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Scattering Pattern of Lightning-Induced Ionospheric Disturbances Associated with Early/Fast VLF Events

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Abstract. Simultaneous observations of early/fast Very Low Frequency (VLF) events at nine closely spaced (~65 km) sites are used together with a numerical model of the propagation and scattering of VLF signals in the earth-ionosphere waveguide to directly measure the scattering pattern of associated ionospheric disturbances. In cases when the causative lightning is within 700 km of the north-south array of observing sites, early/fast VLF events are typically observed at no more than 2 or 3 sites, which indicates a narrow beam of the scattered signal in the forward direction. In the different cases studied, forward scattering patterns exhibit 15 dB beamwidths of less than 30° consistent with horizontal extent of 90 ± 30 km.

Introduction

'Early/fast' VLF events are characteristic changes in the amplitude and/or phase of a subionospheric VLF signal that exhibit a rapid onset (<20 ms, i.e., fast) followed by a relatively slow recovery (typically 10 to 100 s) and which occur within 20 ms of a causative cloud-to-ground (CG) lightning discharge (i.e., early) [*Inan et al.,* 1993]. The physical mechanism underlying these events is not yet quantitatively understood; however, available evidence indicates that they may be due to quasi-electrostatic thundercloud fields which quiescently heat the *D* region of the ionosphere and modify its ambient conductivity throughout the duration of an active thunderstorm [*Inan et al.,* 1996a]. Lightning induced changes in the thundercloud charge lead to localized heating/cooling of the *D* region causing small changes in the vicinity of the quiescent value and thus affecting the nighttime reflection height (~80 km) of subionospheric VLF signals. However, it has also been suggested that these events may be due to secondary ionization regions produced by electromagnetic impulses radiated by lightning and associated with optical discharges known as Elves [*Dowden et al.,* 1996a] or ionization columns associated with Sprites [*Dowden et al.,* 1996b], so that the physical nature of ionospheric disturbances involved in these events remains in dispute [*Inan et al.,* 1996b].

Regardless of the underlying physical nature of early/fast disturbances, their sensitive dependence on the *D* region conductivity profile produces a characteristic amplitude and/or phase perturbation signature that is unambiguously identifiable. Figure 1a shows a cross section of the earth-ionosphere waveguide path, with a lightning-induced ionospheric disturbance between the transmitter and receiver. In general the disturbance can be off the Great Circle Path (GCP) between the transmitter and receiver as shown in Figure 1b. Figure 1c shows a three-minute time period illustrating rapid signal amplitude changes followed by exponential-like recoveries to ambient signal levels. A typical early/fast event onset (Figure 1d) is simultaneous (within one 20 ms sample) with the causative sferic (Figure 1e). Early/fast VLF events are observed only when the causative lightning discharge occurs within 50 km of the GCP from the transmitter to receiver, consistent with a disturbed region having a lateral extent of ~100 to 150 km [*Inan et al.,* 1996c]. In this paper, we directly measure the VLF diffraction patterns of ionospheric disturbances for individual early/fast events. Our results indicate that VLF early/fast disturbances have horizontal extents of 90 ± 30 km and exhibit forward scattering patterns with 15 dB beamwidths of <~30°.

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Description of the Experiment

Data analyzed here were collected during the summer of 1998 by a set of nine VLF receivers with ~65 km spacing and aligned in a north-south orientation (Figure 2b) constituting the Holographic Array for Ionospheric Lightning research (HAIL) system. The HAIL array provides sufficient resolution [*Chen et al.,* 1996] for the measurement of lightning-associated ionospheric disturbances and also allows coverage of a large part of the midwestern thunderstorm centers by continuously observing VLF transmitter signals from Washington, Maine, Hawaii, and Puerto Rico.

