile. The heights show large temporal variations of several kilometers on some nights and the relatively stable behavior on others. Statistical calculations indicate that the hourly average heights during the two months range between 82.0 km and
87.2 km with a mean value of 84.9 km and a standard deviation of 1.1 km. We also observed spatial variations of height as large as 2.0 km over 5 degrees latitudes on some nights, and no spatial variation on others. In addition, the measured height variations exhibited close correlations with local lightning occurrence rate on some nights but no correlation with local lightning or displaced lightning on others. The nighttime profile sharpness during 2.5 hours in two different nights was calculated, and the results were compared to the equivalent sharpness derived from International Reference Ionosphere (IRI) models. Both the absolute values and variation trends in IRI models are different from those in broadband measurements.

Based on sferic data similar to those for nighttime, we also measured the daytime $D$ region electron density profile variations in July and August 2005 near Duke University. As expected, the solar radiation is the dominant but not the only determinant source for the daytime $D$ region profile height temporal variations. The observed quiet time heights showed close correlations with solar zenith angle changes but unexpected spatial variations not linked to the solar zenith angle were also observed on some days, with 15% of days exhibiting regional differences larger than 0.5 km. During the solar flare, the induced height change was approximately proportional to the logarithm of the X-ray fluxes. During the rising and decaying phases of the solar flare, the height changes correlated more consistently with the short (wavelength 0.5–4 Å), rather than the long (wavelength 1–8 Å) X-ray flux changes. The daytime profile sharpness during morning, noontime and afternoon periods in three different days and for the solar zenith angle range 20 to 75 degrees was calculated. These broadband measured results were compared to narrowband VLF measurements, IRI models and Faraday rotation base IRI models (called FIRI). The estimated sharpness from all these sources was more consistent when the solar zenith angle was small than when it was large.

By applying the nighttime and daytime measurement techniques, we also derived
the \( D \) region variations during sunrise and sunset periods. The measurements showed that both the electron density profile height and sharpness decrease during the sunrise period while increase during the sunset period.
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<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>A/D</td>
<td>Analog to digital</td>
</tr>
<tr>
<td>ATD</td>
<td>Arrival Time Difference</td>
</tr>
<tr>
<td>CG</td>
<td>Cloud to ground</td>
</tr>
<tr>
<td>DOY</td>
<td>Day of year</td>
</tr>
<tr>
<td>EDT</td>
<td>Eastern Daylight Time</td>
</tr>
<tr>
<td>ELF</td>
<td>Extreme low frequency</td>
</tr>
<tr>
<td>EMP</td>
<td>Electromagnetic pulse</td>
</tr>
<tr>
<td>FDTD</td>
<td>Finite difference time domain</td>
</tr>
<tr>
<td>FWEM</td>
<td>Full wave electromagnetic model</td>
</tr>
<tr>
<td>GPS</td>
<td>Global positioning system</td>
</tr>
<tr>
<td>HAIL</td>
<td>Holographic Array for Ionospheric Lightning</td>
</tr>
<tr>
<td>HF</td>
<td>High frequency</td>
</tr>
<tr>
<td>IC</td>
<td>Intra-cloud</td>
</tr>
<tr>
<td>IRI</td>
<td>International reference ionosphere</td>
</tr>
<tr>
<td>ISR</td>
<td>Incoherent scatter radar</td>
</tr>
<tr>
<td>LASA</td>
<td>Los Alamos Sferic Array</td>
</tr>
<tr>
<td>LEP</td>
<td>Lightning induced electron precipitation</td>
</tr>
<tr>
<td>LF</td>
<td>Low frequency</td>
</tr>
<tr>
<td>LSE</td>
<td>Least square error</td>
</tr>
<tr>
<td>LT</td>
<td>Local time</td>
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</tbody>
</table>
LWPC Long Wave Propagation Capability
NBE Narrow bipolar event
NLDN National Lightning Detection Network
PEC Perfect Electrical Conductor
PML Perfect Matched Layers
QE Quasi-electrostatic
QTE Quasi-Transverse electric
QTEM Quasi-Transverse electro magnetic
QTM Quasi-Transverse magnetic
RF Radio frequency
SAA South Atlantic Anomaly
SIBC Surface Impedance Boundary Conditions
SNR Signal noise ratio
STARNET Sferic Timing And Ranging Network
TE Transverse electric
TEC Total electron content
TEM Transverse electro magnetic
TM Transverse magnetic
ULF Ultra low frequency
UT Universal time
VHF Very high frequency
VLF Very low frequency
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The solar flare X-ray fluxes and NOAA–18 particle fluxes are provided by NOAA’s National Geophysical Data Center (NGDC): http://spidr.ngdc.noaa.gov/spidr/.

The IRI data are provided by NASA’s SPDF/Modelweb:
http://modelweb.gsfc.nasa.gov/models/iri.html (for IRI2001) and

The USA terrain elevation near Duke University (used for measured heights sealevel correction) are provided by National Imagery and Mapping Agency (NIMA):

The global Earth magnetic fields are provided by NOAA’s NGDC:
1

Introduction

The $D$ region is one layer of the ionosphere that exists approximately 60 to 90 km above the Earth’s surface. It is difficult to study because its height is too high for balloons to reach but too low for satellites to take in situ measurements. Most measurements have been made using rockets or ground-based techniques [125]. However, these measurements were sporadic or local. The electromagnetic waves radiated from lightning discharges and propagating in the Earth-ionosphere waveguide are reflected several times by the upper boundary (lower ionosphere, $D$ region) of the waveguide before being recorded by radio receivers. The characteristics of the recorded radio signals (called atmospherics, or sferics for short) are thus decided by the lightning discharges, lower ionosphere and the ground. The correlation between sferics and the lower ionosphere makes them a useful tool for ionospheric $D$ region remote sensing [36]. The purpose of this work is to propose a method to extract $D$ region electron density profiles from massive recorded sferics, so as to monitor the $D$ region variation in nighttime, daytime and solar terminator.
1.1 The Ionosphere

The ionosphere is the uppermost part of Earth atmosphere and exists in plasma state. In the daytime, the major ionization sources are ultraviolet ray and X-ray radiation, whereas non-solar ionizing sources such as energetic particle precipitations, cosmic rays, Lyman-α background scattering and meteors play the major role at night [53]. The presence of free electrons and ions in the ionosphere makes it a good conductor and influences the radio wave propagation. The ionosphere is dynamic due to the unstable ionization sources. It undergoes changes from hour to hour, day to night and season to season.

Because the atmosphere compositions, densities and ion production rates change with the altitude, the balance between ionization and recombination processes leads to the formation of several distinct ionization peaks. These peaks are called D layer, E layer and F layer (including F$_1$ and F$_2$). The D layer is the lowest region, ∼60–90 km above Earth surface. The ionization here is mainly due to Lyman series-α rays and solar X-rays in the daytime. During the night, galactic cosmic rays and Lyman-α background scattering produce the stable but weak ionization [83, 114]. Therefore, the electron density in nighttime is much lower than that in the daytime in D layer. Usually, the nighttime D region electron density is lower than 10$^3$ cm$^{-3}$, but the daytime density can be as large as 2.5 × 10$^3$ cm$^{-3}$ [94, 53]. Both positive and negative ions exist in this region. The cluster ions dominate D region below 85 km and they form via hydration starting from the primary ions NO$^+$ and O$_2^+$ [124]. The D region is closely related to the attenuation of High-frequency (HF) radio waves, although they are not reflected by it. The energy absorption in this layer can severely interfere with HF radio signal transmissions if the electron density is enhanced by particle precipitations into the lower ionosphere during solar events. The E layer is located ∼100–150 km above the ground. Ionization in this layer is due to soft X-ray
and far ultraviolet solar radiation. Dominant ions are NO$_2^+$, O$_2^+$ and N$_2^+$, and the photochemistry prevails in this layer [124]. The electron density and ion density are in the order of $10^5$ cm$^{-3}$ in the daytime and more than one order lower at night. Radio waves having frequencies lower than about 10 MHz are mostly reflected back by this layer. However, sometimes, the presence of Sporadic E (or $E_s$) layer, which is a thin layer having unusual high electron density in the E layer altitudes, can reflect radio waves having frequency up to 50 MHz. In the F region (150–800 km), the atomic species O$^+$ and O dominate [124]. The electron density in this layer is typically $2 \times 10^6$ cm$^{-3}$ by day and $2 \times 10^5$ cm$^{-3}$ by night. The F layer consists of two sublayers $F_1$ (150–250 km) and $F_2$ (250–800 km) in daytime, while the $F_1$ layer disappears at nighttime. The $F_2$ layer is closely related to HF communications, and most HF waves are reflected by this layer. The region higher than $F_2$ layer is the magnetosphere which is not a part of the ionosphere.

1.2 Lightning and Radio Atmospherics

Lightning is the transient, high-current electric discharge whose path length is generally measured in kilometers. It always occurs during thunderstorms within a cloud, between two clouds, or between clouds and the ground [145]. Usually, in the cloud, smaller particles acquire a positive charge and become positive, while larger particles become negatively charged. These charged particles separate with smaller particles in the top side and the larger particles in the bottom side. As the charge accumulation increases, the electric fields between clouds become more and more intense. Finally, the electrical field is large enough to generate neutral air breakdown. A conducting channel forms between two clouds and the lightning occurs. This kind of lightning is called intra-cloud (IC) lightning. If the discharge occurs between clouds and the ground, the lightning is called cloud-to-ground (CG) lightning. Each CG lightning stroke begins with a weakly luminous predischarges, called leader process,
Figure 1.1: A cartoon of the Earth-ionosphere waveguide (adapted from [28]).

which propagates from cloud to ground and which is followed immediately by a very luminous return stroke [145]. In nature, there are two types of CG lightning, negative CG (–CG) and positive CG (+CG). –CG lightning which discharges the negative charges from the clouds to the ground accounts for almost 95% of all lightning while +CG lightning accounts for 5%. [146]. For a detailed discussion of lightning, refer to [116].

The electromagnetic energy from a lightning discharge distributes over an extremely broad bandwidth, from a few hertz [25] to many megahertz [149]. However, most of the energy concentrates in the very low frequency (VLF, 3–30 kHz) and extremely low frequency (ELF, 3–3000 Hz) bands [36]. These electromagnetic waves, called atmospherics (or sferics for short), propagate in the Earth-ionosphere waveguide and are bounced by the ground and the lower ionosphere but suffer low attenuations (a few decibels per 1000 km [135]). Therefore, the VLF and ELF sferics can be observed literally around the world from their source lightning discharges. Figure 1.1 (adapted from [28]) shows the VLF and ELF sferic propagation in the Earth-ionosphere waveguide.
Sferics which propagate long distances and have long delayed components are called “tweeks” [150]. However, if sferic waves escape from the Earth-ionosphere waveguide and enter the magnetosphere, bouncing between two hemispheres along a magnetic line and propagating long distances in the magnetosphere while suffering high dispersion, they become “whistlers” [41, 11, 133, 55]. Early research on sferics mainly focused on their discovery and property analysis. Burton and Broadman [26] found that the “tweek” waveform showed a sharp frequency cutoff and long tail near 1.7 kHz which was generated by a transient signal propagating in a waveguide with an upper boundary altitude from 61-85 km. After this, the research was focused on the variability and applications of sferics. Horner and Clarke [57] studied the occurrence rates of different sferics for different time of day, arrival bearings, and propagation distances. Jean et al. [74] and Taylor [135] analyzed the same sferic recorded at 4 locations in order to study VLF attenuation rates and phase characteristics. Hayakawa et al. [54] applied a field-analysis direction finding technique to derive the “tweek” characteristics including incident and azimuthal angles, wave polarization, and their frequencies. More recent work was focused on $D$ region electron density measurements using sferics due to their bounces in the Earth-ionosphere waveguide, which will be discussed in detail in this dissertation.

### 1.3 $D$ Region Measurements

Because the $D$ region is closely related to the radio wave communication, precise measurements of $D$ region are very important. Direct measurements are difficult because the $D$ region altitude is too high for balloons but too low for satellites to take in situ measurements. Radio waves are widely employed to measure $D$ region parameters including thermal plasma densities, temperatures, and velocities, as well as magnetic currents.
1.3.1 Ground Based and Space Based Techniques

Since the ionosphere electron density varies with altitudes, radio waves having different frequencies are reflected by different layers. Usually, the higher of the wave frequency, the greater is the reflective altitude because the ionosphere reflection ability is restricted by the plasma frequency which increases as the electron density increases.

Ionosonde is the first technique applied to explore the ionosphere by transmitting sweeping frequency (0.5–25 MHz) pulses which are reflected at various ionosphere layers [60]. However, ionosonde pulses can only be reflected by $E$ layer and $F$ layer, with no echo received from $D$ layer [118]. Coherent scatter radar is designed to receive echoes from turbulent irregularities of electron density within the ionosphere. Systems used to measure $E$ region and $F$ region are different. In the $E$ region they are used to observe the radio aurora and operated in very high frequency (VHF) band at about 70 MHz, whereas in the $F$ region they are operated in HF frequency band (e.g. at 8–20 MHz) [53]. However, no VLF band system is at present operated for probing the $D$ region [60]. A relatively new technique is the incoherent-scatter radar (ISR) which was first developed during 1960s. It can measure electron density, ion temperature and electron temperatures, ion composition and plasma velocity at the same time [42, 43, 94, 38, 82]. Because the ISR has to work with very weak signals, it requires a high-power transmitter, a large antenna, and the most sensitive receiver and sophisticated signal processing techniques, all of which add up to a considerable expense [53]. Other ground-based techniques including cross modulation [44, 126] and partial reflection [51, 13, 78] were also used to measure the ionosphere. However, when the ionosphere electron density is lower at night, the reflected waves become very weak. This makes the nighttime $D$ region measurements using these techniques very difficult.
Several space-based techniques have also been tried. Satellites and balloons cannot take in situ measurements in the $D$ region altitudes. The most common measurements were made by rockets since late 1940s and a variety of radio frequency (RF) probes have been used [81]. Radio wave propagation between ground instruments and rocket-borne equipments was used to derive the lower ionosphere electron density profiles along the wave propagation paths [97, 69, 49, 50], and Langmuir probes detect the electron density through measuring the electrical currents to an electrode at a fixed potential [128]. Although these measurements are precise, the rocket techniques are local, episodical and restricted by economical factors. Other space-based techniques including radio beacons for total electron content (TEC), radio beacons for scintillation, and topside sounders [60] are always used to measure high altitude ionosphere but rarely deal with $D$ region.

1.3.2 Narrowband VLF Measurements

The fact that VLF waves are mostly reflected by the $D$ region and propagating in the Earth-ionosphere waveguide makes them an effective tool for measuring the electron density in the $D$ region altitude range. Large man-made VLF transmitters were built world widely for military usage. These transmitters, located in different places, radiate VLF signals in different power and frequencies. For example, the NAA transmitter is located in Cutler, Maine, with a power of 1800 kW and operating frequency of 24 kHz. The VLF signals are reflected by lower ionosphere and recorded by different receivers.

Several researchers contributed to the early work of $D$ region electron density measurements using single frequency radio waves radiated from these VLF transmitters. By analyzing the experimental data over a range of frequencies from 16 to 100 kHz using the full wave method, Bracewell et al. [22], Belrose [12] and Deeks [39] deduced the $D$ region electron density profile over England and discussed its variations
with the time, year and sunspot cycle as well as eclipse effects. Later, average $D$ region electron density profiles across VLF wave propagation paths were estimated by comparing measured signals with computer modeled results. Bickel et al. [15] compared airborne measurements of the VLF signals to Naval Electronics Laboratory Center (NELC) [110, 107, 131] modeled results in order to verify the Earth magnetic field effects on VLF propagation. Thomson [136] compared measured field strengths from several VLF transmitters with the Naval Ocean Systems Center (NOSC) [108] program modeled results to determine improved daytime values of ionospheric parameters in order to enable improved VLF propagation predictions. Following this work, McRae and Thomson [95] refined the correlation between daytime $D$ region electron density profiles and solar zenith angles for solar minimum years, by using several narrowband VLF signals transmitted from Omega Japan, Omega Hawaii, NPM (Hawaii) and NLK (Seattle). Thomson et al. [139] estimated the nighttime $D$ region electron density profile from measurements of several frequencies in the range of 10 kHz to 41 kHz on long, mainly all-sea paths. And similar data and methods were used to compare the equatorial and nonequatorial nighttime $D$ region [140]. Thomson [137] also computed daytime $D$ region electron density profiles from short path VLF amplitudes and phases.

Besides these measurements made for ambient $D$ region electron density profiles, $D$ region perturbations in short time windows were also qualitatively or quantitatively measured from narrowband VLF waves. In past three decades, a lot of research work on narrowband VLF measurements of $D$ region perturbations induced by lightning discharges has been completed. Armstrong [3] gave the earliest experimental evidence of the “early/fast” VLF perturbation. The perturbation is caused by direct energy coupling released by lightning discharges into the lower ionosphere, which changes the electron density, temperature and other parameters of the $D$ region, and thus the subionospheric VLF signal amplitude and phase. Following research
work related to this topic was mainly completed by the VLF group in Stanford University. Inan et al. [67] studied the subionospheric VLF signatures associated with $D$ region perturbed by lightning discharges, and found the disturbances were confined within $\sim 150$ km of the causative lightning discharges and occurred $<50$ ms later than them. Inan et al. [66] studied a sequence of ‘early’ VLF perturbations and estimated the intensity of the peak E-field of the first causative return stroke. Inan et al. [61] presented the first evidence of lightning flashes which produced both sprites and VLF perturbations. Inan et al. [65] proposed the Quasi-electrostatic (QE) mechanism for the sustained heating of the lower ionosphere, which was evidenced by “early/fast” VLF events. Inan et al. [68] analyzed an eight hour-long episode of lightning-associated VLF and LF events observed in association with a persistent storm in Missouri. Bainbridge and Inan [8] reported measured ionospheric electron density profiles realized with 13 VLF receivers of the Holographic Array for Ionospheric Lightning (HAIL). Several researchers contributed to the modeling of “early/fast” VLF perturbations as well. Baba and Hayakawa [7] investigated the effect of lower ionosphere perturbations on subionospheric VLF propagation by using 2D finite element methods. Johnson et al. [76] measured the lower ionosphere disturbance scattering pattern by combining simultaneous observations of “early/fast” VLF events and VLF propagation and scattering simulated by a numerical model. Moore [102] compared magnitudes of three different “early/fast” VLF events with those produced by the electron density changes simulated by a full-wave electromagnetic (FWEM) model.

Different from the “early/fast” VLF events which typically occur several tens of milliseconds after causative lightning strokes and have rapid onsets, VLF perturbations caused by lightning induced electron precipitation (LEP) exhibit delays of 0.3–1.0 seconds with respect to causative lightning discharges and onset durations of 0.5–1.5 seconds [66]. In the LEP event, whistler waves excited by lightning
discharges couple into the magnetosphere and scatter the radiation belt electrons into loss cone, and these electrons precipitate into the lower ionosphere and alter the electron density there through the secondary ionization. In the early research work, subionospheric VLF perturbations caused by LEP were called “Trimpi effects” [56, 27]. In following years, more detailed measurements and analysis of LEP perturbed VLF events were presented and discussed in several papers [62, 63, 67]. There are two types of LEP events. The duct-LEP is generated by whistler waves excited by lightning discharges and propagating along geomagnetic lines [24]. More recent work was focused on non-duct LEP events. Whistler waves propagate obliquely into the magnetosphere and change the trapped particle pitch angle in Earth radiation belt by wave particle interactions. Johnson et al. [75] compared VLF perturbations associated with non-duct LEP observed in multiple stations to model simulated results calculated using combined ray tracing and test particle formulations [85]. Peter and Inan [112] studied the occurrence and spatial extent of D region perturbations caused by non-duct LEP using VLF signals radiated by large man-made transmitters and recorded by the HAIL. Bortnik et al. [20, 21] presented both the methodology and global signatures of model simulated precipitating radiation-belt electrons driven by whistler waves initiated by a single CG lightning discharge. For a detailed review of subionospheric VLF associated to lightning discharges, refer to [119].

