Broadband VLF measurements of lightning-induced ionospheric perturbations

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[1] Very low frequency (VLF) electromagnetic pulses radiated by lightning are an effective tool for probing the *D* region ionosphere. We detect and measure the *D* region ionospheric disturbances caused by the strong lightning flash by analyzing the broadband VLF spectrum from lightning that occurred just before and after a nearby intense lightning discharge. Comparing the measured electron density changes to those from previous measurements and the theoretical expectations, we find the detected perturbations are consistent with the theoretically predicted ionization changes produced directly by the lightning electromagnetic pulse. **Citation:** Cheng, Z., and S. A. Cummer (2005), Broadband VLF measurements of lightning-induced ionospheric perturbations, *Geophys. Res. Lett.*, *32*, L08804, doi:10.1029/2004GL022187.

1. Introduction

[2] The first experimental evidence of the impulsive direct coupling of energy released by lightning discharge to the lower ionosphere was reported by *Armstrong* [1983] in the form of early/fast perturbations of narrowband subionospherically propagating VLF signals, which exhibit rapid change beginning within 20 ms of the causative lightning, followed by a relatively slow recovery (typically 10–100 s) [*Inan et al.*, 1993]. Several different mechanisms have been advanced to explain the direct lightning-ionosphere interactions. *Inan et al.* [1993] suggested that fast VLF perturbations are produced by ionization changes in the *D* region over the thunderstorm due to the heating of ionospheric electrons by the electromagnetic pulse (EMP) from lightning (in a manner similar to that which produce fast optical emissions called elves [*Fukunishi et al.*, 1996]) with the disturbance expanding to radial distances of up to 150 km [*Inan et al.*, 1996a]. Later, *Barrington-Leigh et al.* [2001] suggested that early/fast VLF perturbations may be associated with sprite halos which result from intense quasi-electrostatic (QE) fields formed above thunderstorms and produce substantial ionization changes over altitude 70–85 km by modeling the diffuse region of sprites with a more general fully electromagnetic model and more realistic viewing geometry. *Moore et al.* [2003] found that at least some of the fast VLF perturbations are related to sprite halos due to intense QE ionization by measuring the electron density changes using a full wave electromagnetic propagation model together with narrowband and geographically distributed measurements. Moreover, *Moore et al.* [2003] indicates that the scattering pattern of the sprite halo disturbance agrees well with that of the VLF perturbations observed by *Inan et al.* [1996b] and *Johnson et al.* [1999], which indicates that the lateral extent for QE type VLF perturbation should be around 100 km.

[3] Similar narrowband VLF measurements have also indicated that VLF perturbations may be produced by narrow plasma columns associated with sprites [*Dowden*, 1996]. It has also been reported that VLF perturbations can be produced by scattering from perturbations produced by lightning EMP and elves [*Hobara et al.*, 2001]. The interpretation of these observations remains somewhat in dispute [*Dowden*, 1996; *Inan et al.*, 1996b], and a consistent picture of the mechanism or mechanisms responsible for these *D* region perturbations remains elusive. More and repeatable measurements are clearly needed to better understand the nature of lightning-ionosphere coupling.

[4] It has been shown that large scale *D* region electron density profiles can be measured reliably using the broadband VLF radiation from lightning discharges [*Cummer et al.*, 1998]. One of the main anticipated differences between *D* region perturbations produced by the QE and EMP mechanisms is the altitude extent of the perturbation; QE electron density changes are expected from 60–85 km altitudes [*Moore et al.*, 2003], while EMP perturbations are expected primarily between 80–95 km altitudes [*Taranenko et al.*, 1993]. Thus the height profiles of electron density changes inside *D* region perturbations should help distinguish the source of the perturbation, and we applied this broadband VLF technique to measuring these profiles. Although it has been conclusively shown that some fast VLF perturbations are produced by the QE mechanism [*Moore et al.*, 2003], we find that the 5 ionospheric perturbations detected and reported here are consistent with the EMP mechanism. This indicates that the EMP mechanism can also produce ionospheric perturbations as expected by theory.