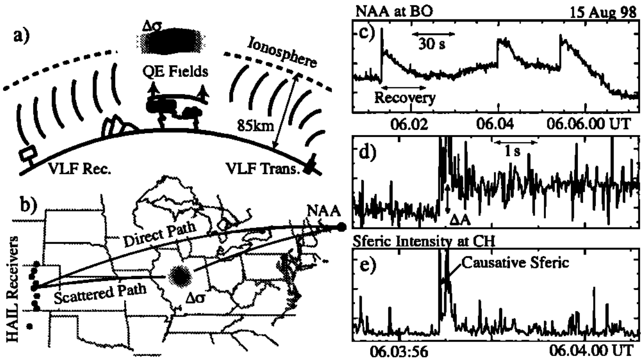

Figure 1. The left two panels schematically illustrate the scale of the thunderstorm/ionosphere interaction region in an early/fast VLF event. In panel (c), a three minute record of the amplitude of the NAA transmitter signal received at the Boulder site (BO) shows three typical early/fast events which recover to pre-event levels in 30 s. The middle event is expanded in panel (d) and plotted together with broadband sferic intensity (e) to show the simultaneity of the causative sferic with the event onset.

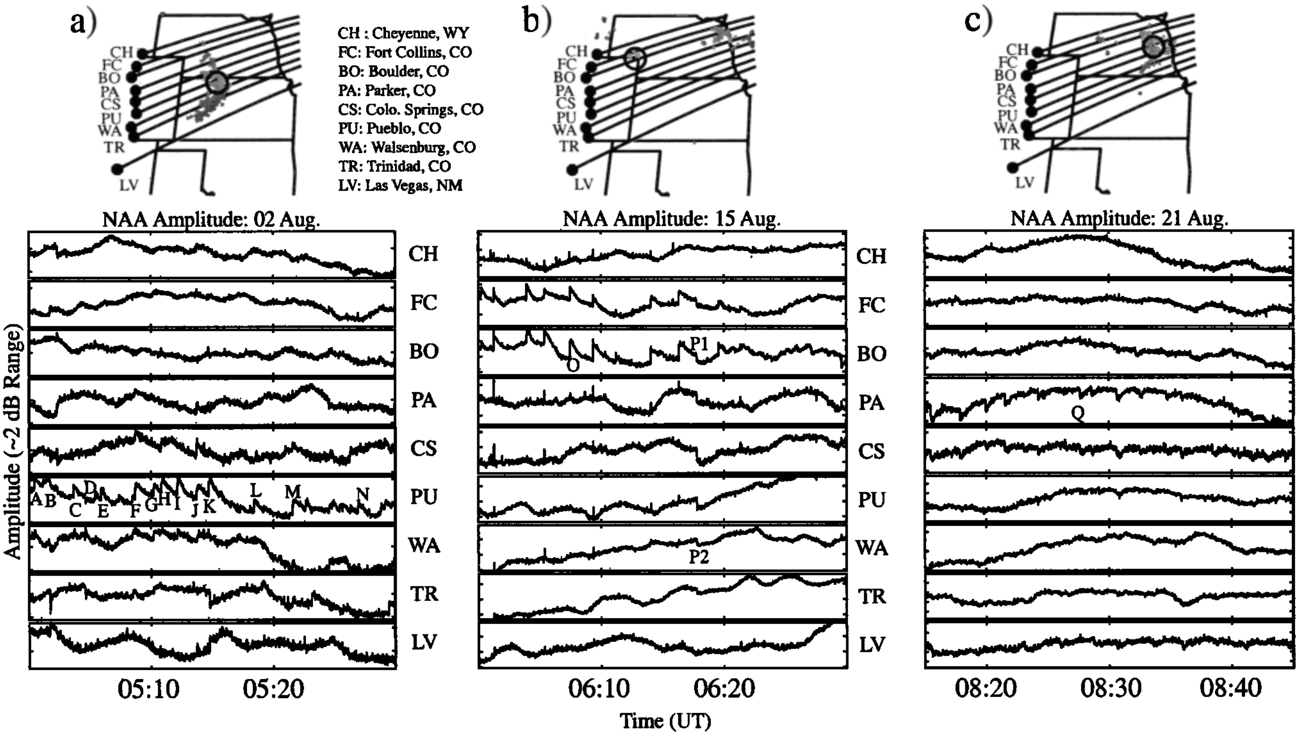

Figure 2. Early/fast event sequences measured at HAIL sites on three days in August 1998. Although not shown, phase was also measured and shows similar perturbations. Lightning locations are plotted above, together with NAA–HAIL GCPs, corresponding to the time period of the amplitude record for each case.