Narrowband VLF waves were also used to remote sense D region perturbations caused by energetic particle precipitation during magnetic storms. Cummer et al. [35] determined the location and time of nighttime high-energy particle precipitation in high latitude regions from the perturbations of ground-based VLF transmitter signals. During the magnetic storm time, energetic particle precipitation is not restricted in high latitudes but extends to midlatitude regions. Peter et al. [111] demonstrated that subionospheric VLF signals can be used as a diagnostic of high-energy auroral precipitation at midlatitudes during geomagnetic storm time, by examin-
ing the perturbations of VLF signals correlated to geomagnetic activity changes in two storms in both the northern hemisphere and southern hemisphere. Rodger et al. [122] derived the $D$ region electron density profile variation during a magnetic storm by comparing measured VLF amplitudes with a simple chemical model and a subionospheric propagation model simulated results. Rodger et al. [121] reported short-lived VLF perturbations detected by sensors located in Sodankylä, Finland, which were probably caused by short bursts of relativistic electron precipitation.

In the daytime, VLF remote sensing has been used to measure the ionosphere perturbations induced by solar flare X-rays. The major ionization source of the undisturbed ionospheric $D$ region from which the VLF signals are reflected is the Lyman-$\alpha$ ultraviolet from solar radiation. When a solar flare (X-ray) occurs, the X-ray fluxes increase suddenly and those with wavelength appreciably below 1 nm are able to penetrate down to $D$ region and increase the ionization rate there [138]. A lot of work has been done regarding the correlation between X-ray fluxes and VLF perturbations as well as $D$ region electron density profiles. By comparing the solar flare X-ray flux data between 1977 and 1983 to the measured VLF phase shifts, Pant [106] showed that the VLF phase deviation increased linearly with the logarithm increase of X-ray fluxes. McRae and Thomson [96] studied the VLF amplitude and phase perturbations during several solar flare events, and quantitatively correlated the two parameter exponential $D$ region electron density profile changes with X-ray fluxes when they achieved their peak values. Thomson et al. [142, 141] deduced X-ray fluxes for several big solar flares including the one on November 4, 2003 from VLF phase shifts during the solar flare periods. Most of these studies focused on correlating the maximum X-ray flux and the maximum $D$ region change during the periods of solar flare events.

All these measurements require large man-made transmitters and are restricted to the regions between transmitters and receivers. Also, only VLF amplitude and phase
information is provided in the measurement. Cummer et al. [36] developed a new $D$ region measurement technique based on broadband VLF signals, which contain rich information in a wide frequency range and are launched by lightning discharges. This technique potentially enables the multi-path measurements simultaneously since lightning discharges occur world widely every day.

### 1.3.3 Remote Sensing by Sferics

Because the characteristics of sferics highly depend on the upper boundary ($D$ region) of the Earth-ionosphere waveguide, they are also used to remote sense the $D$ region. One method of $D$ region remote sensing by sferics is to infer the wave reflection height of the waveguide from the arrival time difference between the ground wave and sky hops or between different sky hops of sferic waveforms. Ryabov [123] gave a theoretical analysis of “tweek” propagation in the Earth-ionosphere waveguide and calculated the eigenmodes of the waveguide. Rafalsky et al. [115] inferred the effective ionospheric reflection height from sferic observations, but the precision of results was limited by the unknown lightning locations. Smith et al. [127] derived the 24 hour $D$ region reflection height variations from the VLF and low frequency (LF) electric fields excited by intracloud lightning and recorded by the Los Alamos Sferic Array (LASA). Jacobson et al. [70] retrieved the $D$ region reflection height variations over a three year period using Narrow Bipolar Event (NBE) lightning. Lay and Shao [88] presented the temporal and spatial image of $D$ region fluctuations measured by using time-domain lightning waveforms. However, in most of these measurements, the upper boundary of the Earth-ionosphere waveguide, $D$ region, was roughly approximated to be a Perfect Electrical Conductor (PEC), which is far from the true ionosphere [23].

Another method is to compare the measured sferic spectrum to model simulated spectra. In the model simulations, the $D$ region electron density, ion density as well
as collision frequency were treated as functions of altitudes [35]. Cummer et al. [36] used the sferics recorded by Stanford University VLF radiometer to calculate the $D$ region electron density profiles by comparing the measured sferic spectra to Long Wave Propagation Capability (LWPC) [109] modeled spectra. Cheng et al. [30] extended their work and measured electron density profile variations of 16 nights in 2004 using similar methods. Sferics were also used to remote sense the $D$ region perturbations. Cheng and Cummer [29] measured the $D$ region disturbances caused by a strong lightning stroke through comparing the broadband VLF spectrum from the lightning stroke that occurred just before and after the strong one. In addition, Jacobson et al. [72] proposed the broadband, single-hop method to derive the two-parameter exponential $D$ region electron density profile, and pointed out that this method can be potentially used to study the localized and transient disturbances. However, in all these works, systematic measurements of $D$ region variations showing time and spatial scales are lacking.

In this work, we derived the $D$ region electron density profile height by comparing the measured sferic spectra to Finite-difference time-domain (FDTD) model simulated results [59]. Two simulated sferic databases were set up for sferics excited by lightning strokes from different locations and for different $D$ region electron density profiles, for both nighttime and daytime. Massive sferic data in July and August 2005 were analyzed. Systematic $D$ region electron density profile variations in both the nighttime and daytime were derived.

1.4 Contributions

The major content of this dissertation has been published or accepted for publishing in three first author papers in Journal of Geophysical Research -Space Physics. Most parts have been presented in conferences of related research areas. The contributions are as follows:
Chapter 3: for the first time, broadband sferics were used to continuously monitor the nighttime $D$ region electron density profile height variations. The profile heights were extracted from sferics in July and August 2005 by comparing measured broadband VLF spectra to a series of simulated spectra. A database was set up for simulated sferics for different $D$ region electron density profiles, azimuth bearings, and propagating distances using the FDTD code [59]. An automatic computer fitting code was used to find the best fitted profile height for each sferic. The statistical results of 260 independent hourly average measurements were calculated. The temporal variations of $D$ region electron density profile heights on time scales of minutes to hours were studied, as were spatial variations. Possible mechanisms accounting for the temporal variations were explored (Han and Cummer, 2010, “Midlatitude nighttime $D$ region ionosphere variability on hourly to monthly timescales”).

Chapter 3: nighttime $D$ region electron density profile sharpness was derived by comparing higher frequency mode interference features of measured and simulated sferic spectra. We calculated the nighttime $D$ region sharpness during 2.5 hour periods on two nights and compared our broadband VLF measurements with International reference ionosphere (IRI) modeled results.

Chapter 4: by using data and methods similar to those for nighttime, for the first time, we calculated the midlatitude daytime ionospheric $D$ region electron density profile height continuous variations in July and August 2005 near Duke University. The variations in time scales of minutes to hours were calculated. Instantaneous measurements of geographical variations beyond the solar zenith angle effects were studied by comparing the measured effective heights in two different regions. The solar zenith angle dependence of measured heights was quantitatively analyzed. Measured heights were correlated to X-
ray fluxes in the solar flare rising phases, peaks and decaying phases (Han and Cummer, 2010, “Midlatitude daytime $D$ region ionosphere variations measured from radio atmospherics”).

- Chapter 4: by using data and methods similar to those for nighttime, we calculated the midlatitude daytime $D$ region sharpness variations during morning, noontime and afternoon periods in three different days. We compared our results to narrowband VLF measurements, IRI modeled results and a semiempirical model of the lower ionosphere (FIRI) which is only based on radio wave propagation data from rocket soundings (Han et al., 2011 “Daytime ionospheric $D$ region sharpness derived from high frequency range of VLF radio atmospherics”).

- Chapter 5: by using the nighttime and daytime measurement techniques, for the first time, we derived the $D$ region variations during sunrise and sunset periods from broadband sferics. Both the profile height and sharpness in more than 2 hours during the sunrise and sunset periods in two different days were calculated.
The purpose of this dissertation is to extract the $D$ region electron density profiles from measured sferics by comparing them to model simulated results. In order to measure the electron density as precisely as possible, we need accurate individual sferic measurements and the modeling of their propagation in the Earth-ionosphere waveguide. A detailed description of the sferic measurement by the broadband ELF/VLF receiver near Duke University, as well as its propagation modeling by a 2D cylindrical FDTD code for different $D$ region parameters, are given in this chapter.

2.1 Sferic Measurement by the Duke Receiver

2.1.1 Data Acquisition System

Broadband ELF/VLF receivers located near Duke University, with latitude 35.97° N and longitude 79.10° W, have been operated with the aim of recording sferic waveforms generated by lightning discharges which occur from nearby regions to several thousand kilometers away. The recording system has a large dynamic range
and can adapt to different amplitudes. This large dynamic range guarantees that the sferics discharged by nearby lightning strokes are not large enough to be saturated but those generated by lightning strokes far from the sensors are distinguishable from noise. The sensors are positioned underground in the Duke Forest in order to lower the noise level.

The configuration of the sferic receiver is shown in Figure 2.1. The whole system consists of orthogonal magnetic loop antennas, electronic circuits (including pre-amplifiers, a line driver, a line receiver and an anti-aliasing filter), a Global Positioning System (GPS), and the data sampling system (including a 16 bit analog-to-digital (A/D) converter and data storage media). Two orthogonal magnetic loops oriented in geomagnetic north south (labeled N/S) and east west (labeled E/W) are used to measure two orthogonal horizontal magnetic components. The current induced by magnetic flux variations in the antenna loops flows to matched preamplifiers. The current signals are converted to voltage signals and amplified. These signals are not directly sent to the anti-aliasing filter but converted to differential signals from single-end signals by the line driver, and will be converted back to single-end signals

**Figure 2.1**: The sferic receiver.
in the line receiver. These two conversions are used to lower the noise interference for the signal transmissions between antennas and the data processing system 300 meter apart. The magnetic coils and electronics in front of the anti-aliasing filter have a frequency response of the first order butterworth high pass at 100 Hz and first order butterworth low pass at 13 kHz. The anti-aliasing filter, which has a frequency response of the sixth order type I Chebyshev low pass at 25 kHz, is used to restrict the bandwidth of signals before they are sampled by A/D converter. The GPS provides the inter-range instrumentation group (IRIG) time code, a 1 pulse per second (1PPS) signal which is used to start the sampling, and 100 kHz sampling pulses. The A/D converter is used to sample the analog signals at 100 kHz frequency, and the digital samples are saved on computer hard drives. The data sampling system has two work modes, continuous mode and triggering mode. In the continuous mode, the data acquisition card samples the signals continuously and records all the sferics. In the triggering mode, the system only records the sferics whose amplitudes are larger than a certain threshold, so as to avoid too much data accumulation. The sferic data we used in this work were sampled in the continuous mode.

2.1.2 Data Post-processing

The sferic data acquired by the system are uncalibrated binary raw data. Before being compared to FDTD model simulated results, they must be denoised, calibrated, and converted to radial component $B_r$ and azimuthal component $B_\phi$ in the geographic north-south and east-west coordinate. Figure 2.2 shows typical uncalibrated sferic waveforms $B_1$ (from the N/S loop) and $B_2$ (from the E/W loop). The sferic was discharged by a lightning stroke 664 km away to the northwest of the receiver at nighttime. The uncalibrated $B_1$ and $B_2$ have no unit. The very slow variations in the signals were generated by the electrical power lines near the data acquisition system and have a frequency of 60 Hz. This interference is excluded by the denoise
code in the data processing procedure. The true magnitudes (unit in nT) of two orthogonal magnetic components are calculated using the gains of antenna loops and the electronics.

After calibration, $B_1$ and $B_2$ are converted to $B_{ng}$ and $B_{eg}$ which represent signals in geographic north and east directions. Figure 2.3 shows this calculation. The $\theta$ is magnetic declination which is the angle between magnetic north and geographic north. Near Duke University, this angle was $\sim -8.5$ degrees in 2005 (The negative sign means the magnetic north is west of geographic north). The $B_{ng}$ and $B_{eg}$ are calculated using

$$B_{ng} = B_1 \cos(\theta) - B_2 \sin(\theta)$$  \hspace{1cm} (2.1)

$$B_{eg} = B_1 \sin(\theta) + B_2 \cos(\theta)$$  \hspace{1cm} (2.2)

The radial component $B_r$ and azimuthal component $B_\phi$ are calculated using

$$B_r = -B_{ng} \cos(\phi) - B_{eg} \sin(\phi)$$  \hspace{1cm} (2.3)

$$B_\phi = -B_{ng} \sin(\phi) + B_{eg} \cos(\phi)$$  \hspace{1cm} (2.4)

where $\phi$ is the lightning azimuth angle, defined as the angle from the geographic

\[\text{Figure 2.2: Typical uncalibrated sferic data. $B_1$ is recorded by the N/S sensor; $B_2$ is recorded by the E/W sensor.}\]
north to the lightning arrival direction in a clockwise sense.

$B_\phi$ and $B_r$ calculated from the uncalibrated raw data illustrated in Figure 2.2 are shown in Figure 2.4. In the time domain, the sferic waveform is the superposition of a series of rays [33]. Usually, the first peak represents the ground wave and has no relationship with the ionosphere. The second peak represents the first sky hop, and is reflected once by the lower ionosphere. Following peaks are reflected more and more times by the ionosphere and become weaker and weaker. The magnitude of $B_r$ is not zero even in the far field, but as large as one fifth of that of $B_\phi$. This is because the ionosphere is anisotropic and the sky hops of $B_r$ are always enlarged. In our data analysis, only $B_\phi$ is used in order to maximize the signal to noise ratio (SNR). The SNR is also improved by using a late-time filter which low-pass filters a
Figure 2.4: Typical $B_\phi$ and $B_r$. The amplitude of $B_\phi$ is larger than that of $B_r$. Upper panel: time domain waveforms; Lower panel: frequency spectra.

portion of the sferic waveform, from $\sim 4$ ms after the start of the sferic to the end, because the sferic signals are dispersive and higher frequencies arrive at the receiver earlier [36, 30]. In this work, we use a zero phase shift low pass filter with $-6$ dB cutoff frequency of 9.2 kHz.

The lower panel of Figure 2.4 shows the $B_\phi$ and $B_r$ spectra. The peaks and valleys (termed “fine frequency structures”) in lower frequency bands are caused by Earth-ionosphere waveguide mode interference. Both the ground and ionosphere are good conductors, and sferics radiated from lightning discharges can propagate long distances in waveguide modes Quasi-TE (QTE), Quasi-TM (QTM), or Quasi-
TEM (QTEM), analogous to TE, TM and TEM modes in an ideal parallel-plate waveguide [64]. The interference among these modes generates the fine frequency structures. In lower frequency bands, the interference patterns are simple because the quantity of waveguide modes is very limited. However, in higher frequency bands, the interference patterns become more and more complicated, and it is from these patterns that the $D$ region information is extracted.

2.1.3 Sferic Locating

Although the accurate waveform of a sferic is measured by the data acquisition system, the location of the lightning stroke that generates this sferic is unknown. The National Lightning Detection Network (NLDN), which has more than 100 sensors across the United States continent, can detect CG flashes with peak currents larger than 5 kA, with an efficiency ranging from 80% to 90%, and provides lightning information including the timing (with a resolution less than one millisecond), locations (with a resolution less than 500 m), and peak currents [14, 37]. The lightning data are combined with sferic data to find the corresponding sferic waveform for a certain lightning stroke by using time alignment.

2.2 Sferic Propagation Modeling

The FDTD model simulation of sferic propagation in the Earth-ionosphere waveguide is necessary since the $D$ region electron density profile is extracted by comparing the measured sferic spectra to simulated spectra. The 2D cylindrical FDTD model we use was constructed by Hu [58, 59] and can calculate sferic waveforms discharged by different lightning waveforms and propagating in the Earth-ionosphere waveguide with different boundary configurations.
return stroke current waveform is given by
\[ I(t) = I_0 \nu_0 \gamma \left[ \exp(-at) - \exp(-bt) \right] \left[ 1 - \exp(-\gamma t) \right] / t \]
where \( I_0 = 20 \text{kA} \), \( \nu_0 = 8 \times 10^7 \text{m/s} \), \( \gamma = 3 \times 10^4 \text{s}^{-1} \), \( a = 2 \times 10^4 \text{s}^{-1} \), \( b = 2 \times 10^5 \text{s}^{-1} \), and \( L \) is the lightning discharge channel length.

Since we are mostly interested in vertically aligned lightning discharge currents (from an application standpoint) in this work, thus the problem is simplified from a 3-D system to 2-D cylindrical problem to substantially increase the size of problem that can be solved. The geometry of the problem is shown in Figure 2.3. When the sample points are very close to the source current, the model deviates from the real case due to the existence of Earth magnetic field \( B_E \) (with \( z \), \( r \), and \( \phi \) components), which is not circularly symmetrical in reality. However, when the model is used for far-field calculation, this kind of approximation is accurate enough. The numerical simulation results will show that the circular symmetry approximation results in excellent agreement with mode theory results, even for near-field calculation. This point will be discussed in Chapter 4.

As shown in Figure 2.2, the domain is surrounded by absorbing boundary layers to absorb the outgoing electromagnetic waves sufficiently and avoid the artificial

2.2.1 2D Cylindrical FDTD Model

The sferic wave propagation in the Earth-ionosphere waveguide can be described by Maxwell equations. The basic ideal of FDTD method is to solve the equations in the time domain by discretizing them to the space and time partial derivatives using central-difference approximations. A 3D FDTD model can simulate the sferic wave propagation accurately. However, in order to reduce the computation expense of massive simulations for the work in this dissertation, the 3D model is simplified to a 2D model by treating the sferic wave propagation cylindrical symmetrical and only performing the simulations in the wave propagation plane between lightning and the sferic receiver. Figure 2.5 (adapted from [58]) shows the geometry of the 2D domain. Measured sferics are compared to the simulated sferics in the sample point in order to extract the ionosphere information.

We performed simulations using both the 3D and 2D models to validate the 2D approximation. The simulations are for propagation distance 100 km and the sample points are in 10 km altitude. The comparison between 3D and 2D simulated results
Figure 2.6: The comparison of 3D and 2D FDTD model simulations. The sferic waveforms are almost the same.

is shown in Figure 2.6. The consistency indicates that the 2D FDTD simulation can repeat almost all the sferic features from the 3D model. This means the $D$ region electron density profiles extracted from the broadband sferics by comparing them to 2D model simulated results are reliable.

2.2.2 $D$ Region Profiles

In the cylindrical 2D FDTD model simulations, we use the standard $D$ region electron density profile parameterizations of

$$N_e(h) = 1.43 \times 10^7 \exp(-0.15h') \times \exp[(\beta - 0.15)(h - h')] \text{ cm}^{-3} \quad (2.5)$$

with $h'$ in km and $\beta$ in km$^{-1}$. This was first given by Wait and Spies [147]. Sechrist [125] compared this to directly observed $D$ region profile and found they agreed well. By constraining our measurements to this functional form, we can measure equivalent exponential profiles that may be different from the more complex true profiles [52, 130]. Cheng et al. [30] showed that the sferic spectra under rocket measured electron density profiles [98, 129] and equivalent two-parameter exponential profiles are in good agreement, and also that an equivalent profile can reproduce
Figure 2.7: The effects of $h'$ and $\beta$ on D region electron density profiles.