2. Detection of the Ionospheric Disturbances

[5] The broadband ELF/VLF (~50–7000 Hz) magnetic field waveforms from lightning were continuously recorded (25 kHz sampling frequency) at Duke University during the summer of 2000. Data from National Lightning Detection Network (NLDN) is used to determine the time, location and the peak current [*Cummins et al.*, 1998] of the source lightning discharges. To apply the technique of *Cummer et al.* [1998] to search for small (~100 km in extent) and short-lived (tens of seconds duration) ionospheric perturbations, a number of specific conditions must be met. The propagation path of the probe lightning discharges (those

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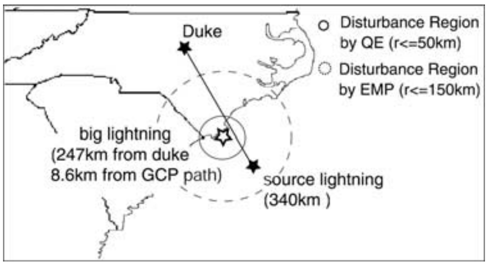

Figure 1. Measurement map showing the location of the source lightning, the big causative lightning and the receiver site (Duke).

used to measure the electron density profile) must be short enough that any ionospheric perturbation covers a significant fraction of the path, but not so short that the influence of the ionosphere on the received signal is small. We take a propagation distance range of 300–500 km to be optimal. The lightning that causes the disturbance must occur close to the propagation path between the sensor and the probe lightning strokes (in most cases the source and probe lightning strokes occur in approximately the same location). The probe lightning strokes must also occur with specific timing. One must occur at most a few minutes before the disturbance-causing stroke to measure the undisturbed ionosphere, and one must occur at most a few seconds after the disturbance-causing stroke to detect the disturbance. In most cases a later stroke can confirm that the ionosphere has returned to its original, unperturbed state.

[6] According to NLDN data of June, July and August of 2000, there were in total 11 days that have lightning strokes within 300–500 km away from the southeast of our sensor (where signals are generally the cleanest) during the nighttime period of 0300–0500 UT. We focused on the four days (June 30, July 12, July 25 and July 31) that have plenty of lightning strokes so that we could find as many events as possible with satisfactory timing. In total, we found 21 events with the desired geometry and timing during 0300–0500 UT on those four days. Of these 21 lightning strokes, 5 were found to produce detectable ionospheric perturbations.

[7] One case from July 25, 2000 is summarized in Figure 1 (geometry) and Table 1 (timing). The three probe lightning flashes happened approximately at 33.3°N 77.4°W, around 0327 UT, and one bigger causative lightning discharge happened at 34°N 78°W at 03:27:16.497 UT. In this case, the perturbation-producing lightning is only 8.6 km away from the GCP path, and the source lightning is 340 km away from the receiver.

Table 1. The NLDN Data of the Associated Lightning in the VLF Event on July 25, 2000, From 03:26 to 03:29 UT

Lightning Strokes	Time, UT	Latitude	Longitude	Peak Current, kA
Probe 1	03:26:34.088	33.275	−77.445	−48.1
Perturbation-Producing	03:27:16.497	33.953	−77.962	−123.2
Probe 2	03:27:28.112	33.249	−77.460	−36.7
Probe 3	03:28:19.744	33.259	−77.454	−41.2

[8] As in Table 1, the first probe lightning stroke happened 42 s before the perturbation-producing lightning stroke and we used it to probe the ambient ionosphere. The stroke with high peak current (−123.2 kA) is the lightning that produced the ionosphere perturbation over the propagation path. The second probe stroke happened 12 s later and was used to measure the ionospheric perturbation. The third probe stroke happened 63 s later and was used to detect the recovery of the disturbed ionosphere.

[9] To demonstrate that these perturbations are robustly detectable using this technique, we chose 100 lighting discharges with good signal-to-noise ratio (SNR) that occurred during 03:04 UT to 03:38 UT on that day from the same source location. The normalized spectra for all of these signals are shown in Figure 2 (top).

[10] Every spectrum has the same shape except for the one from the lightning stroke that immediately followed (12 s) the high peak current stroke in Table 1. This is strong evidence that this spectral change is caused by ionospheric changes and not source current variability. It also shows that when these perturbations occur, they can be easily identified. Figure 2 (bottom) shows the normalized sferic spectra of the three probe lightning strokes in Table 1. Between 3000 Hz and 6000 Hz the sferic spectrum characteristics, which are produced by interference between distinct propagation modes within the earth-ionosphere waveguide, do have significant amplitude change and small frequency shift of the modal interference variations. The waveguide mode interference of VLF spectrum depends on *D* region reflection height and sharpness, thus the clear change in the modal interference reflects the changing of the *D* region ionosphere due to the lightning stroke. In this measurement we detected a strong ionosphere perturbation 12 s after the bigger causative lightning, and with essentially complete return to the ambient profile 63 s later.