In this paper, we use data on the measured amplitude/phase of the signal from the NAA transmitter in Cutler, Maine, radiating ~1.2 MW at 24.0 kHz. At each receiver the wideband signal detected by a 1.7 x 1.7 m^2 magnetic loop antenna is bandpass filtered to a range of 9 - 45 kHz and sampled at 100 kHz with triggers provided by GPS timing. This broadband signal is subsequently rectified, averaged, and recorded with 20 ms resolution to allow the unambiguous detection of occurrence times and durations of sferics radiated by lightning discharges. The receivers digitally down-convert the individual VLF transmitter signals and record the demodulated amplitude and phase with 20 ms and 100 ms time resolution, respectively, typically during 01:00 to 13:00 UT when most of the observed VLF paths are in the nighttime sector. Typical nighttime noise conditions result in resolutions of 0.1 dB in amplitude and 0.5° in phase. GPS receivers provide absolute timing accuracy to a greater degree than the sample rate, thereby providing a stable reference for the phase demodulation.

Data from the National Lightning Detection Network (NLDN) provides the time, location, and peak current of most CG lightning discharges [*Orville,* 1994], and is used in this work to locate particular discharges which were coincident (<20 ms) with the onset of the early/fast events observed. Temporal alignment of the NLDN data with the HAIL sferic channel data provides clear identification of VLF events as being early/fast, or Lightning Induced Electron Precipitation (LEP) events which are characterized by a several hundred millisecond onset delay [*Inan et al.*, 1993].

Experimental Results

On seventeen days in August 1998, HAIL data clearly show early/fast event activity on the NAA signal at one or more of the HAIL sites. Of these seventeen, ten days have records during which repeated (>10 in one hour) and clearly identifiable (>0.5 dB) early/fast events occur. Three half-hour records were selected on the basis of the event magnitudes decreasing to negligible levels at the northern and southern-most receivers and varied proximity of the causative lightning (200, 400, and 700 km) to the HAIL array. For a description of the occurrence statistics of early/fast VLF events observed with the HAIL array, the reader is referred to *Sampath et al.* [1999].

The early/fast nature of the events is ascertained by high resolution analysis, as exemplified in Figures 1d and 1e. In all of these events, the causative discharge as identified in NLDN data is located nearest the particular HAIL paths with the largest signal perturbations. In each of the top panels of Figure 2, the locations of lightning discharges (which occurred during the time period corresponding to the amplitude record shown) are indicated. The region of lightning activity containing the time-correlated causative discharges is circled, and in each case these regions encompass the perturbed GCPs. To determine the scattering pattern beamwidth for the cases discussed below, amplitude and phase changes from an event are converted into scattered field magnitudes by vector addition of the unperturbed and scattered field vectors (see *Poulsen et al.* [1993a]) and are plotted as a function of azimuth from the disturbance location.

CASE 1: 2 AUGUST 1998: Lightning activity from 05:00 to 05:30 UT was situated about 500 km to the east of the HAIL array and spanned most of the NAA–HAIL GCPs. Fourteen early/fast events identified as A through N in Figure 2a were observed at PU, with some also seen at the adjacent sites. The causative lightning discharges all lie within 50 km of the NAA–PU path. The average event amplitude was ~0.5 dB and the average event phase (not shown) was