The major sferic propagation effects. This equivalent exponential profile has been successfully used in VLF measurements [36, 95, 30, 139]. The parameter $h'$ controls the height of the electron density profile while $\beta$ controls the sharpness of the profile. As shown in Figure 2.7, a larger $h'$ means a higher profile while a larger $\beta$ leads to a faster increase of the electron density as a function of altitude. Usually, in daytime, the profile is lower, i.e., $h'$ is smaller due to solar radiation ionization. Figure 2.7 shows three typical nighttime profiles and three typical daytime profiles.

The positive ion density is approximated to be the same as the electron density above a certain altitude where $N_e$ equals some predetermined value $N_{i^{+\min}}$ which is assumed to be 100 cm$^{-3}$ in all simulations, and is consistent with observations made by Narcisi [105, 104]. To maintain the charge neutrality, under this altitude, $N_{i^-} = N_{i^+} - N_e$. The ion density profiles have uncertainties and are not well constrained in real measurements. We performed FDTD model simulations and found that an increase in the ion density by a factor of 10 only affects the amplitude of the spectrum but has a negligible effect on waveguide mode interference patterns from which the equivalent exponential profile is extracted for both the nighttime and daytime measurements.
Collision frequency is another important factor that must be taken into account since the wave attenuation in the Earth-ionosphere waveguide is mainly caused by collisions between electrons, ions and other particles. Wait and Spies [147] analyzed laboratory experiment data [113], partial reflection data [13] and rocket measurements [79], and concluded that the electron neutral collision frequency can be analytically approximated to be

\[ \nu_e = 1.816 \times 10^{11} \exp(-0.15z) \text{ s}^{-1} \] (2.6)

where \( z \) is the latitude measured in kilometers. The ion-neutral collision frequency was given by Morfitt and Shellman [103]

\[ \nu_i = 4.54 \times 10^9 \exp(-0.15z) \text{ s}^{-1} \] (2.7)

for both positive and negative ions. There are also uncertainties in the \( D \) region collision frequency profiles [113, 143, 48]. We performed FDTD model simulations and found that a change from the profile adapted from [143] to the profile from [147], around an increase of 3 times of the collision frequency, can shift the sferic spectrum, which is equal to a shift caused by 0.2 km \( h' \) change for nighttime measurements and 0.6 km \( h' \) change for daytime measurements. This means an error of 0.2 km for the nighttime or 0.6 km for the daytime of the measured \( h' \) is caused by an uncertainty of 3 times the collision frequency density. Although the true ion density profiles and collision frequency profiles can be different from the profiles we used in this work, the insensitivity of the waveguide mode interference pattern of a spectrum on ion densities and collision frequencies means the derived equivalent exponential profile is precise and reliable. Typical \( D \) region electron density profiles, ion density profiles, and collision frequency profiles adapted from [34] are shown in Figure 2.8. In the \( D \) region, the electron density and collision frequency can be modeled by exponential profiles given in (2.5), (2.6) and (2.7). In the higher region, the profiles are calculated using IRI [16, 117, 17].
2.2.3 The Ground Boundary

The upper boundary of the simulation domain is modeled by the exponential profiles described by (2.5), (2.6) and (2.7). The lower boundary, the ground, is treated as a PEC in previous work [34, 92]. In this work, for the $h'$ derivation from sferic spectrum lower frequency features, the PEC approximation has no effect on the results because the true ground can be treated as a PEC for lower frequency ($\leq 8$ kHz) signals [9]. FDTD simulations showed that a change from the PEC boundary to soil or water mainly affects upper VLF frequency range and the spectrum change below 8 kHz is negligible.

Therefore, the PEC approximation definitely affects the $\beta$ measurement since $\beta$ is derived from the higher frequency features, which will be discussed in following chapters. The physical parameters of the lower boundary depend on the sferic propagation paths. If the sferic propagation path is over the ocean, the lower boundary can be treated as a PEC since the sea water conductivity is large enough. FDTD model simulations showed that sferic spectra at frequencies less than 30 kHz are al-

**Figure 2.8**: Typical $D$ region profiles (adapted from [34]). Left panel: electron and ion density profiles; Right panel: collision frequency profiles.
most identical for the PEC boundary and Surface Impedance Boundary Conditions (SIBC) [93, 80] with the typical sea water conductivity 4 S/m [9]. However, if the sferic propagation path is over land, the small ground conductivity 0.004 S/m near Duke University [46] must be taken into account, and only SIBC can be used for the ground boundary. Therefore, for a sferic wave from south, west, and northeast, (azimuth angle from 180° to 360° and 0 to 45°), the whole propagation path is over land and SIBC are used for all the FDTD model simulations. For a sferic wave from northeast to south (azimuth range from 45° to 180°), since more than half of the wave propagation paths for all the measurements in this dissertation are over the ocean, we use the PEC ground boundary condition.

The FDTD model does not support partial ground and partial sea water boundary condition. The PEC approximation of the partial sea and partial soil leads to an error in the β measurement. FDTD model simulations showed that a change from all sea (treated as a PEC) to all soil with conductivity 0.004 S/m in a 720 km propagation path caused an increase of 0.05 km$^{-1}$ in daytime β measurement and 0.08 km$^{-1}$ in nighttime measurement. If we consider a smaller ground conductivity $\sigma = 0.001$ S/m which has been used by Thomson [137], this increase is 0.08 km$^{-1}$ in daytime and 0.11 km$^{-1}$ in nighttime. However, in all our measurements for azimuth angle in 45°–180° range, the real sferic wave propagation paths have more than half in the sea water, and therefore the β measurement error caused by the PEC approximation is less than 0.04 km$^{-1}$ in daytime and 0.06 km$^{-1}$ in nighttime for ground conductivity $\sigma = 0.001$ S/m, whereas it is less than 0.03 km$^{-1}$ in daytime and 0.04 km$^{-1}$ at nighttime for ground conductivity $\sigma = 0.004$ S/m, if we assume a linear change of the error with distance. This means the measured β values in this work using PEC approximation for the partial sea and partial ground are smaller than the true values by less than 0.03–0.04 km$^{-1}$ in daytime and by less than 0.04–0.06 km$^{-1}$ in nighttime. For the sferic in an all land path (azimuth angle from 180° to 360° and 0 to 45°), the
measured $\beta$ is 0.03 km$^{-1}$ smaller if we use the ground conductivity $\sigma = 0.004$ S/m instead of 0.001 S/m for the daytime measurement. In addition, Perfect Matched Layers (PML) were used to absorb outward propagating sferic waves so as to avoid artificial reflections [59].

2.2.4 Earth Magnetic Field

Earth background magnetic field affects the radio wave significantly since the motions of charged particles in the ionosphere plasma are subject to the static field, and the currents generated by these motions are coupled into the Maxwell equations and lead to a complicated process describing the wave propagation in magnetized cold plasma. The vector magnetic field is treated as homogenous in the whole simulation domain with magnitude $5 \times 10^4$ nT and dip angle 65°, since the simulated sferic wave propagation is in the midlatitude and the size of simulation domain is much smaller than Earth radius. The azimuth dependence of the wave propagation is also included. It means the geomagnetic field is uniform in the simulation domain but is domain relative to wave propagation. It varies to reflect the real propagation geometry. The uniform Earth magnetic filed in the 2D simulation domain is approximated by taking the 3D Earth magnetic filed along the sferic wave propagation path and rotating it to make it $\phi$ symmetrical. We only need to rotate the radial and $\phi$ components. There is no need to rotate $z$ component since it is already $\phi$ symmetrical [58]. The absolute value of Earth magnetic filed also has some effects on sferic spectra. For the daytime sferic spectra, FDTD model simulations showed that lowering one order of the total magnetic field decreases the magnitude of the waveguide mode interference pattern to one fifth of its original value due to the attenuation of the TM modes in the Earth-ionosphere waveguide. The weaker waveguide mode interference pattern makes the positions of those peaks and valleys in the mode interference pattern more difficult to locate.
2.2.5 Earth Curvature Correction

When the sferic propagation distance is short, the Earth curvature can be neglected. However, it must be taken into account if precise simulated results are needed for long propagation distances. The method used in this FDTD model is modified refractive index [19, 23, 148]. The main idea of this method is to replace the larger physical distance of the upper boundary of the waveguide with a larger electrical distance using a fictitious refractive index correction factor \( n_m(z) = n \cdot f_m(z) \), where \( f_m(z) = (1 + z/r_0) \), \( r_0 \) is the Earth radius, and \( z \) is much smaller than \( r_0 \) [58].

2.2.6 Lightning Strokes

Although the sferics radiated from vertical current moment of lightning return strokes [4] have smooth spectra over the whole VLF band [84], a specific form of the current moment is needed in order to implement the FDTD model simulation. In this work, we use the model given by Jones [77],

\[
I_m(t) = I_0 \frac{\nu_0}{\gamma} [e^{-at} - e^{-bt}] [1 - e^{-\gamma t}] \tag{2.8}
\]

where \( I_0 = 20 \text{ kA}, \nu_0 = 8 \times 10^7 \text{ m/s}, \gamma = 3 \times 10^4 \text{ s}, a = 2 \times 10^4 \text{ s}, b = 2 \times 10^5 \text{ s/}[40].

Figure 2.9 shows the waveform and spectrum of this current moment. The spectrum of the lightning return stroke is smooth before the sferic propagation in the Earth-ionosphere waveguide. The spectra of sferics recorded by the Duke receiver have obvious fine frequency structures which are caused by waveguide mode interference and thus independent of the smooth spectrum related to specific lightning current moment [36, 30]. The measurement of \( h' \) and \( \beta \) only depends on the fine frequency structures. Therefore, this current moment of the source lightning is used in all the FDTD model simulations no matter where and when the lightning occurs. In the analysis discussed in following chapters, the source spectrum is normalized.
Figure 2.9: The lightning current moment. Upper panel: the time domain waveform; Lower panel: the frequency spectrum.

out, and the source waveform does not influence the results. Some lightning source spectra are not flat and cannot be completely normalized out. However, they do not affect the major variation trend of the measured $h'$ and $\beta$ values from average spectra because they are rather uncommon.
Nighttime $D$ Region Measurement

Significant temporal variations of the nighttime $D$ region are well known, but its inaccessibility means that the time scales, magnitudes and sources for these variations are not well understood. In order to uncover these unknowns, people have done a lot of nighttime $D$ region measurements using VLF remote sensing. One technique is using the narrowband VLF signals to measure the $D$ region ambient variations or disturbances [136, 61, 76, 139]. Unfortunately, this technique can only be used to measure the $D$ region between the transmitters and receivers. Another approach widely employed in recent years is to extract ionosphere information from the broadband sferics radiated by lightning discharges [36, 29, 30, 70, 88]. This approach is potentially capable of measuring $D$ region around the receivers in all azimuthal directions since lightning may occur in any locations everyday. However, systematic measurements of $D$ region variations from sferics showing time and spatial scales are lacking.

In this chapter, we used the sferics excited by 61,726 lightning strokes in July and August 2005 to almost continuously monitor the $D$ region profile height variations on 59 different nights from 00 to 05 Local Time (LT), i.e., 04–09 Universal
Time (UT) because Eastern Daylight Time (EDT) used in this work, by comparing measured broadband sferic spectra to a series of FDTD model simulated sferic spectra. A database was set up for simulated sferics for different $D$ region electron density profiles, azimuth bearings, and propagating distances using the FDTD code [59]. An automatic computer fitting algorithm was used to find the best fitted $D$ region electron density profile height for each sferic. The statistical results of 260 independent hourly average measurements were calculated. The temporal variations of $D$ region electron density profile heights on time scales of minutes to hours were studied, as were spatial variations. Possible mechanisms for the temporal variations were explored.

For the profile sharpness $\beta$ measurements, Cummer et al. [36] suggested a method based on the interference amplitude, but our attempts to apply it to many signals indicated that it does not work reliably. In this chapter, we described and applied a different technique for measuring $\beta$, which is based on the frequency of spectral minima from waveguide mode interference at upper VLF frequencies ($\sim 25$ kHz). FDTD model simulations of broadband VLF propagation were used to show that the frequencies of these minima are dependent on $\beta$. To demonstrate the technique, we measured the midlatitude nighttime $D$ region electron density profile sharpness variations at two different nights, and compared the measured $\beta$ with the equivalent exponential profiles for IRI models. The equivalent exponential profiles mean they can best duplicate the sferic spectral characteristics for IRI models.

3.1 Nighttime Data Analysis

The sferic data analyzed in this dissertation are recorded by the broadband VLF/ELF sensors located near Duke University. The lightning data provided by the NLDN are combined with sferic data to find the corresponding sferic waveform for a certain CG or IC lightning flash.
Figure 3.1: Nighttime sferic spectra for lightning at different time but from almost the same location. (a) the general shape of the nighttime sferic spectrum across full wave bandwidth; (b) the lower frequency features for events on July 29, 2005 demonstrate strong variations of the nighttime D region; (c) the lower frequency features for events on July 5, 2005 show little variation; (d) the spectra minima in higher frequency range for the events on July 29, 2005 also demonstrate the D region variation; (e) the spectra minima in higher frequency range for the events on July 5, 2005 show some uncertainties.
Figure 3.1 shows seven typical measured nighttime $B_\phi$ spectra excited by NLDN recorded lightning strokes. Figure 3.1a shows the general shape of a typical nighttime sferic spectrum. The fine frequency structures between 3 kHz and 8 kHz as well as near 22 kHz are a result of Earth-ionosphere waveguide mode interference. Their sensitive dependence on the $D$ region electron density profile [36] forms the basis of nighttime $D$ region measurement technique. In this work, the parameter $h'$ is derived from 3–8 kHz frequency range while $\beta$ is derived from the sferic spectrum valley position near 22 kHz.

Three sferic spectra in Figure 3.1b, which were generated by lightning strokes 615 km from the east coast of the United States on July 29, 2005, show a 3 hour period that exhibits significant frequency changes, and thus ionosphere variations over that time. Three sferic spectra in Figure 3.1c which were generated by lightning strokes around 540 km north of Duke station on July 5, 2005, show a 2.5 hour period in which the ionosphere was relatively stable. Although the spectra magnitudes are different between 5.5 kHz and 8 kHz, the fine frequency structures (those peaks and valleys) positions which are closely related to ionosphere state are almost the same. Figure 3.1d and 3.1e show the higher frequency features for the sferic spectra shown in Figure 3.1b and 3.1c, respectively. On July 29, 2005, the higher frequency spectrum minima in 26–28 kHz range shifts in the same trend as the lower frequency features. However, on July 5, 2005, although the three sferic spectra have the same features in the lower frequency range, the higher frequency spectra minima are not the same. These uncertainties can lead to the measured $\beta$ uncertainties and can be lowered by taking the average spectrum of a group of sferic spectra, and this will be discussed in detail in following sections in this chapter.

We only analyzed the the sferic data in July and August 2005 since the data acquisition system worked in continuous mode in these two months, which made the ionospheric $D$ region monitored in almost a continuous fashion. Only local nighttime
(00–05 LT, 04–09 UT) data were studied and the daytime data will be analyzed in next chapter because the daytime sferic component $B_\phi$ shows significantly different features compared to those of nighttime sferics. The amplitude variations between 3 kHz and 8 kHz from which the $D$ region electron density profile height is extracted are clear in the night time sferic spectrum but almost disappear in the daytime sferic spectrum. In addition, only lightning strokes that occurred between 500 and 800 km from the receiver are considered. These propagation distances ensure that we are measuring the ionosphere in a relatively small geographic region to minimize the spatial averaging of any variability. On the other hand, sferics generated by lightning strokes too near the receivers have fewer mode interference features, and therefore contain less ionosphere information in the spectra. A criterion of 30 kA threshold was applied to the lightning peak current selection to ensure each sferic has a favorable SNR.

3.2 Influence of $D$ Region Parameters on VLF Spectra

In all simulations, we use the electron density profiles modeled by (2.5). The parameters $h'$ and $\beta$ have different effects on a sferic spectrum [36], and this is illustrated in Figure 3.2 and Figure 3.3. In all these simulations, we chose distances = 700 km and azimuth angles = 90° as representatives. Figure 3.2 shows the $h'$ effects on a sferic spectrum in different frequency ranges and Figure 3.3 shows the $\beta$ effects. Figure 3.2a shows five sample nighttime electron density profiles for the same $\beta$ value but different $h'$ values, and Figure 3.2b shows the corresponding simulated sferic spectra across the full VLF bandwidth for these profiles. As shown in Figure 3.2c and 3.2d, a larger $h'$ alters the positions of the waveguide mode interference fringes by lowering the cutoff frequencies of all modes in the waveguide [36], and thus causes the waveguide mode interference fringes in 3–8 kHz and 24–29 kHz ranges to shift to lower frequency bands. And it is from the fringe positions in 3–8 kHz that $h'$ is
Figure 3.2: Five typical nighttime $D$ region electron density profiles and corresponding simulated sferic spectra under these profiles. (a) electron density profiles; (b) the general shapes of sferic spectra; (c) the sferic spectra in lower frequency band; (d) the sferic spectra in higher frequency band. The mode interference patterns in both the lower and higher frequency VLF spectra are sensitive to $h'$ changes.

In contrast, as shown in Figure 3.3, in the lower VLF frequency range from $\sim$3–8 kHz, a change in $\beta$ affects the magnitudes of those fringes but very minimally changes the positions of the fringes [28], as shown in Figure 3.3c. FDTD model simulations showed that increasing $\beta$ from 0.55 to 0.65 km$^{-1}$ leads to the measured $h'$ change of $\sim$0.2 km. This magnitude difference has been attributed to improved reflection from a sharper ionosphere, leading to lower attenuation of near-cutoff waveguide modes [36]. We find that, in practice, it is difficult to use this amplitude change to infer $\beta$
Figure 3.3: Five typical nighttime D region electron density profiles and corresponding simulated sferic spectra under these profiles. (a) electron density profiles; (b) the general shapes of sferic spectra; (c) the sferic spectra in lower frequency band; (d) the sferic spectra in higher frequency band. The parameter $\beta$ affects the positions of the fringes in lower frequency range very minimally but change those in the higher frequency range obviously.

because variations in received signals, perhaps due to small differences in lightning current waveforms and channel orientations, are too large. However, as shown in Figure 3.3d, the spectrum minimum in the higher VLF frequency range (26–27 kHz) clearly shifts down as $\beta$ increases. It is from the position of this minimum that the nighttime $\beta$ is derived.

Consequently, in this work, we assumed a fixed $\beta$ for the $h'$ measurement from the frequency features in 3–8 kHz range. We assumed the long-term average nighttime
Figure 3.4: The distance and azimuth angle effects on sferic spectra. Left panel: lower frequency range; Right panel: higher frequency range. The distance increase of 20 km causes the sferic spectrum shifting to upper frequency while the azimuth angle change of 30 degrees causes no shift.

The modal interference fringe pattern in both lower frequency and higher frequency ranges are sensitively dependent on propagation distance, as shown in Figure 3.4. For the same electron density profiles, larger propagation distance causes the spectrum stretched, i.e., the fine frequency structures generated by waveguide mode inferences shift up in frequency. The effect of the propagation direction, relative to the background magnetic field azimuth, also influences the spectrum but less sensitively than distance, as also shown in Figure 3.4. For this reason, our simulations require precise values of propagation distance for comparison, but less precise values of propagation azimuth.

value of $\beta = 0.65 \text{ km}^{-1}$ measured by Thomson et al. [139]. The statistical results of $h'$ measured in this way are meaningful because the error caused by the fixed $\beta = 0.65 \text{ km}^{-1}$ is very small compared to the $h'$ spatial and temporal variations. Once the $h'$ is measured from the modal interference pattern alignment in the lower frequency range, we derive $\beta$ from the spectrum minimum in the higher frequency range.
3.3 Method of $h'$ Measurement

In order to extract the parameter $h'$ from a measured sferic spectrum, we compare the measured spectrum to a series of FDTD model simulated sferic spectra under different electron density profiles. A simulated sferic database was set up for different lightning distances, azimuth angles (bearing clockwise from north of Duke station) and $D$ region electron density profiles. Propagation distances vary with step 20 km; azimuth angles vary from 0 to 360 degrees with step 30 degrees; electron density profiles modeled with $h'$ changes from 80 to 88 km with step 0.2 km, and $\beta$ is fixed to be 0.65 km$^{-1}$. An automatic fitting algorithm was constructed to find the best fitted simulated sferic spectrum for each recorded sferic excited by a lightning stroke in a certain azimuth and distance, i.e., to derive the average electron density profile parameter $h'$ for $\beta = 0.65$ km$^{-1}$ across the wave propagation path.