[11] Since in general a sharper ionospheric electron density gradient provides a better reflection for all waveguide modes especially near the cut off frequency, the spectral changes in Figure 2 indicate that the lightning disturbance caused the sharpening of the *D* region electron density profile due to the bigger sferic spectrum amplitudes

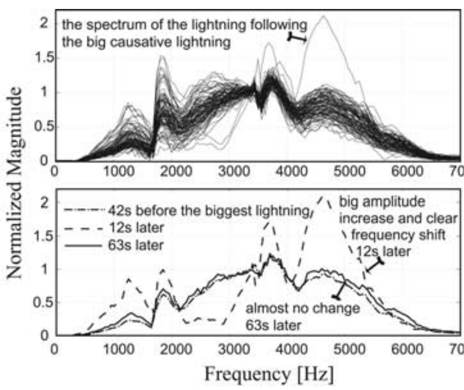

Figure 2. (top) Spectra of 100 lighting discharges with good SNR from 03:04 UT to 03:38 UT on July 25, 2000 at the same location. (bottom) Spectra of 3 probe strokes from 03:26–03:29 UT on July 25, 2000 at the same source location.

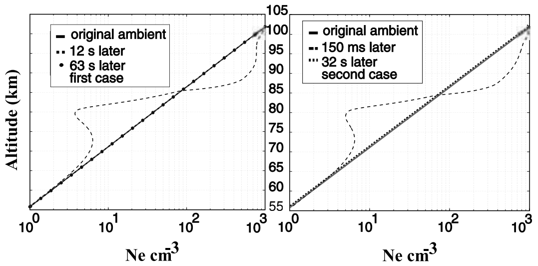

Figure 3. (left) The measured *D* region electron density profiles during the perturbation on July 25, 2000, from 03:26–03:29 UT. (right) The measured *D* region electron density profiles during the perturbation on June 30, 2000, from 04:21–04:23 UT.

12 s after lightning disturbance, which is consistent with the sharpening of the *D* region density profile predicted by *Taranenko et al.* [1993].

3. Measurement of the Electron Density Changes

[12] To measure the actual *D* region electron density perturbation we compare the observed sferic spectrum against a model calculation [*Cummer et al.*, 1998]. For accuracy we use the LWPC VLF-ELF propagation model [*Pappert and Ferguson*, 1986] that can account for finite ground conductivity, arbitrary background magnetic fields, and arbitrary electron density and collision frequency profiles. This model solves the time-harmonic propagation problem using mode theory [*Budden*, 1961], in which the fields at a distance from the source are described as a sum of independently propagating waveguide modes. In the frequency band that we are interested in (3–7 kHz), 7 propagating waveguide modes need to be included in the calculation.

[13] We calculate the model sferic spectrum under a number of different ionospheres to find that which most closely matches the measured sferic spectrum. This procedure requires a parameterization of the electron density profile so that it can be varied in a controlled manner. In this work, we assume that the original *D* region (ambient) electron density can be described by a two-parameter exponential profile,

$$N_e(h) = 1.43 \times 10^7 \exp(-0.15h') \cdot \exp[(\beta - 0.15)(h - h')]\ \mathrm{cm}^{-3}, \quad (1)$$

with h' in kilometers and β in km^{-1}. The two parameters h' and β control the height of the profile and the sharpness of the ionospheric transition, respectively [*Bickel et al.*, 1970]. For the disturbed *D* region electron density, we assume it can be described as,

$$N_D = No + \Delta N, \quad (2)$$

where N_D is the disturbed electron density, No is the ambient electron density, and ΔN is electron density change. Since the disturbed electron density can be generated in a Gaussian manner [*Moore et al.*, 2003], ΔN can be described as,

$$\Delta N = A1 e^{-\left(\frac{h-h1}{\sigma 1}\right)^2} - A2 e^{-\left(\frac{h-h2}{\sigma 2}\right)^2}. \quad (3)$$

[14] Figure 3 (left) shows the best-fit inferred *D* region ionosphere profiles for the ionospheric perturbation on July 25, 2000. From the spectral fitting we found ionosphere parameters of $h' = 82.8$ km and $\beta = 0.3\ \mathrm{km}^{-1}$ which is illustrated by the solid line. By the same method, we found the disturbed propagation is consistent with an exponential ionosphere with h' = 84.4 km and $\beta = 0.75\ \mathrm{km}^{-1}$. However, we know that the actual ionospheric disturbance is limited in altitude range. We thus fit the disturbed exponential profile to a sum of the ambient profile and a series of altitude limited perturbations based on (3). As the final measurement, we choose the perturbation parameters that give the smallest possible total perturbation that is still consistent with the measured broadband VLF data. The resulting perturbed ionospheric profile is also shown in Figure 3 (left). Figure 3 (right) shows the very similar best-fit inferred D region ionosphere profiles during another perturbation case on June 30, 2000.