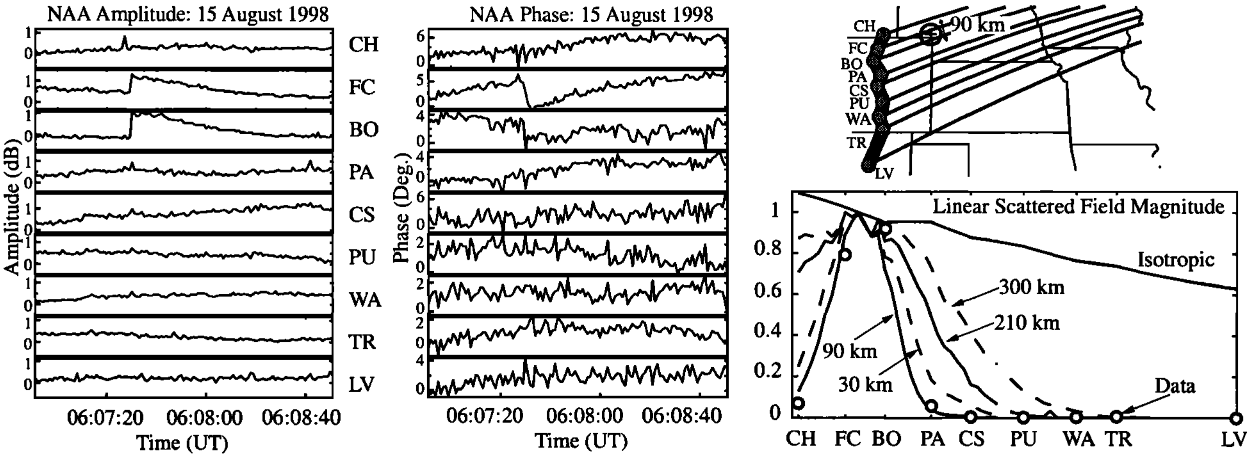

Figure 3. Measured and modeled disturbances along the HAIL array for event O. Amplitude and phase plots are shown as well as a map with the causative lightning location. The magnitude of the scattered field changes measured along the HAIL array are shown as circles in the lower right hand plot, with modeled scattering patterns for ionospheric disturbances of several different extents. A predicted scattering pattern from an isotropic source is also shown for reference.

~1°. The scattering pattern of the ionospheric disturbance had a 15 dB beamwidth with an 18° angular width. Other events which appear to occur simultaneously, such as B and K, are in fact distinct events with onsets separated by several seconds, and are produced by discharges at different locations.

CASE 2: 15 AUGUST 1998: Figure 2b shows data from 06:00 to 06:30 UT. While there was lightning activity along HAIL paths in Nebraska, the events shown originated from lightning located near the north-east corner of Colorado within the circled region. Event O at 06:07:25 UT shown in Figure 2b and with high resolution in Figure 3 was typical of the sequence and perturbed the NAA–FC and NAA–BO signals with a 15 dB beamwidth with an angular width of <~30°. Although event P appears to be observed at 7 HAIL receivers, it is actually two separate events, P1 and P2.

CASE 3: 21 AUGUST 1998: The lightning activity in Figure 2c from 08:15 to 08:45 UT was approximately 700 km from the array in eastern Nebraska. Event Q at 08:27:40 UT in Figure 2c was typical of the sequence and perturbed only NAA–PA and NAA–CS. For this event, the scattered signal projected a 15 dB beamwidth of 20°.

An interesting question arises from the spatial distribution of lightning activity during this period. With positive and negative lightning discharges occurring over regions covering most of the central HAIL paths, early/fast events might be expected to occur over many of these paths. The peak current of the causative discharges associated with early/fast events ranged from −24 to −64 kA and from +18 to +52 kA. During this period, there were 10 discharges with peak current magnitudes greater than 64 kA that did not produced a VLF event, despite being located on a HAIL GCP. This observation suggests that characteristics of the lightning discharges other than the peak electric field as recorded by NLDN may be a more important measure of the effectiveness of the lightning-ionosphere interaction, consistent with previous findings [*Inan et al.*, 1993].

VLF Diffraction Pattern

The VLF early/fast magnitude of the amplitude and phase changes observed are determined by the directional scattering properties of the associated ionospheric disturbance, dependent primarily on its lateral extent. In this section, we quantitatively interpret the observed amplitude/phase changes in terms of the scattering pattern of the associated disturbance using a three-dimensional multiple-mode waveguide model of VLF propagation and scattering. This model accounts for the presence of localized *D* region disturbances using realistic parameters for the ground conductivity, the earth's magnetic field, and the altitude profile of nighttime ionospheric conductivity. Although the physical nature and the conductivity profile of ionospheric disturbances that produce early/fast VLF events remains in dispute [*Inan et al.*, 1996b; *Dowden et al.*, 1996b], the VLF scattering pattern of the disturbance is largely determined by its lateral extent [*Poulsen et al.*, 1993b; *Chen et al.*, 1996]. For our purposes, we use a conductivity profile with a 20% enhancement at 80 km, assumed to fall off as a Gaussian function of radial distance (i.e., as $e^{-(r/a)^2}$, where a is the disturbance radius). The assumption that the scattering pattern does not depend sensitively on the altitude profile is only valid if the unperturbed (ambient) signal does not exhibit a deep null located at the receivers. Both our measurements and our model calculations indicate that this is a good assumption for the cases studied.