The $h'$ is derived in following four steps. At first, the program code fetches from the database the simulated sferics that have the azimuth angle and two distances nearest to the azimuth angle and distance of the measured sferic. Then, it selects several simulated sferic spectra which have one peak aligned with the biggest peak of the measured sferic spectrum in the frequency range 3–4 kHz. This range has the largest sferic energy distribution, and thus the positions of fine frequency structures caused by waveguide mode interference are clear due to the high SNR. These selected simulated sferics are termed “first batch sferics”. Usually, the best fitted sferic is one of the “first batch sferics”. But many other sferics are also included in the “first batch sferics” because the $h'$ change causes those peaks shift in 3–4 kHz frequency range and other peaks can also align with the biggest peak of the measured sferic spectrum. And the “second batch sferics” are generated by adding other sferics corresponding to $h'$ 0.2 km smaller and 0.2 km larger than the $h'$ for each of the “first batch sferics” to it. This is used to avoid the absolute dominance of the biggest peak alignment.
among all those peaks in 3–4 kHz frequency range.

In the second step, the fine frequency structures caused by waveguide mode interference in frequency range 3–8 kHz are extracted from both the “second batch sferics” spectra and the measured sferic spectrum, through subtracting a sferic spectrum by a smooth spectrum extracted from that using zero phase shift low pass filter and treated as the spectrum of VLF waves before propagation in the Earth-Ionosphere Waveguide [36]. The frequency range is enlarged to 3–8 kHz since most fine frequency structures caused by waveguide mode interference are contained in this range. The correlation between those fine frequency structures of measured sferic spectrum and the “second batch sferics” spectra are calculated. Three fitted sferic spectra corresponding to three largest correlation coefficients are selected. These three selected sferics are termed “third batch sferics”. We choose three not only one because the fitting having the largest correlation coefficient does not necessarily has the best fine frequency structures alignment. However, if the the fine frequency structures are not well aligned, the correlation coefficients are definitely small. The correlations are performed between those fine frequency structures caused by waveguide mode interference instead of the original spectra in order to avoid the effect of difference between practical lightning current spectrum and the lightning spectrum used in the simulation on the correlation coefficients comparison.

Figure 3.5a and 3.5b show this procedure. The sferic spectra fitting between measured and simulated is more obviously shown by the comparison of processed signal in 3.5b, which is actually the fine frequency structures caused by mode interference, than by original spectra in 3.5a. It is clear that the spectra fitting for \( h' = 85.4 \) km is better than that for \( h' = 86.4 \) km due to the position alignments of the fine frequency structures. The magnitudes of those fine frequency structures are not important since they have no relationship with the waveguide modes. The “third batch sferics” corresponding to \( h' = 85.2, 85.4 \) and \( 85.6 \) km have the largest
correlation coefficients. The third step is to compare the average fine frequency structures alignments errors between the “third batch sferics” spectra and the measured sferic spectrum, and the $h'$ for the simulated spectrum that has the least mean fine frequency structures alignment error is the best fitting result. In most cases, the $h'$ having the largest correlation coefficient also has the least mean alignment error. And finally, linear interpolation is applied to two best fitted $h'$, for two different distances used in simulations that are nearest to the lightning distance, to calculate the final best fitted $h'$ value according to distance differences.

Figure 3.5c shows the typical correlation coefficients between the measured and simulated processed signals for different $h'$ values. The $h' = 85.4$ km simulation gives the best fit and is usually the “measured” value. The width of the correlation indicates the uncertainty in measured $h'$ from a single sferic. In this case, the correlation coefficient drops to approximately 60% of the maximum value at $\pm 0.6$ km from the best value. This indicates a typical uncertainty of $\pm 0.6$ km in $h'$ from a single sferic. This uncertainty can be improved by averaging many single sferic measurements in a narrow time window.

Figure 3.5d shows the histogram of measured $h'$ from 79 sferics in a 5-minute window for lightning strokes from almost the same location on July 1, 2005. The $D$ region $h'$ is stable during that 5 minutes and we thus expect that the distribution of individual $h'$ measurements should be as wide as the uncertainty in a single measurement. The measured $h'$ had a mean value of 84.4 km and standard deviation of 0.63 km. This 0.6 km standard deviation matches the $\pm 0.6$ km uncertainty we expect for a single measurement. Thus, by averaging many single measurements, we can significantly reduce the measurement uncertainty. We chose a 5-minute window for averaging as this typically provides at least several tens of sferics, and thus the uncertainty reductions of 5 to 10, and precision of 0.1 km or better.

The maximum correlation coefficient acquired in the second step of the algorithm
Figure 3.5: The sferic spectrum fitting procedure. (a) fitting for the original spectrum; (b) fitting for the peaks and valleys caused by waveguide mode interference; (c) correlation coefficients between the measured and simulated processed signals for different $h'$ values; (d) the histogram of individual $h'$ in a 5-minute window; the standard deviation is 0.63 km.

is used to judge the reliability of the measured $h'$. Usually, the larger is the correlation coefficient, the more reliable of the measured $h'$ value because a larger correlation coefficient means better fitting between fine frequency structures by waveguide mode interference of a measured spectrum and a simulated spectrum. We only keep the single sferic measurement in which the maximum correlation coefficient is larger than 0.5 to ensure reliability of the single measurement in the averaging procedure.
3.4 Statistical Results

3.4.1 Measured $h'$ Distribution in Two Months

To give an overview of the $h'$ variation in the two months of observation, we first compute hourly averages of $h'$. Figure 3.6 shows this hourly $h'$ distribution in July and August 2005 measured from 61,726 lightning strokes that occurred from 00 LT to 05 LT and 500–800 km from the Duke sensors. Since in the FDTD model the ground altitude is treated as constant for all simulations, the true $h'$ values corresponding to the sea level were calculated by adding the average real ground altitude (ranging from 0 to $\sim 500$ m near Duke University) along the wave propagation path to the $h'$ values derived from the spectra fittings. All the $h'$ measurements shown in following sections are referenced to the sea level.

Figure 3.6a shows the time variation of measurements on a single night as connected by a line. The maximum nightly $h'$ variation is close to the maximum variation over two months. Some periods exhibit discernable slow variation across several nights (for examples, DOY215 to 230). This slow variation may be induced by planetary waves since they were observed at periods near 16 days in stratosphere and mesosphere (20-90 km) [47, 100], and can modify the electron density in lower ionosphere ($<100$ km) [86, 87]. And sometimes, the variations are unconnected from night to night. Figure 3.6b shows a closeup of a typical 5 night period. Nightly $h'$ variations come in all forms from steady drops, to steady increases to oscillatory variations. It is notable, however, that the nights with the biggest $h'$ changes are frequently nights with dropping $h'$, as shown in both Figure 3.6a and 3.6b. The measured $h'$ variations in these 5 nights indicate that the nighttime ionospheric $D$ region is far from static and the electron density profile height variation trend can be completely different from night to night.

Figure 3.6c is the histogram of those hourly measurements. The hourly average $h'$
ranges from 82.0 km to 87.2 km, with a mean $h'$ of 84.9 km and a standard deviation of 1.1 km. This mean value is consistent with the measurements by Thomson et al. [139], who calculated the nighttime global average $h'$ from single frequency VLF signals generated by man-made transmitters, and found a mean value of $85.1 \pm 0.4$ km.

3.4.2 **Nightly Temporal Variations**

Nighttime also shows variations on time scales much less than an hour. In order to illustrate the detailed measured $h'$ variation with time, we present three examples
of complete nightly $h'$ measurements. In each case, there are several hundreds of individual measured $h'$ from which we calculated the high precision 5-minute average $h'$ values.

The first example is from July 29, 2005, from 00 to 05 LT. The top panel of Figure 3.7 shows the $h'$ variation extracted from 755 sferics excited by NLDN recorded lightning strokes over the ocean to the east of the sensors and at a range of 580–650 km from the sensors. The $D$ region electron density profile almost maintained a constant height from 00 LT to 01 LT, and then dropped quickly beginning at 0130 LT from 85.8 km to 82.0 km at 0430 LT. The lack of measurements between 01 LT and 0130 LT as well as between 0315 LT and 0340 LT was due to missing data.

In contrast, the $D$ region height varied little on July 5, 2005, based on 524 sferics originating to the north of the sensors at a range of 550 km. The middle panel of Figure 3.7 shows a nearly constant of about 84.0 km from 01 LT to 05 LT. The bottom panel of Figure 3.7 shows the $h'$ on July 22, 2005, extracted from 3,137 sferics from lightning to the northwest (azimuth around 300 degrees) and 650–800 km from Duke sensors. This $h'$ variation is complex, first dropping 1.0 km from 84.5 km to 83.5 km from 00 LT to 0115 LT. Then, the $h'$ changed sharply reaching 85.4 km at 0205 LT. Then, it began to drop again and finally reached 82.0 km at 05LT. The lack of measurements between 0225 LT and 0250 LT was also due to missing data. This oscillation may indicate the gravity waves in the lower ionosphere which have periods of tens of minutes to several hours [87].

These three examples show the wide varieties of nighttime $h'$ variation observed. As discussed above, dropping $h'$ dominated and was observed on 20 nights while $h'$ on 19 nights had less than 0.5 km variation in 5 hours. Only 9 nights showed upward trends and 12 nights exhibited $h'$ oscillations. The maximum observed $h'$ variation in the 5 hour period is a drop of just above 4.0 km. The measured $h'$ variation on July 13, 2005 had the maximum variation 1.3 km in one hour period and sharper
Figure 3.7: Typical measured $h'$ distributions at three nights. Top panel: $h'$ dropped quickly on July 29, 2005; Middle panel: $h'$ has little variation on July 5, 2005; Bottom panel: $h'$ showed oscillations on July 22, 2005.
gradients were observed on shorter time scales.

3.4.3 Nightly Spatial Variations

Unique among $D$ region measurement techniques, this approach can be applied simultaneous in different geographic regions for an instantaneous measurement of the spatial variation of the $D$ region ionosphere. Figure 3.8 shows two examples of simultaneous multiple $D$ region measurements. Although we could measure $h'$ using all lightning groups, for these two examples we only select lightning whose sferic waves propagate across two different regions as probing lightning in order to compare the measured $h'$ in these regions. Two groups of lightning strokes from different directions were used to measure $h'$ in different regions on August 5, 2005. A total of 1,176 NLDN recorded lightning strokes from the northwest of Duke sensors was used to measure $h'$ in region 1, and 763 strokes from the south of Duke sensors were used to measure $h'$ in region 2. Figure 3.8a shows the geographic distributions of lightning strokes during the 5 hour nighttime period. A lightning group means there is at least one NLDN recorded lightning stroke in a $0.5^\circ \times 0.5^\circ$ geographical region. Figure 3.8b shows a significant different measured $h'$ of 1–2 km in two regions. The southern region had a lower and relatively constant $h'$, while 6 degrees latitude to the north, the $D$ region was higher and descending. In contrast, there was almost no spatial variation in $h'$ on July 21, 2005 as shown in Figure 3.8c and 3.8d. A total of 1,302 NLDN recorded lightning strokes from the northwest of Duke sensors was used to measure $h'$ in region 1, and 2,394 strokes from the east of Duke sensors were used to measure $h'$ in region 2. The measured $h'$ in these regions 500 km apart descended from 84.0 km to 82.0 km during 5 hours of nighttime with nearly identical time variations.

The above examples show that the $D$ region electron density profile height can but not always exhibit spatial variations. Of 59 nights in two months, 15 nights
had useful lightning strokes in at least two different directions. Six of these showed significant spatial variation in $h'$ while the $D$ region electron density profile heights in the other nine nights showed no spatial variation over $\sim 500$ km. Nights with both lower and higher $h'$ at higher latitudes were observed. The maximum observed $h'$ difference across $\sim 500$ km separation was around 2.0 km which appeared on August 5, 2005 and August 19, 2005. However, this 2.0 km difference decreased to 0.8 km during 1 hour and 40 minutes period on August 5, 2005 while it maintained the same
value of 2.0 km on August 19, 2005.

3.5 Possible Mechanisms for $h'$ Variations

The variation in the nighttime $D$ region ionosphere is driven by many processes. Scattered Lyman-$\alpha$ is an important source of nighttime middle and lower latitude $D$ region ionization [10, 134]. High energy ($\geq 30$ keV) radiation belt electron precipitation also contributes. The drivers of this precipitation can be the interaction between whistler waves and energetic particles [73, 18, 120]. However, the accuracies and availabilities of these data in certain time windows and measured regions restrict the direct quantitative comparison with our measured $h'$ variations. Direct lightning–ionosphere coupling can also drive $D$ and $E$ region ionosphere variations. Electromagnetic pulses (EMP) radiated by lightning strokes can directly couple into the lower ionosphere, heat the electrons, change the ionization rate and perturb the VLF signal propagation [66]. Geomagnetic activity in July and August 2005 was significant with several storms and periods of $K_p > 5$. However, we see little connection between this variation and our measured $h'$. This is perhaps not surprising given the lower latitudes ($L = 2$ to 3) of the probed region.

Figure 3.9 shows a night with a remarkable correlation between $h'$ and the rate of lightning strokes directly beneath the probed ionosphere. The top panel of Figure 3.9 shows lightning distribution on July 21, 2005. Although all lightning groups can be used to measure $h'$, we only show the $h'$ measured by lightning from the east since we are interested in $h'$ change in region 1. And the definition of lightning groups is explained in last section. There was no lightning to the south of the measured region, and thus non-duct LEP is not expected to produce any changes. A total of 2,394 strokes from the east of Duke sensors was used to measure $h'$ in region 1, and the measured results are shown in the middle panel. Distinct largely descending $h'$ temporal variation was observed. We calculated the lightning occurrence rate per
Figure 3.9: The derived $h'$ distribution on July 21, 2005. Top panel: lightning distribution during 5 hours; Middle Panel: derived $h'$ variation in region 1 versus local time; Bottom panel: the lightning occurrence rate compared to measured $h'$ in 5-minute window in region 1.
5-minute directly under the probed ionosphere in region 1, which is compared to the 5-minute average $h'$ and shown in the bottom panel of Figure 3.9. The measured $h'$ variation almost perfectly tracks the lightning occurrence variation trend. Beginning at 0030 LT, the lightning occurrence rate in region 1 increased quickly. Meanwhile, the measured $h'$ decreased rapidly. The obvious minimum lightning occurrence rate at 0305 LT was corresponding to the local maximum measured $h'$ 83.3 km. The general measured $h'$ variation trend was also consistent with the lightning occurrence rate after that time.

In contrast, Figure 3.10 shows a night with similar large $D$ region changes that could not be driven by local lightning strokes. The lightning distribution on August 13, 2005 is shown in the top panel of Figure 3.10. A total of 441 NLDN recorded lightning strokes from northwest of Duke sensors was used to measure $h'$ in region 1 and the results are shown in the middle panel. The measured $h'$ using lightning in region 2 is not shown since we are not interested in $h'$ between those lightning strokes and the receivers. Region 1 is composed of two slightly separated regions that we lump together because the measured $h'$ values are identical. In this case, there was almost no lightning below the probed regions, yet the $h'$ still dropped 3.0 km over the night. The measured $h'$ showed a weak correlation with the lightning rate in region 2 which is significantly south of the probed region. This could occur for non-duct LEP [85, 112]. The overall lightning rate, however, is much lower than in the previous case. It is very possible that the $D$ region variation on this night is driven by some other mechanisms. Several mechanisms can affect the nighttime $D$ region simultaneously and thus the measured variation can be complex. Direct energy coupling between local lightning and lower ionosphere as well as LEP are two major mechanisms that change the $D$ region height.
**Figure 3.10**: The derived $h'$ distribution on August 13, 2005. Top panel: lightning distribution during 5 hours; Middle Panel: derived $h'$ variation in region 1 versus local time; Bottom panel: the lightning occurrence rate in 5-minute windows in region 2.
3.6 Nighttime $\beta$ Measurement

We derived nighttime $\beta$ values from the higher frequency minima because their positions change with $\beta$ variations. To give an overview of typical nighttime $\beta$ variations, we computed $\beta$ in two nights: July 19, 2005 with little $h'$ variation, and August 22, 2005 with obvious $h'$ descending trend. We selected 0230–0500 LT in both nights because in this period there were sufficient sferics in 5-minute time windows originating from small geographical regions. In every $\sim$30 minute, we chose a 5-minute time window that is long enough to include several tens of lightning strokes but short enough so that the large-scale $D$ region electron density is not likely to change significantly [36, 30]. In each 5-minute time window, we calculated the average spectrum from a group of sferics excited by lightning strokes in a small geographical region ($\sim$20 km × 20 km). We use the PEC as the ground boundary condition for the FDTD model simulations, since in both nights the sferics used were radiated by lightning strokes $\sim$700 km to the east of the Duke receiver. More than half of the sferic wave propagation paths are in the sea.

The upper and middle panels of Figure 3.11 show $h'$ and $\beta$ extracted from the average sferic spectrum at 0236 LT, on July 19, 2005. The average sferic spectrum is the average of 19 spectra generated by lightning strokes approximately 696 km from Duke sensors and located in the east direction (azimuth angle $\sim 90^\circ$). The best fitted $h' = 84.4$ km and $\beta = 0.80$ km$^{-1}$ are derived from the waveguide mode interference pattern alignments in lower and higher frequency ranges, respectively. In most situations, $\beta$ is acquired from the linear interpolation of two simulated spectra according to the big valley positions in the higher frequency ranges.

By applying this procedure to 12 cases of 5-minute averaged sferic spectra, we inferred $\beta$ values in two nights. The bottom panel of Figure 3.11 shows the derived $h'$ and $\beta$ variations with local time on July 19 and August 22, 2005. The measured
Figure 3.11: Nighttime $D$ region measurement. Top panel: $h'$ derived from the lower frequency mode interference pattern at 0236 LT on July 19, 2005; Middle Panel: $\beta$ derived from the higher frequency mode interference pattern at 0236 LT on July 19, 2005; Bottom panel: broadband measurements for nighttime $h'$ and $\beta$ on July 19 and August 22, 2005.
$h'$ during the 2.5 hours on July 19, 2005 had a rather constant trend with an average value of 84.3 km and the small uncertainty. However, the measured $\beta$ during the same period had the average value of 0.73 km$^{-1}$, and the uncertainty was as large as $\pm0.075$ km$^{-1}$. The measured $h'$ on August 22, 2005 decreased from 84.3 km at 0226 LT to 83.0 km at 0400 LT and then maintained a constant trend. The measured $\beta$ during the same period showed a weak descending trend but with the uncertainty also as large as $\pm0.075$ km$^{-1}$. The average $\beta$ value during that near 2.5 hours was 0.68 km$^{-1}$, which is consistent with the long-term average nighttime $\beta = 0.63 \pm 0.04$ km$^{-1}$ given by Thomson et al. [139].