[15] Figures 3 and 4 show that in this measurement case after the bigger causative lightning the electron density profile become sharpened, with electron density decreasing over h = 65 $\sim$ 85 km and increasing over h = 85 $\sim$ 95 km. Figure 4 shows these two measured electron density perturbation profiles (defined as the absolute, not relative, change in electron density) along with three theoretically predicted perturbation profiles. The EMP perturbation profile was estimated by scaling the computations for a single lightning stroke with peak current equal to 60 kA by *Taranenko et al.* [1993] by a factor of 4 to represent the perturbation from a lightning stroke with a peak current of approximately 120 kA as indicated by *Inan et al.* [1996a]. The QE perturbation profile was approximately estimated from *Moore et al.* [2003] for a lightning stroke with a peak current of 100 kA and the estimated change in electron density was added to a different ambient profile. The LEP perturbation profile was adapted from *Lev-Tov et al.* [1995]. The measured perturbations are larger than but completely consistent with the altitude range predicted for the EMP mechanism. The QE perturbation is substantially different, and propagation calculations (not shown) indicate that a

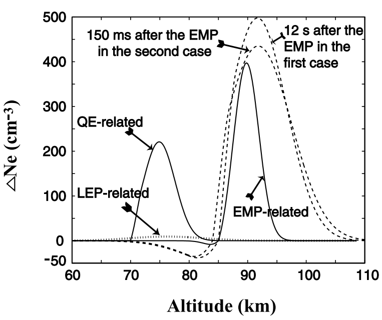

Figure 4. The resulting electron density change caused by the big lightning on July 25, 2000 in the first case and that on June 30, 2000 in the second case and compared to the qualitative shape of ΔN produced by QE-related, EMP-related and LEP-related model.

Table 2. Properties of the Five Investigated Lightning Discharges

Lightning No.	Peak Current, kA	Charge Moment, C km	Ionospheric Perturbation
1	−123.2	Unavailable	Strong
2	−115.7	124	Strong
3	−101.8	Unavailable	Moderate
4	−56.5	95	Strong
5	−47.4	48	Strong

QE-type perturbation cannot reproduce the measured broadband VLF propagation changes. In addition, the LEP perturbation profile is also quite different, which shows a smaller (less than 10 cm^{-3}) electron density enhancement over a wider altitude range 60 ~ 85 km.

[16] For the remaining 3 events, the electron density changes are also primarily at 75–100 km altitudes, and the Ne increases above 83.6 km and decreases at lower altitudes. The magnitudes of ΔN of these 3 events are within a factor of 0.6 ~ 1.2 of that of the first case. Thus, our measured results in total 5 measurement cases are more consistent with the EMP-related model rather than with the QE-related model.

[17] The charge moment changes of the perturbation-producing lightning strokes are also expected to be different for QE and EMP mechanisms. According to *Barrington-Leigh et al.* [2001], the QE mechanism requires many hundreds of C km of charge moment changes to produce significant ionization around 70 km altitudes. We calculated the charge moment changes in three of the perturbing strokes (the signals from two lighting strokes were saturated at Duke and could not be analyzed but they are no more than ~1.5 times bigger than #2 lightning stroke) using the method described by *Cummer and Inan* [2000]. The measured charge moment changes, summarized in Table 2, do not exceed 124 C km. Based on ongoing comparisons with other measurements, these numbers are at most in error +50/−33%. This is further evidence that the detected ionospheric perturbations are not associated with the QE mechanism.

4. Conclusions

[18] In an effort to better understand the direct coupling between lightning discharges and the lower ionosphere, we used VLF energy radiated from individual lightning discharges as a broadband probe to search for and quantify disturbances in the lower ionosphere caused by lightning. We found 5 clear cases where VLF propagation parameters were significantly modified for a period of 30–60 seconds after a high peak current lightning stroke in the area. We quantitatively analyzed the *D* region electron density perturbations caused by the intense lightning flash and found that the changes are consistent with a sharpening of the electron density profile where Ne increases above ~85 km and decreases below ~85 km. The magnitude and altitude of these perturbations are in close agreement with the theoretically expected ionization changes produced by lightning EMP [*Taranenko et al.*, 1993; *Inan et al.*, 1996a]. We note that smaller (in radius) and lower altitude perturbations consistent with QE heating (an entirely different mechanism) have been found previously using single frequency VLF probe waves [e.g., *Moore et al.*, 2003]. We conjecture that EMP perturbations are more common near the U.S. East Coast, where high peak current negative lightning strokes are relatively common, while QE perturbations are more common in the U.S. High Plains, where high charge transfer positive lightning strokes are more common. This work is thus the first detection of ionospheric perturbations caused by lightning EMP, and we attribute this detection to higher sensitivity (compared to traditional VLF probing of the *D* region) resulting from broadband probe signals and shorter propagation paths. Determining the conditions under which these perturbations occur and more closely comparing experiment and theory are the next steps in this research.