The linear projected width of the main beam of the scattering pattern along the HAIL array is determined by the transmitter and disturbance locations, and the horizontal extent of the ionospheric disturbance. As discussed in *Chen et al.* [1996], two limiting cases of disturbance widths can cause this projected linear width to be large. For narrow disturbance widths (< 50 km), the angular width of the scattering pattern increases with decreasing disturbance size diameter, becoming nearly isotropic for disturbances less than a wavelength (~15 km) in diameter (although such isotropic

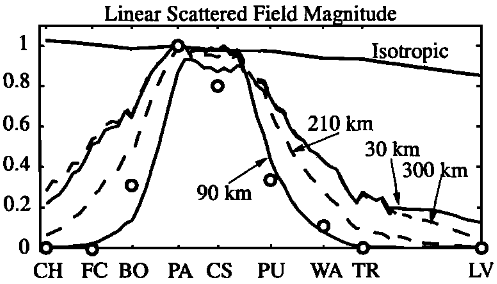

Figure 4. Measured and modeled disturbances along the HAIL array for event Q.

radiation scatters much less energy to a given receiver, making event detection less likely). At the other extreme, for relatively large disturbances (> 500 km) the projection of the scattering pattern along the HAIL array is large since the disturbance overlaps more of the VLF paths. For any given disturbance location, an ionospheric disturbance width thus exists at which the angular width of the scattering pattern is minimized, producing a beam highly focused in the forward direction.

Scattering patterns for Event O are displayed in Figure 3 for disturbances of different gaussian horizontal extents. The patterns have been normalized so that the beamwidths can be accurately compared, and normalized scattered field changes from the HAIL receivers are shown superimposed. The 90 km wide disturbance has a narrow main beam which fits the data more closely than the wide beam patterns associated with the larger (and smaller) disturbance widths.

Modeled radiation patterns for event Q, along with the HAIL normalized scattering patterns, are shown in Figure 4. For brevity, the high-resolution amplitude and phase data are not shown. The causative CG for this case was located in the region circled in Figure 2c, 700 km from PA (along the NAA–PA path). Although the causative lightning in this example was quite distant compared to the August 15 case, the derived angular beamwidth is remarkably similar and the data points remain consistent with the 90 km disturbance curve. The slight lateral shift of the data points with respect to the modeled curves may be due to the difference between the lightning location and the center of the ionospheric disturbance.

Discussion and Summary

Three typical examples of VLF early/fast event sequences are found to exhibit narrow scattering patterns in the forward direction. Available evidence indicates that the nature of early/fast disturbances can be summarized as:

- The ionospheric disturbance lies overhead (±50km) the causative lightning discharge.
- Lightning peak current does not appear to be directly related to the occurrence or magnitude of a VLF early/fast event.
- The ionospheric region within which the conductivity changes occur is 90±30 km across (i.e., about six wavelengths at the 24.0 kHz NAA carrier frequency).

It should be noted here that other types of VLF events which do not fit the early/fast event definition (i.e., rapid onset coincident with causative lightning or sferic followed by a 10-100 s recovery) have been reported by *Inan et al.* [1996c] and *Dowden et al.* [1996a]. It has also been suggested that columnar groupings of ionization, such as those found in sprites, may create isotropic radiation patterns *Dowden et al.* [1996b]. Preliminary examination of the data from the summers of 1997 and 1998 has not revealed a single event that both fits the early/fast prototype [*Inan et al.,* 1996c] and exhibits a broad scattering pattern.

Electrodynamic coupling of energy between thunderstorms and the ionosphere occurs quite regularly as evidenced by the high occurrence rates of early/fast VLF events [*Sampath et al.,* 1999]. The long term global effect of these frequent and large scale ionospheric disturbances is yet to be evaluated and may prove to be significantly larger than the energy processes involved in optical phenomena such as sprites and elves. The result reported here quantifies the lateral extent of the affected ionospheric regions to be 90±30 km.

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