The measured $\beta$ in both nights showed the uncertainty as large as 0.15 km$^{-1}$. This is because the nighttime D region electron density change is not so obvious if we change the $\beta$ value, and thus the higher frequency range big valley position which is determined by D region electron density and used to derive $\beta$ is not so sensitive to $\beta$ change. Therefore, any interference of the big valley position will cause a large $\beta$ uncertainty.

3.7 Comparison with IRI Model

The IRI is a widely used standard for the specification of ionosphere parameters and is recommended for international use [17]. For a given time and location, it provides an empirical standard model of the ionospheric electron density and other parameters in the altitude range from $\sim$60 km to $\sim$2000 km based on all kinds of data sources. Here we treat propagation simulations with IRI ionospheres as synthetic data and extract the effective $h'$ and $\beta$ to gain some insight into the relationship of these parameters to more complex ionospheric electron density profiles.

We fitted several simulated sferic spectra from using two parameter exponential electron density profiles to the simulated sferic spectrum from using a certain IRI model, and calculated the best fitted $h'$ and $\beta$. In all the FDTD simulations, we set
Figure 3.12: The equivalent $h'$ and $\beta$ derived for IRI at 0230 LT on July 19, 2005. Top panel: $h'$ derived from the lower frequency mode interference pattern; Middle Panel: $\beta$ derived from the higher frequency mode interference pattern; Bottom panel: the best fitted exponential profile compared to IRI2001 modeled profile at 0230 LT; electron density in the IRI model below 80 km is extended from its variation trend above 80 km and plotted as dot line.
the azimuth angle as 90° and the distance as 700 km. And only the PEC ground was used. The upper and middle panels of Figure 3.12 show an example for the sferic spectrum fitting between those from using IRI2001 models and that from using the exponential profile.

The upper panel shows the best fitted $h' = 83.0$ km retrieved from alignments of those valleys of the mode interference pattern in the lower frequency range, as discussed in previous sections in this chapter. However, the spectrum in this frequency range is not sensitive to $\beta$ and gives equally good fits for $\beta = 0.60$ and 0.55 km$^{-1}$. In contrast, the frequency of the mode interference minimum in the simulated spectrum 26–27 kHz is sensitive to $\beta$, which is shown in the middle panel of Figure 3.12. By using linear interpolation, we found the best fitted $\beta = 0.58$ km$^{-1}$. The bottom panel shows the comparison between the IRI2001 modeled electron density profile and the best fitted exponential profile. Two profiles are averagely consistent in the electron density range from several tens to several hundred cm$^{-3}$, indicating that the electron density in this range plays the major role in reflecting the nighttime sferic propagations. The electron density below 80 km is not given in the IRI model. We extend the electron density to lower altitudes according the profile variation trend above 80 km.

By applying the fitting procedure discussed above, we derived the best fitted $h'$ and $\beta$ for both IRI2001 and IRI2007 modeled $D$ region electron density profiles between 0230 and 0500 LT on July 19 and August 22, 2005 near Duke University. In 2.5 hours from 0230 LT to 0500 LT, we calculated six sets of best fitted $h'$ and $\beta$ with each set in every half hour. The upper panel of Figure 3.13 shows $h'$ and $\beta$ derived from IRI2001 models, and the lower panel shows their variations derived from IRI2007 models. Different from the broadband measured results during the same time, which are shown in the bottom panel of Figure 3.11, both the $h'$ and $\beta$ derived from both the IRI2001 and IRI2007 models in two different nights show clear
descending trends. In addition, the absolute values of \( h' \) and \( \beta \) in our broadband measurements are larger than those derived from IRI models. For example, broadband measured \( h' \) on July 19, 2005 had a near constant value of 84.3 km during the 2.5 hour period, but the IRI2001 model showed an descending trend from 83.0 km to 80.4 km in the same time window. The broadband measured \( \beta \) was bounded between \( \sim 0.65 - 0.8 \) km\(^{-1}\). However, all the \( \beta \) values derived from IRI models are less than 0.65 km\(^{-1}\). These obvious differences between broadband measurements and IRI models suggest that the two parameter exponential profile may not well describe the true nighttime ionospheric \( D \) region.

**Figure 3.13:** The best fitted nighttime \( h' \) and \( \beta \) for IRI on July 19 and August 22, 2005. Upper panel: for IRI2001; Lower panel: for IRI2007.
3.8 Summary of Nighttime Measurement

In this chapter, we derived the midlatitude nighttime $D$ region equivalent exponential electron density profile height and sharpness by comparing the lower and higher frequency mode interference patterns of measured sferic spectra to FDTD model simulated results. A total of 61,726 lightning strokes in July and August 2005 near Duke University provided nearly continuous measurements $h'$ during 5 hour nighttime windows over a two month period. The $\beta$ values on two nights were extracted from broadband VLF propagation spectra on relatively short ($\sim 700$ km) propagation paths. These $\beta$ values were compared to narrowband VLF measurements and the IRI models.

Condensing these measurements to 260 independent hourly averages, the hourly $h'$ was bounded between 82.0 km and 87.2 km, with a mean value of 84.9 km and a standard deviation of 1.1 km. This mean value is in close agreement with the long-term average value reported by Thomson et al. [139]. The magnitude of the hourly $h'$ variation on a single night is almost as large as the variation observed across the entire 2 month period, indicating that much of the dynamics of the nighttime $D$ region occur on time scales less than one day.

Five minute average $h'$ measurements reveal the temporal dynamics on shorter time scales. Some nights exhibit little variation while on others $h'$ can vary by as much as 4.0 km. The largest observed change in 1 hour was a drop of 1.3 km, with sharper gradients observed on even shorter timescales. Nights with steadily descending $h'$ dominated the observations of these two months, although some with oscillatory variations and with ascending $h'$ were also seen.

When lightning locations are favorable, this approach also enables the measurement of simultaneous spatial gradients in $h'$. On the nights when multipath measurements could be made, significant gradients on spatial scales of approximately
500 km were observed about half of the time. The maximum observed $h'$ difference for two different probed regions was 2.0 km. Gradients in which $h'$ increases to the north and to the south were both observed, and sometimes the temporal variation of $h'$ in locations 500 km apart could be significantly different.

In an effort to understand some of the possible sources driving the observed variations, we examined them in the context of local and spatially offset lightning rates. On one night, a remarkably close correlation is observed between $h'$ and the rate of lightning strokes occurring directly under the probed ionosphere. This overall lightning rate on this night was the highest observed in the dataset. This connection suggests that either direct energy coupling to the ionosphere or ducted lightning-induced electron precipitation can drive significant $D$ region variations on timescales from minutes to hours. However, many other nights with significant variations reveal no such a clear correlation, which probably reflects the many possible drivers of $D$ region electron density variation.

We also derived the representative nighttime $\beta$ in two nights by fitting the higher frequency features of observed and FDTD model simulated. Typical nighttime $\beta$ measured from broadband VLF signals is bounded between 0.65 and 0.8 km$^{-1}$. It is larger than the equivalent $\beta$ derived from IRI models which is less than 0.65 km$^{-1}$ in all the measurements. In addition, $\beta$ from broadband measurement has no obvious variation trend whereas that from IRI models shows obvious descending trend. These discrepancies suggest that the two parameter exponential profile may not well describe the true nighttime ionospheric $D$ region.
Daytime $D$ Region Measurement

VLF remote sensing can also be used to derive the average daytime $D$ region electron density profiles. Deeks [39], Thomson [136, 137], and McRae and Thomson [95] contributed to the average ambient $D$ region electron density profile measurements in long and short paths using narrowband VLF signals radiated from different large man-made transmitters. The basic idea is to extract the best fitted $h'$ and $\beta$ by comparing the recorded narrowband VLF amplitudes and phases with LWPC modeled results.

Another important application of narrowband VLF is to measure the ionosphere disturbances caused by solar flare X-rays. The major ionization source of the undisturbed ionospheric $D$ region from which the VLF signals are reflected is the Lyman-$\alpha$ from solar radiation. When a solar flare (X-ray) occurs, the X-ray flux increases suddenly and those with wavelength appreciably below 1 nm are able to penetrate down to $D$ region and increase the ionization rate there [138]. Pant [106], McRae and Thomson [96], and Thomson et al. [142, 141] contributed to the correlation between X-ray fluxes and VLF perturbations as well as $D$ region electron density profiles.

Broadband VLF and LF sferic signals excited by lightning strokes were used to
remote sense the daytime $D$ region as well. Smith et al. [127] and Jacobson et al. [70] contributed to the daytime $D$ region measurements. In these measurements, the ionosphere was treated as a PEC and only the reflection heights were acquired by comparing the arrival time of ground waves and ionospheric echoes. Although Jacobson et al. [71, 72] proposed the broadband, single-hop method to derive the smooth $D$ electron density profile, systematic measurements of daytime $D$ region electron density profile variations are still lacking.

In this chapter, we use similar data and methods to those described in last chapter to calculate the midlatitude daytime ionospheric $D$ region electron density profile variations in July and August 2005 near Duke University. A total of 285,029 NLDN recorded lightning strokes was used to almost continuously monitor the $D$ region height $h'$ variations on daytime between 06 and 20 LT (10–24 UT). Because the local time we used in this dissertation is the EDT, the solar zenith angle is not the minimum at 12 LT. The variations of $h'$ on time scales of minutes to hours were calculated. Instantaneous measurements of geographical variations beyond the solar zenith angle effects were studied by comparing the measured effective $h'$ in two different regions. The solar zenith angle dependence of measured heights slightly differs from previous results from single frequency measurements [45, 95], but is restricted to small midlatitude regions, rather than long paths spatially averaged. We correlated the X-ray fluxes with the measured $h'$ in X-ray rising phases, peaks and decaying phases, and found that the logarithm of the flux is approximately proportional to the measured $h'$ change. However, the solar flare has stronger effects on the $D$ region in the X-ray rising phase than in the decaying phase.

For the daytime sharpness measurement, we used the similar technique to those for nighttime, which is based on the frequency of spectral minima from waveguide mode interference at upper VLF frequencies ($\sim$20 kHz). FDTD model simulations of broadband VLF propagation were used to show that the frequencies of these minima
are strongly dependent on $\beta$ in a way that the lower frequency spectral variations used to measure $h'$ are not.

To demonstrate the technique, the midlatitude daytime $D$ region electron density profile sharpness variations across solar zenith angles from 20 to 75 degrees from three different days were extracted from measured average broadband VLF spectra. The resulting sharpness variations show weak dependence on solar zenith angles, which is somewhat different from what have been previously reported based on narrowband VLF propagation measurements on much longer propagation paths. We also derived the equivalent exponential profiles for IRI profiles and a semiempirical model from rocket-based measurements, called FIRI empirical model [49], and found that both the magnitudes and solar zenith angle variations of the sharpness for broadband measurements, narrowband measurements, IRI and FIRI models are significantly different.

## 4.1 Daytime Data Analysis

Similar to the nighttime data processing, we use the lightning data provided by the NLDN and sferic data recorded by VLF/ELF sensors located near Duke University. We also use the $B_\phi$ component to derive $D$ region electron density profile variations.

Figure 4.1 shows seven typical measured daytime $B_\phi$ spectra excited by NLDN recorded lightning strokes in different frequency bandwidth. Figure 4.1a shows the general shape of a typical daytime sferic spectrum. Different from the nighttime $B_\phi$ which contains the fine frequency structures caused by the Earth-ionosphere waveguide mode interference in 3–8 kHz range, these frequency structures of daytime $B_\phi$ appear in the 1.5–4 kHz band. The spectrum in 4–15 Hz frequency range is typically smooth for a daytime sferic. It is from those fine frequency structures in 1.5–4 kHz range that the daytime $D$ region electron density profile height $h'$ is extracted. And the sharpness $\beta$ is derived from the spectrum minima near $\sim20$ kHz.
Figure 4.1: Daytime sferic spectra for lightning at different time but from almost the same location. (a) the general shape of the daytime sferic spectrum across full wave bandwidth; fine structures in $\geq 4$kHz and $\leq 15$ kHz ranges disappear; (b) the lower frequency features for events in the morning of July 1, 2005 demonstrate the strong variation with time of the daytime $D$ region; (c) the lower frequency features for events during noontime of July 1, 2005 show little variation; (d) the spectra minima in higher frequency range for the events in the morning of July 1, 2005 also demonstrate the $D$ region variation; (e) the spectra minima in higher frequency range for the events in the noontime of July 1, 2005 show some uncertainties.
Three sferic spectra in Figure 4.1b, which were generated by lightning strokes 650 km away and from the east coast of the United States in the morning on July 1, 2005, show a two hour period between 0710 LT and 0917 LT that exhibits significant frequency changes, and thus ionosphere variations over that time. Three sferic spectra in Figure 4.1c, which were generated by lightning strokes around 550 km west of Duke sensors during the noontime on July 1, 2005, show a one hour period between 1316 LT and 1419 LT in which the ionosphere was relatively stable. Although the spectral magnitudes are slightly different between 1.5 kHz and 4 kHz, the fine frequency structure (peaks and valleys) positions which are closely related to the ionosphere state are almost the same. Figure 4.1d and 4.1e show the higher frequency features for the sferic spectra shown in Figure 4.1b and 4.1c, respectively. In the two hour morning period, the higher frequency spectrum minima shift in the same trend as the lower frequency features. However, as shown in Figure 4.1e, during the noontime period, the higher frequency spectrum minima for three sferic spectra are not the same although these peaks and valleys in the lower frequency range are well aligned. In the daytime $\beta$ measurement, we also take the average sferic spectrum to lower the uncertainties.

Similar to the nighttime measurement, we only analyze here the sferic data in July and August 2005 since the data acquisition system was operated in the continuous mode in these two months. Only daytime data between 06 and 20 LT (10–24 UT, approximately between sunrise and sunset near Duke University) were used. In addition, only lightning strokes that occurred between 500 km and 800 km away were used to minimize spatial averaging of any ionosphere variation and that the signals exhibit clear mode interference patterns in 1.5–4 kHz frequency range. A criterion of 30 kA threshold was applied to the lightning peak current selection to ensure that each sferic has a favorable SNR.
Figure 4.2: Five typical daytime $D$ region electron density profiles and corresponding simulated sferic spectra under these profiles. (a) electron density profiles; (b) the general shapes of sferic spectra; (c) the sferic spectra in lower frequency band; (d) the sferic spectra in higher frequency band. The mode interference patterns in both the lower and higher frequency VLF spectra are sensitive to $h'$ changes.

4.2 Influence of $D$ Region Parameters on VLF Spectra

Similar to nighttime, the parameters $h'$ and $\beta$ have different effects on a daytime sferic spectrum, and this is illustrated in Figure 4.2 and Figure 4.3. In all these simulations, we chose distances $= 500$ km and azimuth angles $= 90^\circ$ as representatives. Figure 4.2 shows the $h'$ effects on a sferic spectrum in different frequency ranges and Figure 4.3 shows the $\beta$ effects. Figure 4.2a shows five sample daytime electron density profiles for the same $\beta$ value but different $h'$ values, and Figure 4.2b shows the corresponding
Figure 4.3: Five typical daytime $D$ region electron density profiles and corresponding simulated sferic spectra under these profiles. (a) electron density profiles; (b) the general shapes of sferic spectra; (c) the sferic spectra in lower frequency band; (d) the sferic spectra in higher frequency band. The mode interference patterns in the lower frequency range are not sensitive to $\beta$ but those in the higher frequency range are obviously sensitive to $\beta$.

simulated sferic spectra across the full VLF bandwidth for these profiles. As shown in Figure 4.2c and 4.2d, the waveguide mode interference fringes in 1.5–4 kHz and 15–20 kHz ranges are altered by $h'$ variation in the same way as they are at night, i.e., a larger $h'$ causes the waveguide mode interference fringes to shift to lower frequency bands. It is from the fringe positions in 1.5–4 kHz that $h'$ is extracted.

In contrast, as shown in Figure 4.3, a change in $\beta$ only affects the magnitudes of these fringes in 1.5–4 kHz range but very minimally changes their positions. FDTD
model simulations showed that increasing $\beta$ from 0.3 to 0.45 km$^{-1}$ leads to the measured $h'$ change of less than 0.1 km. These magnitude changes cannot be directly used to infer $\beta$ because variations in received signals are perhaps due to differences in lightning current waveforms and channel orientations. However, as shown in Figure 4.3d, the spectral minimum in the higher VLF frequency range (15–20 kHz) clearly shifts down as $\beta$ increases. It is from the position of this minimum that the $\beta$ is derived.

Consequently, in this work, we assume a fixed $\beta$ for the $h'$ measurement from the lower frequency features. McRae and Thomson [95] found that, at solar minimum, $\beta$ varied from $\sim 0.24$ km$^{-1}$ near dawn/dusk to $\sim 0.4$ km$^{-1}$ around mid-day. We assume an average daytime value of $\beta = 0.3$ km$^{-1}$. The results are reliable and quantitatively meaningful because the sferic feature we used to derive $h'$ is insensitive to $\beta$ changes. Once the $h'$ is measured, we derive $\beta$ from the spectrum minimum in the higher frequency range.

Additional simulations for daytime ionosphere show that both the lower and upper VLF mode interference patterns are sensitive to propagation distances but only weakly dependent to the propagation azimuth angle, i.e., a larger distance shifts the fine frequency structures up in frequency, whereas a change of 30 degrees of the azimuth angle has little effect on them. This requires the precise values of propagation distance but less precise values of propagation azimuth in all FDTD simulations.

4.3 Method of $h'$ Measurement

Similar to the procedure for nighttime measurements discussed in last chapter, we extracted the parameter $h'$ from a measured daytime sferic spectrum by comparing it to a series of simulated sferic spectra from the FDTD model simulations under different electron density profiles. A simulated sferic database was set up for lightning
strokes from different distances and azimuth angles. Propagation distances vary with step 20 km; azimuth angles vary from 0 to 360 degrees with step 30 degrees; electron density profiles were modeled with $h'$ varying from 60 to 80 km with step 0.2 km, and $\beta$ fixed to be 0.3 km$^{-1}$. An automatic fitting algorithm was constructed to find the best fitted simulated sferic spectrum for each recorded sferic excited by a lightning stroke in a certain azimuth and distance, i.e., to derive the average electron density profile parameter $h'$ for $\beta = 0.3$ km$^{-1}$ across the wave propagation path.

The $h'$ value is derived in following four steps. At first, the program fetches from the database the simulated sferics that have the azimuth angle and two distances nearest to the azimuth angle and distance of the measured sferic. Then, the program code selects several simulated sferic spectra, with an appropriate range of $h'$, whose middle valleys align with one valley of the measured sferic spectrum in 1.5–4 kHz frequency range. Usually, the daytime sferic spectrum has three obvious valleys in 1.5–4 kHz frequency range and the valley that has the smallest amplitude is the middle one. As shown in Figure 4.4a, the middle valleys are at around 2.5 kHz and have the smallest amplitude values for both measured and simulated sferic spectra. However, for some simulations, the amplitudes of the middle valleys can be slightly larger than the amplitudes of valleys in their left or right. Therefore, before running the code, the middle valley positions for all the simulated sferic spectra are saved in a lookup table. Although the amplitudes of the middle valleys are the smallest for some sferics but not for others, they can be located precisely according to their shift with $h'$ and distance variations. The selected simulated sferic spectra whose middle valleys align with one valley of the measured sferic spectrum in 1.5–4 kHz frequency range are termed “first batch sferics”. The “second batch sferics” are generated by adding other sferics corresponding to $h'$ 0.2 km smaller and 0.2 km larger than the $h'$ for each of the “first batch sferics” to them, which is similar to the method used for nighttime sferics.
In the second step, the fine frequency structures caused by waveguide mode interference in frequency range 1.5–4 kHz are extracted from both the “second batch sferics” spectra and the measured sferic spectrum using the same method as for nighttime sferic fitting. However, the correlation coefficients are calculated in the frequency range of 1.5–4 kHz since most mode interference patterns of daytime sferic spectra are located in this frequency range. The “third batch sferics” are generated by selecting three fitted sferic spectra corresponding to the three largest correlation coefficients.