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References

Armstrong, W. C. (1983), Recent advances from studies of the trimpi effect, *Antarct. J. U. S.*, *18*, 281–283.
Barrington-Leigh, C. P., U. S. Inan, and M. Stanley (2001), Identification of sprites and elves with intensified video and broadband array photometry, *J. Geophys. Res.*, *106*, 1741–1750.
Bickel, J. E., J. A. Ferguson, and G. V. Stanley (1970), Experimental observation of magnetic field effects on VLF propagation at night, *Radio Sci.*, *5*, 19–25.
Budden, K. G. (1961), *The Wave-Guide Mode Theory of the Wave Propagation*, Logos, London, UK.
Cummer, S. A., and U. S. Inan (2000), Modeling ELF radio atmospheric propagation and extracting lightning currents from ELF observations, *Radio Sci.*, *35*, 385–394.
Cummer, S. A., U. S. Inan, and T. F. Bell (1998), Ionospheric D region remote sensing using VLF radio atmospherics, *Radio Sci.*, *33*, 1781–1792.
Cummins, K. L., E. P. Krider, and M. D. Malone (1998), The US National Lightning Detection Network and applications of cloud-to-ground lightning data by electric power utilities, *IEEE Trans. Electromagn. Compat.*, *40*, 465–480.
Dowden, R. L. (1996), Comment on "VLF signatures of ionospheric disturbances associated with sprites" by Inan et al., *Geophys. Res. Lett.*, *23*, 3421–3422.
Fukunishi, H., Y. Takahashi, M. Kubota, K. Sakanoi, U. S. Inan, and W. A. Lyons (1996), Elves: Lighting-induced transient luminous events in the lower ionosphere, *Geophy. Res. Lett.*, *23*, 2157–2160.
Hobara, Y., N. Iwasaki, T. Hayashida, M. Hayajawa, K. Ohta, and H. Fukunishi (2001), Interrelation between ELF transients and ionospheric disturbances in association with sprites and elves, *Geophys. Res. Lett.*, *28*, 935–938.
Inan, U. S., J. V. Rodriguez, and V. P. Idone (1993), VLF signatures of lightning-induced heating and ionization of the nighttime D-region, *Geophys. Res. Lett.*, *20*, 2355–2358.
Inan, U. S., W. A. Sampson, and Y. N. Taranenko (1996a), Space-time structure of optical flashes and ionization changes produced by lightning-EMP, *Geophys. Res. Lett.*, *23*, 113–136.
Inan, U. S., T. F. Bell, and V. P. Pasko (1996b), Reply, *Geophys. Res. Lett.*, *23*, 3423–3424.
Johnson, M. P., U. S. Inan, S. J. Lev-Tov, and T. F. Bell (1999), Scattering pattern of lightning-induced ionospheric disturbances associated with early/fast VLF events, *Geophys. Res. Lett.*, *26*, 2363–2366.
Lev-Tov, S. J., U. S. Inan, and T. F. Bell (1995), Altitude profiles of localized D region disturbances produced in lightning-induced electron precipitation events, *J. Geophys. Res.*, *100*, 21,375–21,384.
Moore, R. C., C. P. Barrington-Leigh, U. S. Inan, and T. F. Bell (2003), Early/fast VLF events produced by electron density changes associated with sprite halos, *J. Geophys. Res.*, *108*(A10), 1363, doi:10.1029/2002JA009816.
Pappert, R. A., and J. A. Ferguson (1986), VLF/LF mode conversion model calculations for air to air transmissions in the Earth-ionosphere waveguide, *Radio Sci.*, *21*, 551–558.
Taranenko, Y. N., U. S. Inan, and T. F. Bell (1993), Interaction with the lower ionosphere of electromagnetic pulses from lightning: Heating, attachment, and ionization, *Geophys. Res. Lett.*, *20*, 1539–1542.

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