Figure 4.4a and 4.4b show this procedure. The sferic spectra fitting between the measured and the simulated is more obviously shown by the processed signal in 4.4b, which is actually the fine frequency structures caused by mode interference, than by original spectra in 4.4a. It is clear the spectra fitting for \( h' = 74.8 \) km is better than that for \( h' = 75.8 \) km due to the position alignments of those fine frequency structures. The “third batch sferics” corresponding to \( h' = 74.6, 74.8 \) and \( 75.0 \) km have the largest correlation coefficients. The algorithms in the third step and the fourth step are the same as in the nighttime sferic fitting procedure, which has been discussed in last chapter.

Figure 4.4c shows the typical correlation coefficients between the measured and simulated processed signals for different \( h' \) values. The \( h' = 74.8 \) km corresponds to the largest correlation coefficient and is thus usually the “measured” value. For this single sferic measurement, the correlation coefficient drops to approximately 60% of the maximum value at \( \pm 0.8 \) km from the best value. This indicates a typical uncertainty of \( \pm 0.8 \) km in \( h' \) from a single sferic.

Figure 4.4d shows a histogram of the measured \( h' \) from 77 sferics in a 5-minute time window for lightning strokes from almost the same location on July 3, 2005. The \( D \) region \( h' \) was stable during that 5 minutes. The measured \( h' \) had a mean value of 73.8 km and standard deviation of 0.77 km. This 0.77 km standard deviation matches
Figure 4.4: The sferic spectrum fitting procedure. (a) fitting for the original spectrum; (b) fitting for the peaks and valleys caused by waveguide interference; (c) correlation coefficients between the measured and simulated processed signals for different $h'$ values; (d) the histogram of individual $h'$ in a 5-minute window; the standard deviation is 0.77 km.

the ±0.8 km uncertainty we expect for a single measurement. Thus, by averaging many single measurements in a 5-minute time window, we can significantly reduce the measurement uncertainty. We chose a 5-minute window for averaging as this typically provides at least several tens of sferics, and thus the uncertainty reductions of 5 to 10, and precision of 0.1 km or better.

We use the maximum correlation coefficient acquired in the second step to judge the reliability of the measured $h'$. We only keep the single sferic measurement with
the maximum correlation coefficient larger than 0.5 to ensure the reliability of the single measurement in the 5-minute averaging procedure.

4.4 Statistical Results of \( h' \)

We applied the algorithm discussed in last section to 285,029 lightning strokes that occurred during the daytime between 06 LT and 20 LT, and 500–800 km from the Duke sensors in July and August 2005, with solar zenith angle range 10–90 degrees. Since in the FDTD model the ground altitude is treated as constant for all simulations, the true \( h' \) values corresponding to the sea level were calculated by adding the average real ground altitude along the wave propagation path to the \( h' \) values derived from the spectra fittings. All the \( h' \) measurements shown in following sections are referenced to the sea level.

4.4.1 Daytime Temporal Variations

The daytime \( D \) region shows variations on time scales less than one hour due to solar radiation and other sources such as solar X-ray flares. To illustrate the detailed measured \( h' \) variation with time, we present two examples of daytime \( h' \) measurements. In both cases, there are several hundreds of individual measured sferics from which we calculate the high precision 5-minute average \( h' \) values. Some individual \( h' \) measurements are far from the 5-minute average values because some irregular sferic spectra caused by noise or unusual source lightning waveforms are not correctly distinguished by the \( h' \) derivation program code. This will not affect the 5-minute average value calculation due to the very limited number of those “outlier” measurements.

The first example is for \( h' \) measurement between 0615 and 2000 LT on July 1, 2005. The upper panel of Figure 4.5 shows the \( h' \) variation extracted from 5,967 sferics excited by NLDN recorded lightning strokes from the east, northeast and southwest of Duke sensors and in a range of 500–800 km from the sensors. The solar
zenith angles are slightly different for measured $h'$ in different geographical regions and their correlation will be discussed in section 4.4.2. The $D$ region electron density profile height began to drop at 0640 LT from 80.0 km and reached the lowest point 71.3 km at 1330 LT. Then, the measured height gradually increased to 77.2 km at 20 LT. The lack of measurements between 1810 LT and 1840 LT was due to missing data.

The $D$ region height variation on August 1, 2005 exhibits different features and is shown in the lower panel of Figure 4.5, base on 5,521 sferics originating to the
south of the Duke sensors in a range of 500–700 km. The general variation trend of the measured $h'$ is similar to that on July 1, 2005, i.e., the $h'$ began to decrease from 80.0 km from the sunrise and reached 71.4 km at 1240 LT and began to increase again. However, there were two $h'$ sudden drops caused by solar flare X-ray in the measurement period. The first one began at 0815 LT and the $h'$ decreased to 72.2 km ten minutes later and recovered to 74.2 km at 0855 LT. The second sudden drop began at 0915 LT but finished at 11 LT, and the minimum measured $h'$ 68.0 km appeared at 0950 LT.

These two examples show two types of daytime $h'$ variations observed. If the sudden drops are not considered, the $h'$ always drops from sunrise to noontime and then increases again until the sunset. Measured $h'$ variations without sudden drops were observed on 48 days. Nine days showed only one sudden drop while 5 days showed more than one sudden drop. Three days had $h'$ drops lower than 65.0 km with the lowest value 63.4 km observed on July 13, 2005. All of the observed sudden drops were associated with X-ray flares.

4.4.2 Dependence of $h'$ on Solar Zenith Angle

The $D$ region electron density profile height variation shows close relationship with solar zenith angle changes, and this was quantitatively analyzed in literature [136, 95, 70]. In order to illustrate this, we compared the measured $h'$ to solar zenith angles at the midpoints of the propagation paths between Duke sensors and lightning stroke locations. The upper panel of Figure 4.6 shows the dependence of the measured $h'$ variation on solar zenith angles extracted from 5,657 NLDN recorded lightning strokes over the ocean to the east of the sensors and in a range of 500–800 km from the sensors. In order to distinguish the periods before noontime and after noontime, we label the morning solar zenith angle as negative values [95]. From sunrise to noontime, the local solar zenith angle decreased from 90 degrees to 17 degrees at
1305 LT, and during the same period, the measured $h'$ decreased from 79.0 km to 71.5 km. The solar zenith angle began to increase and reached 87 degrees at 20 LT when the measured $h'$ increased to 78.5 km. The minimum measured $h'$ 71.5 km on that day appeared when the solar zenith angle was 17 degrees, which was slightly higher than the value 70.8 km given by McRae and Thomson [95] for the same solar zenith angle 17 degrees in near solar minimum years (1994–1997). This is not surprising given that our measurements were restricted to a small geographical region in the midlatitude in a near solar minimum year, while McRae and Thomson [95] used the single frequency VLF signals propagating across the equator to measure $h'$ in lower latitudes. In addition, the measured $h'$ changed quickly when the solar zenith angle was larger than $\sim 50$ degrees, which is consistent with the statistical results given by Jacobson et al. [70].

In order to quantitatively correlate the derived $h'$ variations with solar zenith angle changes, we calculated the statistical results of the measured $h'$ and solar zenith angles in July and August 2005. In each 5-minute time window, the locations of source lightning strokes are grided into $2^\circ \times 2^\circ$ geographical regions. Such a region is large enough to include several tens to hundreds of lightning strokes but small enough to minimize the spatial variation. The mean values of the measured $h'$ and solar zenith angles in the middle points across the sferic wave propagation paths were calculated for each $2^\circ \times 2^\circ$ geographical region and each 5-minute time window that has more than 20 NLDN recorded lightning strokes, so as to ensure the reliability of the statistical result. The measured $h'$ sudden drops caused by solar flare X-rays are not included in this result since they have no direct relationship with solar zenith angle changes. We did not distinguish the $h'$ dependence on solar zenith angle before and after noontime since calculations showed they are the same. The lower panel of Figure 4.6 shows our result compared to results from other models.

We compared our measured result to the polynomial calculation given by McRae
Figure 4.6: The measured $h'$ dependence on solar zenith angles. Upper panel: the measured $h'$ and solar zenith angle variation on July 22, 2005; the measured $h'$ when the solar zenith angle minimum was slightly higher than the result given by McRae and Thomson [95]; Lower panel: the statistical result on two months compared to calculations from [95] and the result given by Ferguson [45]; the general variation trends are similar while the specific values are different for the same solar zenith angle. The solar zenith angle near Duke University was bounded between 10 and 90 degrees during the two months, although the minimum solar zenith angle on July 22, 2005 was 17 degrees.

and Thomson [95] for near solar minimum years. Our measured $h'$ values are higher than the heights calculated from the polynomial model, especially when the solar zenith angle is smaller than 70 degrees. This is possibly due to different measured regions, i.e., our measurements were in small midlatitude regions while McRae and Thomson [95] measured the average $h'$ in the long paths across the equator and in low
latitudes. We also compared our result to the model calculation given by Ferguson [45]. Compared to the polynomial calculation given by McRae and Thomson [95], this model not only includes the solar zenith angle, but also the geographic location, date, sunspot number and geomagnetic activity. However, as shown in the lower panel of Figure 4.6, only the general variation trends are similar. For the same solar zenith angles, our measured $h'$ can also be different from the model results.

4.4.3 Daytime Spatial Variations

Besides the variations caused by solar zenith angle changes, daytime $h'$ measurements show unexpected spatial variations. In order to exclude the solar zenith angle influence (i.e., at the same LT, different regions have different solar zenith angles), we compared the measured $h'$ variations for different probed regions with the same solar zenith angle instead of the same local time.

Figure 4.7 shows two examples of simultaneous multiple $D$ region measurements. Two groups of lightning strokes from different directions were used to measure $h'$ in different regions on July 23, 2005. A total of 1,552 NLDN recorded lightning strokes from the southwest of Duke sensors was used to measure $h'$ in region 1, and 2,017 strokes from the southeast of Duke sensors were used to measure $h'$ in region 2. Figure 4.7a shows the geographic distributions of lightning strokes from 15 LT to 20 LT on that day. Figure 4.7b shows a measured $h'$ difference of $\sim 0.2$ km in two regions for the same solar zenith angle. The west region had a lower $h'$, while $\sim 100$ km to the east, the $D$ region was 0.2 km higher. This spatial difference was not the fluctuation in the measurement process caused by irregular source spectra or the uncertainty in the spectra minima fitting, since the 5-minute averages were calculated from several tens of measurements and the uncertainty was $\sim 0.1$ km. On July 30, 2005, the spatial difference was as large as 1.0 km for the same solar zenith angles during the 5 hour period from 14 LT to 19 LT, which was shown in
Figure 4.7: The $h'$ measurements on July 23, 2005 and July 30, 2005. (a) lightning distribution between 15 LT and 20 LT on July 23, 2005; (b) 5-minute average measured $h'$ variation between 15 LT and 20 LT on July 23, 2005; (c) lightning distribution between 14 LT and 19 LT on July 30, 2005; (d) 5-minute average measured $h'$ variation between 14 LT and 19 LT on July 30, 2005.

Figure 4.7c and 4.7d. A total of 1,802 NLDN recorded lightning strokes from the southwest of Duke sensors was used to measure $h'$ in region 1, and 2,115 strokes from the southeast of Duke sensors were used to measure $h'$ in region 2. Similar to the first example, the west region had a lower ionosphere height, while $\sim$250 km to the east, it was higher.

The above examples show that the daytime $D$ region electron density profile height is dominated but not completely determined by solar radiation. The spatial
variation beyond solar radiation influence exists in daytime. This spatial variation is not an artifact of propagation anisotropy since the geomagnetic azimuth effects are already included in the FDTD model and waveguide mode interference pattern fitting process. Of 61 days in two months, 26 days had useful lightning strokes in at least two different directions simultaneously. Eight of these days showed spatial variations of \( h' \) larger than 0.5 km for the same solar zenith angle in two different probed regions, with the maximum difference 1.0 km observed on July 30, 2005. Other days had \( h' \) difference smaller than 0.5 km, with the minimum difference 0.2 km observed on July 23, 2005.

4.4.4 Correlation of \( h' \) with Solar Flare X-ray Fluxes

Solar flares, particularly at X-ray wavelengths, can penetrate into the ionospheric \( D \) region and change the electron density there and, thus, affect the VLF wave propagation in the Earth-ionosphere waveguide [101]. Quantitative calculations of perturbations caused by solar flare X-ray have been performed in previous work [142, 144, 70]. In order to compare our measured \( h' \) drops to X-ray fluxes during a solar flare, we use the X-ray data recorded by the Geostationary Operational Environmental Satellite 10 (GOES–10) and provided by National Oceanic and Atmospheric Administration (NOAA). The X-ray flux was recorded in two bands: long wavelength band (\( X_l \)) with wavelength 1–8 Å and short wavelength band (\( X_s \)) with wavelength 0.5–4 Å. The \( X_l \) has greater fluxes while \( X_s \) is more penetrating and so is more dominant for ionizing the bottom edge of \( D \) region, i.e., the VLF reflection height [101, 141]. In this section, we will compare both \( X_l \) and \( X_s \) fluxes to the measured \( h' \) disturbances.

We first present measured \( h' \) in two days with significant perturbations induced by solar flare X-rays. The upper panel of Figure 4.8 shows the measured \( h' \) variations with 5 sudden drops in nearly 14 hours on July 12, 2005, from using 1,663 NLDN recorded lightning strokes 500–700 km away from the Duke sensors. The measured
Figure 4.8: The measured $h'$ related to X-ray flux variation; The measured $h'$ sudden drops and the X-ray flux sudden increases are perfectly correlated in time. Upper panel: on July 12, 2005; Lower panel: on July 13, 2005.

$h'$ sudden drops and the X-ray flux sudden increases are perfectly correlated in time. The beginning time of $h'$ sudden drops can be defined as the time when the $h'$ deviates from the unperturbed value corresponding to the typical height only decided by the solar zenith angle at that time. The lower panel of Figure 4.8 shows the solar flare X-ray induced $h'$ perturbations on July 13, 2005. The measured results were extracted from 5,923 lightning strokes 500–700 km from the Duke sensors. Among the four perturbations, the one which began at 10 LT had the $h'$ drop to 63.4 km at 1035 LT, which was the lowest height in two months of measurements.

Figure 4.9 shows the change of $h'$ correlated with solar flare X-ray fluxes. Be-
sides the correlation between peak fluxes and measured $h'$ variations which has been studied in previous work [96], we also studied the relationship between the measured $h'$ and X-ray fluxes in each 5-minute time window during the solar flare period. We divided the measured $h'$ into three groups according to their measurement time in the solar flare process, i.e., they can be in the X-ray rising phase, peak and decaying phase. The $\Delta h'$ is defined as the measured $h'$ subtracted by the unperturbed $h'$ during the flare period. The unperturbed $h'$ is calculated from the average value of $h'$ in two months as we discussed in section 4.4.2. Thirteen 5-minute average $h'$ measurements during fast X-ray increases, particularly in some rising phases, are not included, since the $D$ region may have not enough time to respond to the solar flare, and the measured $h'$ changes are usually smaller than true changes.

We compared $\Delta h'$ to the logarithm of both the long wave and short wave X-ray fluxes during the solar flare periods. Figure 4.9a shows the correlation between $X_l$ fluxes and $\Delta h'$ for 16 solar flare events. The first order polynomial least square error (LSE) fit shows that an increase in flux by a factor of 10 (1 increase using logarithm) leads to 6.3 km decrease of $h'$ in the X-ray peak time, which agrees perfectly with the results from narrowband measurements given by McRae and Thomson [96]. This is also consistent with the results given by Jacobson et al. [70], although the measured height has different meaning from $h'$ here. However, when rising and decaying phase measurements are included, the relationship is more complex. The same X-ray flux increase leads to 5.4 km decrease of $h'$ for both the rising and decaying phase. The solar flare has stronger effects on the $D$ region in the rising phase than in the decaying phase, since the same flux can induce 1.5 km more $h'$ decrease in the rising phase than in the decaying phase. This is also clearly shown in a single solar flare event. Figure 4.9b shows the comparison of $\Delta h'$ correlation with $X_l$ fluxes in the rising and decaying phase for the solar flare beginning at 10 LT on July 13, 2005.

Figure 4.9c shows the correlation between $X_s$ fluxes and $\Delta h'$. An increase in flux
Figure 4.9: The measured $\Delta h'$ related to X-ray flux variation in two months. The $\Delta h'$ is approximately proportional to the logarithm of the X-ray fluxes. The same flux can induce different $\Delta h'$ in rising phases, peaks and decaying phases of solar flares. (a) from 16 solar flare events for the long waveband; (b) from one solar flare event beginning at 10 LT on July 13, 2005 for the long waveband; (c) from 16 solar flare events for the short waveband; (d) from one solar flare event beginning at 10 LT on July 13, 2005 for the short waveband.

by a factor of 10 leads to 4.7 km decrease of the $h'$ in X-ray peak time but 3.7 km in both the rising and decaying phase. However, compared to the long waveband, the difference of the solar flare effects on D region during rising and decaying phases is much smaller. Only $\sim$0.5 km difference is generated by the same flux. This is also clearly shown by the solar flare event beginning at 10 LT on July 13, 2005 in Figure 4.9d. This indicates that $h'$ changes correlate more consistently with the
short, rather than the long wavelength X-ray fluxes.

The 5-minute average measurements in the rising phase as shown in Figure 4.9c exhibit a fairly clear nonlinear relationship between $\Delta h'$ and the logarithm of $X_s$ fluxes. We applied the third order polynomial LSE fit to the correlation between the measured $h'$ and X-ray fluxes in rising phases of $X_s$. The same flux increase can lead to different $h'$ decreases in different flux ranges. When the flux is small (logarithm smaller than $-6.5$), an increase in the flux by a factor of 10 only leads to $h'$ decrease of 1.5 km. However, the same flux change can lead to 7.5 km $h'$ decrease when the flux is large (logarithm larger than $-5.5$).

4.5 Method of $\beta$ Measurement

Similar to the method used for the nighttime $\beta$ measurement, we derived daytime $\beta$ from the higher frequency minima of the sferic spectra. To give an overview of typical daytime $\beta$ variations, we computed $\beta$ in three periods: morning, noontime and afternoon. We selected these three periods in three different days (July 19, August 12 and August 6, 2005) for following reasons. In these days, there were sufficient sferics (from 20 to 69) in 5-minute time windows originating from small geographical regions. Each period lasted more than three hours. In each period, in every $\sim 30$ minute, we chose a 5-minute time window that is long enough to include several tens of lightning strokes but short enough so that the large-scale $D$ region electron density is not likely to change significantly [36, 30]. In each 5-minute time window, several tens of lightning strokes from a small geographical region ($\sim 20$ km $\times$ 20 km) were selected. These lightning strokes were located in almost the same geographical region, and thus the sferic spectra excited by them almost had the same features.

In each 5-minute window, we calculated the average sferic spectrum excited by these lightning strokes in order to lower the noise level in the measured sferic spectra.
Figure 4.10: The procedure for the electron density profile measurements from sferic spectra fitting shown by two examples. (a) $h'$ derived from the lower frequency mode interference pattern at 0938 LT on July 19, 2005; (b) $\beta$ derived from the higher frequency mode interference pattern at 0938 LT on July 19, 2005; (c) $h'$ derived from the lower frequency mode interference pattern at 0738 LT on July 19, 2005; (d) $\beta$ derived from the higher frequency mode interference pattern at 0738 LT on July 19, 2005.

[36]. Figure 4.10 shows two examples of the extraction of $h'$ and $\beta$. Figure 4.10a and b show the electron density profile measurement at 0938 LT on July 19, 2005. The measured sferic spectrum is the average of 53 spectra generated by lightning strokes approximately 754 km from Duke sensors and located in the east direction (azimuth angle $\sim 90^\circ$). Figure 4.10a shows the best fitted $h' = 71.6$ km retrieved from alignments of these valleys of the mode interference pattern in the lower frequency
range, as discussed in previous sections in this chapter. However, the spectrum in this frequency range is not sensitive to $\beta$ and gives equally good fits for $\beta = 0.45$ and 0.50 km$^{-1}$. In contrast, the frequency of the mode interference minimum in the simulated spectrum near 20 kHz is very sensitive to $\beta$, which is shown in Figure 4.10b. The best fit to the measured spectrum is located between the simulated spectra for $\beta = 0.45$ and 0.50 km$^{-1}$. By using linear interpolation, we found the best fitted $\beta = 0.47$ km$^{-1}$. Figure 4.10c and 4.10d show the profile measurement in the same day but at 0738 LT. The best fitted $h'$ is 74.9 km and the best fitted $\beta$ is 0.42 km$^{-1}$. As shown in Figure 4.10c, the measured and simulated minima and maxima above 3.5 kHz are not well aligned. This is caused by the difference between the complex real $D$ region electron density profile and the exponential profile profiles we used in the FDTD model simulations. The $h'$ measurement mainly depends on the middle valley alignment (near 2.7 kHz in this example) in the lower frequency range, which has been discussed in previous sections in this chapter. Sometimes, the spectra valleys in both the lower and higher frequency ranges are not precisely aligned, and this leads to an error in $\beta$ measurement. By using the measurement at 0738 LT on July 19, 2005 which is shown in Figure 4.10c and 4.10d, we first estimate the error caused by the uncertainty of the measured sferic spectrum valley position in the “relative flat” higher frequency range 19.33–19.75 kHz. The $\beta$ measurement error caused by such a valley position uncertainty is $\pm 0.014$ km$^{-1}$. In addition, we found, in the lower frequency range, the valley positions of the simulated spectra for $h' \pm 0.2$ km deviation from best fitted $h'$ value and those of measured spectrum are obvious different. This less than $\pm 0.2$ km $h'$ uncertainty leads to the sferic spectrum valley position uncertainty in the higher frequency range. We estimated the $\beta$ measurement error caused by this $\pm 0.2$ km $h'$ uncertainty and found it is $\pm 0.009$ km$^{-1}$. Therefore, the total $\beta$ measurement error caused by the waveguide mode interference pattern alignment uncertainty is $\pm 0.023$ km$^{-1}$. 86
4.6 Measured Daytime $\beta$

We applied the procedure discussed in last section to 23 cases of 5-minute averaged sferic spectra to infer the $\beta$ for solar zenith angles between 20 and 75 degrees (the minimum observable value given our sensor latitude) for morning, noon, and afternoon measurements. The top panel of Figure 4.11 shows the measured $h'$ and $\beta$ variations with local time and solar zenith angles from broadband sferics and narrowband VLF signals [95] during the morning period. We only discuss the broadband measurements in this section and will discuss their comparisons with narrowband measurements in next section. The broadband sferics were excited by lightning strokes in the east coast of United States and 720–760 km from Duke sensors in the morning on July 19, 2005. Since more than half of sferic wave propagation paths were over the ocean, we used PEC as the ground boundary condition in FDTD simulations for this group of sferics. We computed seven $h'$ and $\beta$ values across a 3.5 hour time window, i.e., one measurement in around every 30 minutes. The $h'$ decreased with decreasing solar zenith angle, which is consistent with all previous measurements [95]. In order to distinguish the period before and after noontime, we label the morning solar zenith angle as negative values [95]. The measured $\beta$ was around $0.45 \text{ km}^{-1}$ with some uncertainties during the 3.5 hour period. By computing other two cases when the solar zenith angle was between 60$^\circ$ and 70$^\circ$ in the morning, we estimated the $\beta$ measurement day-to-day variation $\pm 0.035 \text{ km}^{-1}$, which is shown by the error bar in the top panel of Figure 4.11. Given this uncertainty, the measured $\beta$ is consistent with a completely uniform value, and the measured average value is $\beta = 0.44 \text{ km}^{-1}$.

The slight increase in morning $\beta$ with time is probably not significant.

As shown in the middle panel of Figure 4.11, during the noontime period, both the measured $h'$ and $\beta$ were different from in the morning. The NLDN recorded lightning strokes from the west of Duke sensors and 660–720 km away on August
Figure 4.11: Measured $h'$ and $\beta$ from broadband sferics compared to narrowband measurements from [95]. Top panel: broadband measurements on July 19, 2005 compared to narrowband measurements from several day averages during the morning period; Middle panel: broadband measurements on August 12, 2005 compared to narrowband measurements from several day averages during the noontime period; Bottom panel: broadband measurements on August 6, 2005 compared to narrowband measurements from several day averages during the afternoon period.
12, 2005 were used to measure the average electron densities across the sferic wave propagation paths. We used the SIBC ground boundary since sferic wave propagation paths were over land. In this three hour period, as expected [95], the \( h' \) was relatively stable. The measured \( \beta \) was again essentially constant with solar zenith angle, given the measurement uncertainties, with an average value of \( \beta = 0.39 \text{ km}^{-1} \).

The bottom panel of Figure 4.11 shows \( h' \) and \( \beta \) variations during the afternoon period on August 6, 2005. The lightning strokes used in these measurements were located in the northeast (azimuth angle \( \sim 60^\circ \)) of and 720–800 km from the Duke sensors. The ground boundary was treated as a PEC because most wave propagation paths were primarily over the ocean. The \( h' \) increased as the solar zenith angle increased, as expected. However, once again, the measured \( \beta \) during this 4 hour period was essentially constant with an average value of \( \beta = 0.38 \text{ km}^{-1} \). We also estimated the day-to-day variation \( \pm 0.026 \text{ km}^{-1} \) using the similar method to that for the morning period.

These measurements in three daytime periods showed that our measured daytime \( \beta \), while it may exhibit modest day-to-day variability, has only a weak dependence on solar zenith angle from morning, through noontime, and into the afternoon. This is in sharp contrast to the measured \( h' \) discussed in previous sections which does exhibit a very clear solar zenith angle dependence. Below we compare these measurements to previously reported measurements of the same quantities and also these quantities extracted from modeled daytime ionosphere electron density profiles.

### 4.7 Comparisons with Other Measured or Modeled Results

In our work, \( \beta \) was measured from the mode interference pattern in the higher frequency range of broadband VLF sferic spectra. Several other measurements have also been presented in previous work. McRae and Thomson [95] calculated the \( \beta \) dependence on solar zenith angles from amplitudes and phases of narrowband VLF
signals over a variety of long subionospheric paths. There are significant differences
between the measurement approaches in our work and this previous work, i.e. nar-
rowband vs. broadband VLF, short vs. long propagation paths, but a comparison is
still valuable. We also analyzed the effective $h'$ and $\beta$ obtained from IRI and FIRI
modeled daytime electron density profiles.

### 4.7.1 Comparison with Narrowband VLF Measurements

Following the work by Thomson [136], McRae and Thomson [95] calculated curves
for the dependence of $h'$ and $\beta$ on solar zenith angles by comparing LWPC mod-
eled VLF amplitudes and phases with diurnal observed results in a few days over
several long and short paths. In the next step, they verified their measurements by
comparing the observed and model calculated amplitude and phase variations with
time of the day using LWPC and based on their measured $h'$ and $\beta$ for four different
VLF transmitters including Omega Hawaii, Omega Japan, NPM Hawaii and NLK
Seattle. The comparisons between their measurements and our measurements are
shown in Figure 4.11. During the morning period, as shown in the top panel, $\beta$
from narrowband measurements showed obvious monotonic ascending trend, increasing
from 0.26 km$^{-1}$ when the solar zenith angle $\chi$ was 75$^\circ$ to 0.36 km$^{-1}$ for $\chi = 40^\circ$.
However, these absolute values were significantly smaller compared to our broadband
measurements. They were about 0.15 km$^{-1}$ smaller than our broadband measure-
ments in the early morning, and this difference decreased to around 0.05 km$^{-1}$ at
1008 LT.

In contrast, the absolute values of $\beta$ calculated by McRae and Thomson [95] are
in close agreement with our broadband measurements during the noontime period,
which is shown in the middle panel of Figure 4.11. During the afternoon period, as
showed in the bottom panel of Figure 4.11, narrowband measured $\beta$ showed obvious
descending trend. It was consistent with broadband measured $\beta$ when the solar
zenith angle was smaller. But it kept decreasing as the solar zenith angle increasing while $\beta$ from broadband measurements did not change obviously during the same period.

In the narrowband measurements given by McRae and Thomson [95], the parameter $\beta$ was inversely correlated to the solar zenith angle. In our broadband measurements, $\beta$ did not show any obvious increasing and decreasing trends during morning and afternoon periods. Narrowband measured $\beta$ variation was almost symmetrical for the morning and afternoon, i.e., the $\beta$ value was almost the same for the same solar zenith angle during morning and afternoon periods. In broadband measurements, $\beta$ during the morning period was $\sim 0.05$ km$^{-1}$ larger than it in the afternoon period. However, this difference may be attributable to simple daily variability given the small number of measurements in the broadband data set.

It should again be emphasized that the measurement techniques compared here are different, particularly because of the disparate propagation lengths. Our broadband measurement employs short propagation paths and is thus highly local compared to the long path narrowband technique. Nevertheless it is somewhat surprising that these techniques exhibit such a significant discrepancy in the measured daytime $\beta$ given that they agree quite closely in the measured nighttime and daytime $h'$.

### 4.7.2 Comparison with IRI Model

Similar to nighttime, we use propagation simulations with IRI ionospheres as synthetic data and extract the effective daytime $h'$ and $\beta$ to gain some insight into the relationship of these parameters to more complex daytime ionospheric electron density profiles.

We fitted several simulated sferic spectra from using two parameter exponential electron density profiles to the simulated sferic spectrum from using a certain IRI model, and calculated the best fitted $h'$ and $\beta$. In all the FDTD simulations, we set
Figure 4.12: The equivalent $h'$ and $\beta$ for IRI during the morning period on July 19, 2005. (a) $h'$ derived from the lower frequency mode interference pattern; (b) $\beta$ derived from the higher frequency mode interference pattern; (c) the best fitted exponential profile compared to IRI2001 modeled profile at 0930 LT; electron density in the IRI model below 60 km is extended from its variation trend above 60 km and plotted as dot line; (d) the best fitted $h'$ and $\beta$ in three hours during the morning period.

the azimuth angle as 90° and the distance as 700 km. And only the PEC ground boundary condition was used. Figure 4.12a and 4.12b show an example for the sferic spectrum fitting between that from using IRI2001 model and that from using the exponential profile. The good fitting in both the lower and higher frequency range means that the best fitted parameters for the IRI2001 profile are $h' = 72.0$ km and $\beta = 0.35$ km$^{-1}$. Figure 4.12c shows the comparison between the IRI2001 modeled
electron density profile and the best fitted exponential profile. The two profiles are rather consistent in the electron density range $\sim 40-400$ cm$^{-3}$, indicating that it is the electron densities in this range that contribute most strongly to VLF propagation characteristics. The electron density below 60 km is not given in the IRI model. We extended the electron density to lower altitudes according the profile variation trend above 60 km. However, because the electron density below 60 km is rather small, the simulated sferic feature does not change even if the density below 60 km is increased two times.

By applying this fitting procedure, we derived the best fitted $h'$ and $\beta$ for both IRI2001 and IRI2007 $D$ region electron density profiles during the morning period on July 19, 2005 near Duke University. In three hours from 07 LT to 10 LT, we calculated seven sets of best fitted $h'$ and $\beta$ with each set in every half hour. Compared to the broadband measured results during the same time, which are shown in the top panel of Figure 4.11, the $h'$ derived from both IRI2001 and IRI2007 are lower before 0830 LT but higher after that time. It means $h'$ decreasing during the morning period is slower from the IRI model than for the practical measured results using broadband sferics. In addition, there are also difference for the $h'$ for IRI2001 and IRI2007. From 07 LT to 08 LT, the derived $h'$ difference between IRI2001 and IRI2007 model decreased from 1.1 km to 0.2 km.

While the extracted $h'$ measurements are in good agreement with our broadband and past narrowband measurements, the derived $\beta$ values from the IRI model are significantly different from both measurements. In IRI2001 model, the derived $\beta$ decreases monotonically from 0.45 km$^{-1}$ at 07 LT to 0.35 km$^{-1}$ at 10 LT. In IRI2007 model, the derived $\beta$ decreases from 0.39 km$^{-1}$ at 07 LT to near 0.35 km$^{-1}$ at 09 LT. And then, it increases to 0.36 km$^{-1}$ at 0930 LT. The absolute values of $\beta$ from IRI2001 and IRI2007 are smaller than those from our broadband measurements. In addition, the $\beta$ variation trends from the IRI model are opposite to the results given
by McRae and Thomson [95] since $\beta$ increases during the morning period in their measurements. The $\beta$ values from the IRI model are in closer quantitative agreement with our broadband measurements compared to narrowband measurements, although the IRI model exhibits a consistent trend not seen in the broadband measurements.

4.7.3 Comparison with FIRI Model

The FIRI is a semiempirical lower ionosphere model which is exclusively based on Faraday rotation experiments [49]. We adapted three typical daytime electron density profiles for solar zenith angles $30^\circ$, $60^\circ$, and $75^\circ$ from the FIRI model given by Friedrich and Torkar [49]. In the original work, no electron density below 60 km was provided. We use the similar method to that for the IRI model to construct the electron density below this altitude. These profiles are for the condition of low latitude, January and low solar activity. Figure 4.13a and 4.13b show the best fitted $h^\prime = 71.8$ km and $\beta = 0.28$ km$^{-1}$ derived from sferic spectrum fitting, which is similar as the method used for IRI model.

Figure 4.13c shows the comparison between electron density profiles from FIRI and the best fitted exponential profiles. For the solar zenith angle $30^\circ$, the best fitted $h'$ is 71.8 km and the best fitted $\beta$ is 0.28 km$^{-1}$. The $h'$ value is near our measured value from broadband sferics and that provided by McRae and Thomson [95] for the same solar zenith angle. However, the best fitted $\beta = 0.28$ km$^{-1}$ is much smaller than our measured value 0.39 km$^{-1}$ when the solar zenith angle was $30^\circ$ during the afternoon period on August 6, 2005. It is also smaller than the measured value 0.39 km$^{-1}$ given by McRae and Thomson [95]. When the solar zenith angle is $60^\circ$, the measured $\beta$ decreased to 0.23 km$^{-1}$. This value is also smaller than both broadband and narrowband measured values. When the solar zenith angle increases to $75^\circ$, there is no existing equivalent exponential profile since the derived $\beta$ is less than 0.2 km$^{-1}$ and near 0.15 km$^{-1}$. It becomes meaningless in physics since the electron density
Figure 4.13: The electron density profiles from FIRI [49] fitted by equivalent exponential profiles. Below altitude 60 km, the FIRI profiles are extended from their variation trends above 60 km and plotted as dot lines. (a) $h'$ derived from the lower frequency mode interference pattern for solar zenith angle $\chi = 30^\circ$; (b) $\beta$ derived from the higher frequency mode interference pattern for solar zenith angle $\chi = 30^\circ$; (c) the best fitted profiles were found for solar zenith angles 30$^\circ$ and 60$^\circ$; the best fitted $\beta$ for $\chi = 75^\circ$ is smaller than 0.2 km$^{-1}$ and near 0.15 km$^{-1}$, which is meaningless in physics; (d) the best fitted $\beta$ changes with solar zenith angle variations.

in the exponential profile is a constant when $\beta = 0.15$ km$^{-1}$. And the $\beta$ variation trend with solar zenith angle increasing is shown in Figure 4.13d. It is consistent with the result given by McRae and Thomson [95]. However, the absolute values of $\beta$ for FIRI are $\sim$0.1 km$^{-1}$ smaller than those from [95].
4.8 Summary of Daytime Measurement

In this chapter, we derived the midlatitude daytime $D$ region equivalent exponential electron density profile height and sharpness by comparing the lower and higher frequency mode interference patterns of measured sferic spectra to FDTD model simulated results. A total of 285,029 lightning strokes in July and August 2005 near Duke University provided almost continuous measurements of $h'$ during 14 hour daytime windows over a two month period. Temporal and spatial variations of $h'$ were given. Quantitative correlations between $h'$ variations and solar zenith angles and solar flare X-ray fluxes were calculated to compared to previous narrowband measurements. The $\beta$ values during morning, noontime and afternoon periods in three different days were extracted from broadband VLF propagation spectra obtained on relatively short ($\sim 700$ km) propagation paths. These $\beta$ values from broadband VLF sferic spectra were compared to narrowband VLF measurements, IRI model and FIRI model.

As expected, during the 14 hour daytime, the measured $h'$ dropped from the sunrise to the lowest point at around noontime and resumed its ascending trend again. We found, on some days, the $D$ region electron density profile height was also influenced by solar flare X-ray and the sudden drops formed. And they were observed in nine days during the two months. The correlation between 5-minute average $h'$ and the solar zenith angle in a single day is almost the same as the result given by McRae and Thomson [95] except that the minimum $h'$ value 71.5 km when the solar zenith angle equaled to 17 degrees was a little higher than the 70.8 km from narrowband measurement for a solar minimum year and in lower latitudes. In addition, we noticed that the rapid change of measured $h'$ always showed up when the solar zenith angle was larger than 50 degrees, which is consistent with the measurement provided by Jacobson et al. [70]. The statistical correlation between
5-minute average $h'$ and solar zenith angle in two months indicates that our measured $h'$ is slightly higher than the polynomial calculation given by McRae and Thomson [95] for a solar minimum year and the same solar zenith angle, especially when it smaller than 70 degrees. The comparison of our results with a more complex model given by Ferguson [45] also shows that only the general variation trend of $h'$ with solar zenith angle is the same but the specific values of $h'$ can show some differences.

We also measured different regions simultaneously when the lightning locations were favorable. In order to exclude the solar zenith angle influence, we compared the measured $h'$ in different geographic locations for the same solar zenith angle instead of local time. During two months, around half of the days exhibited regional differences not explained by the solar zenith angle. However, only eight days had regional $h'$ difference larger than 0.5 km when the solar zenith angle was the same. These results indicate that the ionospheric $D$ region spatial variation beyond the solar zenith angle exists. The solar radiation is the dominant but not the only determinant source of the lower ionosphere ionization.

Solar flare induced $D$ region perturbations were studied in this chapter. Through comparing measured $h'$ to X-ray fluxes recorded by GOES–10 satellite in two days, we found that those sudden drops in measured $h'$ had good time correlations with the sudden increases of the X-ray fluxes. Using 16 solar flare events during two months, we explored the quantitative relationship between X-ray fluxes and $\Delta h'$ in both the long waveband and short waveband in the X-ray rising phase, peak and decaying phase. The $\Delta h'$ is approximately proportional to the logarithm of X-ray fluxes. In the long waveband, an increase in flux by a factor of 10 leads to 6.3 km decrease of $h'$ in X-ray peak time, which agrees perfectly with the measurement given by McRae and Thomson [96]. The same flux increase leads to 5.4 km decrease of $h'$ in the X-ray rising and decaying phase. In the short waveband, the same flux increase leads to 4.7 km decrease of $h'$ in X-ray peak time but 3.7 km in both the
Figure 4.14: The summary of $\beta$ value changes with solar zenith angles, assumed all measurements in the morning period. Broadband measurements in three different periods are labeled in the figure. All the $\beta$ measurements are different. Broadband measured $\beta$ is independent of the solar zenith angle and close to the values extracted from IRI models. The $\beta$ values from FIRI model are the lowest. The $\beta$ values from all kinds of measurements and models are more consistent when the solar zenith angle is small than when it is large.

Rising and decaying phase. Compared to the long waveband, the difference of the solar flare effects on $D$ region during rising and decaying phases is much smaller in the short waveband. The measurement of $h'$ shows that the relationship between $\Delta h'$ and X-ray flux for the rising phase in the short waveband is weakly nonlinear and we presented a third order polynomial to describe this relationship.

The estimated $\beta$ from broadband measurements, narrowband measurements, IRI models and FIRI models, are surprisingly different, and the comparisons are shown in Figure 4.14. Our broadband, short path measurements show a $\beta$ that is relatively independent of solar zenith angle with a value around 0.39 km$^{-1}$ (although this value may be somewhat variable from day to day). This value is close to the average value extracted from the IRI model ionospheres, but the IRI ionospheres also show a clearly decreasing $\beta$ as time moves towards noon. The narrowband, long path measurements
given by McRae and Thomson [95] show lower values of $\beta$ from about 0.25 to 0.38 km$^{-1}$ with a clearly increasing $\beta$ as time moves towards noon (the opposite trend from the IRI ionospheres). The FIRI model ionospheres exhibit the lowest $\beta$ values of all, varying from about 0.20 to 0.30 km$^{-1}$ also with a clearly increasing $\beta$ as time moves towards noon.

For solar zenith angles less than about 45 degrees, the broadband measurements, the narrowband measurements, and the IRI model values are all in reasonably close agreement, exhibiting $\beta = 0.35$ to 0.40 km$^{-1}$ that is weakly or not dependent on solar zenith angle. The FIRI values are lower and more dependent on solar zenith angle. But for higher solar zenith angles, these different sources exhibit strong differences in the values of $\beta$ that they predict. This suggests that the daytime ionosphere electron density profiles for times significantly away from local noon (i.e., higher solar zenith angles) may not be well approximated by a simple two parameter exponential profile.
The solar terminator is the line that separates the day side and night side of Earth and is also called “twilight zone”. In most time, it is not exactly parallel to longitude lines due to the revolution of Earth. Its angle with respect to the longitude line can be as large as 23.5 degrees during the solstices but near zero during the equinoxes.

The ionosphere parameters such as temperature, ion density and electron density vary rapidly near the terminator due to the quick change of solar radiation [132]. Previous research regarding the solar terminator as well as VLF mainly includes its effects on VLF propagation [89, 32], its effects on Schumann resonance [99], and terminator time correlation with earthquakes [151].

In this chapter, we applied the methods described in last two chapters to $D$ region electron density measurements near solar terminators. Although the sferic propagation paths were probably partially in nighttime side and partially in daytime side, we do not consider the ionosphere $D$ region electron density horizontal gradients. FDTD model simulations showed that the sferic spectrum for a $D$ region electron density profile with horizontal gradients of both $h'$ and $\beta$ and the spectrum with the average $h'$ and $\beta$ are almost identical. Therefore, in this chapter, we only derived
the equivalent exponential profiles instead of considering the complicated horizontal ionosphere gradient. And both the sunrise and sunset periods in two different days were measured.

5.1 Sunrise Measurement

In order to verify the ionosphere $D$ region electron density transition during the sunrise period, we selected 80 sferics which have clear spectra and occurred between 0510 LT and 0730 LT on August 7, 2005. The lightning strokes corresponding to these sferics occurred in the northeast direction (azimuth $\sim 60^\circ$) and in a distance range 500–560 km. They were divided into 11 groups and each group was in a less than 5-minute time window. The sferics in each group almost came from the same location (distance difference less than 20 km). We calculated the average sferic spectrum for each group. Then we derived the best fitted $h'$ and $\beta$ for these average sferic spectra by using the techniques discussed in last two chapters.

The upper panel of Figure 5.1 shows the locations of those lightning strokes used in the measurements. The solar terminator line at 061738 LT exactly passed through the average midpoint (with latitude 37.10\degree N and longitude 76.49\degree W) of those sferic wave propagation paths. It gradually moved to west as time went on. Since around half of wave propagation paths were over the ocean, we used PEC boundary in all FDTD model simulations.

The lower panel of Figure 5.1 shows measured $h'$ and $\beta$ changes with local time and solar zenith angles in the average propagation path midpoint. During the sunrise period, both $h'$ and $\beta$ showed obvious descending trends, although with some uncertainties. Before 060445 LT (sunrise time at the average lightning location), the whole propagation paths were in the nighttime. The $D$ region measurements show clear nighttime features, with $h'$ larger than 81.0 km and $\beta$ larger than 0.55 km$^{-1}$. After 063036 LT (sunrise time at Duke receiver), the whole propagation paths were
in the daytime. The D region measurement show clear daytime features, with \( h' \) smaller than 80.0 km as well as decreasing trend, and \( \beta \) smaller than 0.50 km\(^{-1} \) as well as weak decreasing trend. The D region between 060445 and 063036 LT was in the fast transition from nighttime to daytime, with both \( h' \) and \( \beta \) decreasing quickly.

The broadband measured \( h' \) and \( \beta \) variations during the sunrise period indicate that the ionospheric D region undergoes fast changes during this period due to quick increase of the solar radiation. Both the profile height and sharpness decrease during
the sunrise.

5.2 Sunset Measurement

We used the same strategy as for sunrise to calculate the sunset ionosphere $D$ region electron density change. We selected 56 sferics which have clear spectra and occurred between 1910 LT and 2110 LT on August 6, 2005. The lightning strokes corresponding to these sferics occurred in the northeast direction (azimuth $\sim 60^\circ$) and in a distance range of 715–800 km. They were divided into 10 groups and each group was in a less than 5-minute time window. The sferics in each group almost came from the same location (distance difference less than 20 km). We calculated the average sferic spectrum for each group.

The upper panel of Figure 5.2 shows the locations of those lightning strokes used in the measurements. The solar terminator line at 200118 LT exactly passed through the average midpoint (with latitude 37.22° N and longitude 75.20° W) of those sferic wave propagation paths. It gradually moved to east as time went on. Since more than half of wave propagation paths were over the ocean, we used PEC boundary in all FDTD model simulations.

The lower panel of Figure 5.2 shows measured $h'$ and $\beta$ changes with local time and solar zenith angles in the average propagation path midpoint. Both the $h'$ and $\beta$ variation trends were opposite to the sunrise results. Before 194725 LT (sunset time at the average lightning location), the whole propagation paths were in the daytime. The $D$ region measurements show clear daytime features, with $h'$ smaller than 79.0 km and $\beta$ smaller than 0.40 km$^{-1}$. After 201430 LT (sunset time at Duke receiver), the whole propagation paths were in the nighttime. The $D$ region show clear nighttime features, with $h'$ larger than 81.0 km, and $\beta$ larger than 0.45 km$^{-1}$. The $\beta$ values measured just after the sunset at Duke receiver are smaller than the typical nighttime $\beta$ values given in Chapter 3. This is probably caused by the mea-
Figure 5.2: Measured $h'$ and $\beta$ variations during the sunset period on August 6, 2005. Upper panel: distribution of lightning used in the measurement; terminator position is for 200118 LT; Lower panel: $h'$ and $\beta$ variations with local time.

Measurement uncertainty or because the ionosphere in the sferic wave propagation paths is not completely cooled down. The $D$ region between 194725 and 201430 LT was in the fast transition from daytime to nighttime, with both $h'$ and $\beta$ increasing. These measured $h'$ and $\beta$ values indicate that the sunset ionospheric $D$ region undergoes fast changes opposite to the trend during the sunrise period.
6

Summary and Future Work

6.1 Summary and Conclusions

In this dissertation, we measured midlatitude $D$ region exponential electron density profiles by comparing the spectra of broadband VLF sferics excited by lightning discharges and propagating in the Earth-ionosphere waveguide to a series of FDTD model simulated results. The profile heights in July and August 2005 for both nighttime and daytime were retrieved from more than 340,000 sferics discharged by lightning strokes 500–800 km away. Typical nighttime and daytime profile sharpness values were given. The $D$ region transitions in both sunrise and sunset periods were measured.

The sferic data were recorded by the receiver located near Duke University, and the corresponding lightning information was provided by the NLDN. By using the 2D FDTD model [59], we set up simulated sferic databases for both nighttime and daytime for lightning discharges from different directions as well as distances and the parameterized exponential electron density profiles. In all simulations, other parameters including $D$ region ion densities, collisions frequencies, background Earth
magnetic fields and the source lightning current waveform were assumed fixed.

The 5 hour nighttime $D$ region electron density profile height $h'$ variations on 59 nights of July and August 2005 were extracted from 61,726 sferics. The fine frequency structures in 3–8 kHz range of the measured $B_{\phi}$ spectrum caused by the waveguide mode interference were fitted to those of a series of simulated spectra of sferics which have the smallest azimuth angle and distance differences with respect to the measured sferic. By aligning the fine frequency structures in the measured sferic spectrum with simulated sferic spectra, the automatic fitting algorithm sought the largest correlation coefficients and smallest alignment error, so as to “measure” $h'$. In this process, a typical $h'$ measurement uncertainty of $\pm 0.6$ km was generated. This uncertainty was lowered by averaging several tens to several hundreds of single sferic measurements in a 5-minute time window in which the real electron density profile has little variation.

The statistical variations of measured $h'$ in two months show that the nighttime $D$ region is far from static, and the dynamics frequently occur on time scales less than one day. The measured $h'$ mean value is consistent with the the long-term average value reported by Thomson et al. [139]. Various temporal dynamics on shorter time scales indicate the complex nighttime $h'$ variations, with the descending trend dominating, although some oscillatory and ascending trends observed. Simultaneous and multipath measurements showed that the $h'$ spatial difference can be as large as 2.0 km. However, no azimuth dependence of $h'$ was observed since it was higher on some nights but was lower on some other nights in the north regions. By examining the observed variations in the context of local and spatial offset lightning rates on two nights, we found that the drivers of nighttime $D$ region variations may be very complicated and the direct energy coupling between lightning and the lower ionosphere is only one possibility.

The nighttime $D$ region electron density profile sharpness $\beta$ is derived from sferic
higher frequency features. The typical $\beta$ values in two nights were calculated and the results were compared to IRI models. The $\beta$ values from our broadband measurements are larger than those from IRI models. In addition, broadband measured $\beta$ was relative stable during the 2.5 hour period although some measurement uncertainties were observed. However, the $\beta$ from IRI models showed obvious descending trends.

By using the technique similar to that for nighttime, we extracted the 14 hour daytime $D$ region electron density profile height $h'$ on 62 days of July and August 2005 from 285,029 sferics. By aligning the fine frequency structures in 1.5–4 kHz frequency range, the automatic fitting algorithm sought the best fitted $h'$ with a typical uncertainty of $\pm 0.8$ km generated in this process.

As expected, the daytime $h'$ not only depends on the solar zenith angle but also on solar flare X-ray fluxes. The correlation between the five minute average $h'$ from broadband measurements and the solar zenith angle is similar to the result given by McRae and Thomson [95], who measured the $h'$ dependence on the solar zenith angle using narrowband VLF signals in lower latitude regions. Comparison of the correlation from our measurements with a more complex model given by Ferguson [45] also shows that only the general variation trends of $h'$ dependence on solar zenith angle are the same, but the specific values of $h'$ from broadband measurements and that model can be different for the same solar zenith angle. The daytime spatial difference of $h'$ beyond the solar zenith angle indicates that the solar radiation is the dominant but not the only determinant source of the daytime lower ionosphere ionization. We quantitatively analyzed the relationship between X-ray fluxes and $h'$ perturbations during solar flare periods, and found that $\Delta h'$ is approximately proportional to the logarithm of X-ray fluxes, which is consistent with previous narrowband measurements [96, 141], and the difference of the solar flare effects on $D$ region during solar flare rising and decaying phases is smaller in the short waveband.
than that in the long waveband.

Similar to nighttime, we derived the daytime $D$ region electron density profile sharpness $\beta$ from sferic higher frequency features. The $\beta$ values during morning, noontime and afternoon periods in three different days were measured, and the results were compared to narrowband measurements, IRI models, and FIRI models. The $\beta$ values from all these sources are different. Broadband measured $\beta$ values are relatively independent of solar zenith angle effects. Narrowband measured and FIRI modeled $\beta$ shows increasing trend as the solar zenith angle decreasing. But the equivalent $\beta$ from FIRI is $\sim 0.1$ km lower than the narrowband measurement. The $\beta$ measurements from IRI show the opposite variation trends with solar zenith angles. The $\beta$ values from all these sources are more consistent when the solar zenith angle is smaller than when it is larger. This may indicate that the daytime $D$ region electron density profiles are not well approximated by a simple two parameter exponential profile, especially for the time near noon.

By applying the $h'$ and $\beta$ measurement techniques discussed above, we also calculated $h'$ and $\beta$ values during sunrise and sunset periods. The measurements in two days show that both $h'$ and $\beta$ undergo quick changes in both sunrise and sunset periods. This validated the significant effects of the solar radiation on ionospheric $D$ region changes.

6.2 Suggestions for Future Work

This dissertation gives the detailed strategies, techniques and results of $D$ region electron density profile measurements in the midlatitude regions near Duke University. The focus of future research work should be shifted to the applications of broadband VLF remote sensing. Future researchers can combine $D$ region variations retrieved from sferics with other measurements or models in order to explore the possible reasons for ionosphere changes.
6.2.1 Measurements in High Latitude

The Duke receiver is located in midlatitude regions, and Cheng et al. [30] correlated the energetic electron (2–6 MeV) precipitation measured by Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX) with electron density profiles inferred from sferics. The inverse correlation between measured $h'$ and SAMPEX high-energy electron fluxes at six nights suggests that high-energy electron precipitation might partially account for the midlatitude $D$ region variations. However, both the temporal and spatial resolutions are low for these measurements as well as the correlations. As we discussed in previous chapters, the $D$ region itself has sharp variations on some nights. The $h'$ measurements given by Cheng et al. [30] were only for short time windows at certain nights. But these measured $h'$ values were compared with daily averaged particle fluxes. In the future work, this should be improved by correlating the measured $D$ region electron density profiles with particle fluxes in a certain time and location (or at least for a certain L-shell value).

In addition, because the particles in the radiation belt bounce between two magnetic poles along magnetic lines, they usually enter the high latitude atmosphere more easily compared to low latitude regions. It means, in the magnetic quiet time, the energetic particle fluxes in high latitude regions are larger than those in low latitude regions. Therefore, it is essential to setup a sferic measurement station in high latitude regions. By doing this, researchers can continuously monitor the $D$ region variations in high latitude regions and explore the measured variations quantitatively by combining them with satellite measured energetic particle precipitating fluxes.

The only issue concerned is the low lightning occurrence rate in high latitude regions [31]. As we discussed in previous chapters, the accurate 5-minute average $h'$ variations are based on massive lightning data. Low lightning occurrence rate can lower the accuracy of $h'$ measurements. Probably, lunching a three months campaign
in the summer season is a good start.

### 6.2.2 Measurements during Large Magnetic Storms

During the periods of large magnetic storms, energetic particle population inside the Earth radiation belts increases quickly and decays through precipitating into Earth atmosphere. They can change the lower ionosphere electron density by increasing the ionization rate there [90]. Direct satellite measurement of the precipitating flux is challenging because only the particles in the loss cone (usually a narrow angle range) can escape away from the magnetic fields trap. Several papers have been published about the particle flux measurements during magnetic storms using narrowband VLF signals [122, 121, 111]. The basic ideas of these kinds of measurements are similar. The precipitation flux is derived by comparing the LWPC modeled VLF amplitudes as well as phases with those observed by VLF receivers. Satellite measured precipitation flux was always the initial input of model simulations for ionosphere changes caused by those precipitating particles. One objective of future research is to combine $D$ region electron density profile variations measured by broadband VLF sferics during magnetic storms with the chemical model by Rodger et al. [122] or the Monte-Carlo model by Peter et al. [111], so as to determinate the precipitating particle fluxes.

### 6.2.3 Measurements near SAA

The South Atlantic Anomaly (SAA) is a special region in the souther hemisphere midlatitude where the Earth inner radiation belt approaches the Earth surface due to the weak geomagnetic fields and the loss of their shielding effects. Figure 6.1 shows the weak geomagnetic fields and average enhanced energetic electron fluxes measured by NOAA–18 satellite between July 1 and December 31, 2005. In past several years, research work regarding SAA has been focused on energetic particle
Figure 6.1: The geomagnetic fields and energetic electron flux near SAA. Upper panel: the contour map of geomagnetic fields with unit in $\mu$T; SAA has weak field intensity. Lower panel: 30–100 keV electron flux measured by 0 degree Medium Energy Proton and Electron Detector (MEPED) on board NOAA–18 satellite; compared to other locations, SAA has higher energetic electron fluxes.
precipitation modeling near SAA [2], satellite measurements near SAA [5, 91, 6], and VLF measurements [1].

We can setup a sferic measurement station near SAA, specifically in Southern Space Observatory (SSO), Brazil, with latitude 29.45° S and longitude 53.82° W. SSO has the infrastructure including electrical power supply and internet connections for sferic measurements and data analysis. We already had two campaigns in SSO. The lightning stroke time and location can be acquired from the Sferic Timing And Ranging Network (STARNET). Similar to the NLDN, the STARNET also provides the detailed lightning information by using the Arrival Time Difference (ATD) technique. In the future research, we can combine sferics recorded by our VLF/ELF sensors with STARNET recorded lightning discharges as well as satellite recorded precipitating fluxes, and study the D region near SAA in both quiet time and geomagnetic periods.

6.2.4 D Region Tomographic Imaging

Because thunderstorms frequently occur in multiple locations simultaneously, the sferics recorded by the Duke ELF/VLF receiver can be used to measure the average D region electron density profiles across the sferic wave propagation paths in different directions at the same time. If we set up several ELF/VLF receivers in the U.S. Continent, D region tomographic imaging during summer time is possible.

Figure 6.2 shows the $h'$ imaging from using lightning strokes in multiple locations and only the Duke ELF/VLF receiver. The left panel shows the measured $h'$ on July 21, 2005. The locations in which we mark the $h'$ values in different colors are the midpoints of the sferic propagation paths. The right panel shows the $h'$ imaging in a circle region with radius 161–548 km, which is acquired from the values displayed in the left panel by using distance and azimuth angle iterative interpolations. The D region $h'$ imaging shows some abrupt changes which are purely artificial. The reason
Figure 6.2: One hour average $h'$ between 0130 LT and 0230 LT at nighttime on July 21, 2005. Left panel: average $h'$ across sferic wave propagation paths marked in the midpoints; Right panel: $D$ region imaging acquired from distance and azimuth interpolations.

for this artificial effect is that too limited measurements make the interpolations not precise. Multiple measurements by a large number of sferic receivers can help users avoid the vague $D$ region $h'$ imaging.

Figure 6.3 shows the hypothesized future circumstances of ULF/ELF/VLF/LF stations in the U. S. continents. Each station has the independent ability to record and process sferic data in real time. All these stations are connected to the sferic data processing center in Duke University by high speed internet. The sferic signals are processed and compressed, and then transferred to Duke University. A sophisticated software can immediately calculate the realtime ionospheric $D$ region electron density above the U. S. Continent.
Figure 6.3: The future circumstances of ULF/ELF/VLF/LF stations in the U. S. continent. All these stations are connected to sferic data processing center in Duke University by high speed internet.
Bibliography


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Biography

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Peer-Reviewed Journal Publications


