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Recovery signatures and occurrence properties of lightning-associated subionospheric VLF perturbations

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Abstract. Subionospheric VLF signatures of lightning-associated ionospheric disturbances observed at multiple sites in the central United States are used to investigate the occurrence properties and recovery signatures of characteristic perturbations exhibiting rapid onset followed by slow recoveries. The two different types of events, so-called early/fast and lightning-induced electron precipitation (LEP) [*Inan et al.*, 1996a], are distinguished by the lack of presence of a few hundred millisecond delay between VLF event onsets and causative lightning discharges, respectively. Analysis of recovery signatures of the two types of events indicate subtle but distinct differences in the recovery rates. A majority of early/fast events were found to exhibit a more rapid initial recovery to preevent levels during the first 20 s of recovery, when compared to LEP events. This experimental evidence indicates that the physical nature of the ionospheric disturbance involved in the two classes of events are different, consistent with a recent theoretical suggestion [*Inan et al.*, 1996c]. The occurrence properties of early/fast events observed by the Holographic Array for Ionospheric Lighting (HAIL) receivers indicate that ionospheric disturbances act primarily as forward scatterers.

1. Introduction

In recent years, experimental evidence of ionospheric disturbances produced directly by lightning discharges have been observed in the form of "early/fast" subionospheric VLF perturbations. The onsets of these events occur within 20 ms (i.e., early) of the associated lightning discharges and typically are rather rapid (i.e., fast) with onset durations of less than 100 ms [e.g., *Inan et al.*, 1988, 1993]. Heating and ionization of the lower ionosphere by electromagnetic impulses (EMPs) and by quasi electrostatic (QE) fields produced by lightning discharges were initially put forth [*Inan et al.*, 1996b] as possible causes of such events, although more recently they have been suggested to be due to quiescent heating of lower ionosphere by thundercloud fields [*Inan et al.*, 1996c].

Another class of VLF signatures due to lightning-induced electron precipitation (LEP) has long been observed [e.g., *Burgess and Inan*, 1993, and references therein] and are often referred to as "Trimpi" events, although we refer to them here as "LEP events" to clearly distinguish them from early/fast events. These events are produced in the following manner: VLF electromagnetic impulses generated by lightning couple into the magnetosphere in the form of whistler waves, where they undergo cyclotron resonance with the trapped electrons. Some of the electrons are pitch angle scattered into the loss cone and precipitate into the ionosphere. This produces secondary ionization in the lower ionosphere that causes VLF perturbations.

An illustration of the relevant physical phenomena and the resulting ionospheric disturbances described above, the measurement of these disturbances by a subionospheric VLF signal, and an example of the two types of signatures (early/fast and LEP) are provided in Figure 1. The LEP and early/fast events are shown to be distinguishable based on the time delay between radio atmospheric (sferic) occurrence and the event onset [*Inan et al.*, 1993, 1996]. (A sferic is an impulsive VLF electromagnetic signal launched into the Earth-ionosphere waveguide by individual lightning discharges.) From Figure 1, it can be seen that LEP events are readily recognized through a distinct delay (a few 100 ms to up to 1 s) between the causative sferic and event onset [*Inan et al., 1993*]. In contrast, early/fast events are time-aligned (i.e., within data resolution of 20 ms) with sferic occurrence.

In this paper, we document the recovery signatures and occurrence properties of lightning-induced subionospheric VLF perturbations recorded by the Holographic Array for Ionospheric Lightning (HAIL) array during the summer of 1997. At this time, the HAIL system consisted of five VLF receivers at 170 km spacing in Colorado and New Mexico, whose measurements constitute VLF strip holograms [*Chen et al., 1996*]. Occurrence properties of subionospheric VLF events were studied previously [*Leyser et al.*, 1984; *Inan et al.*, 1990; *Wolf and Inan,* 1990], but no attempt was made to distinguish the recovery signatures of early/fast and LEP

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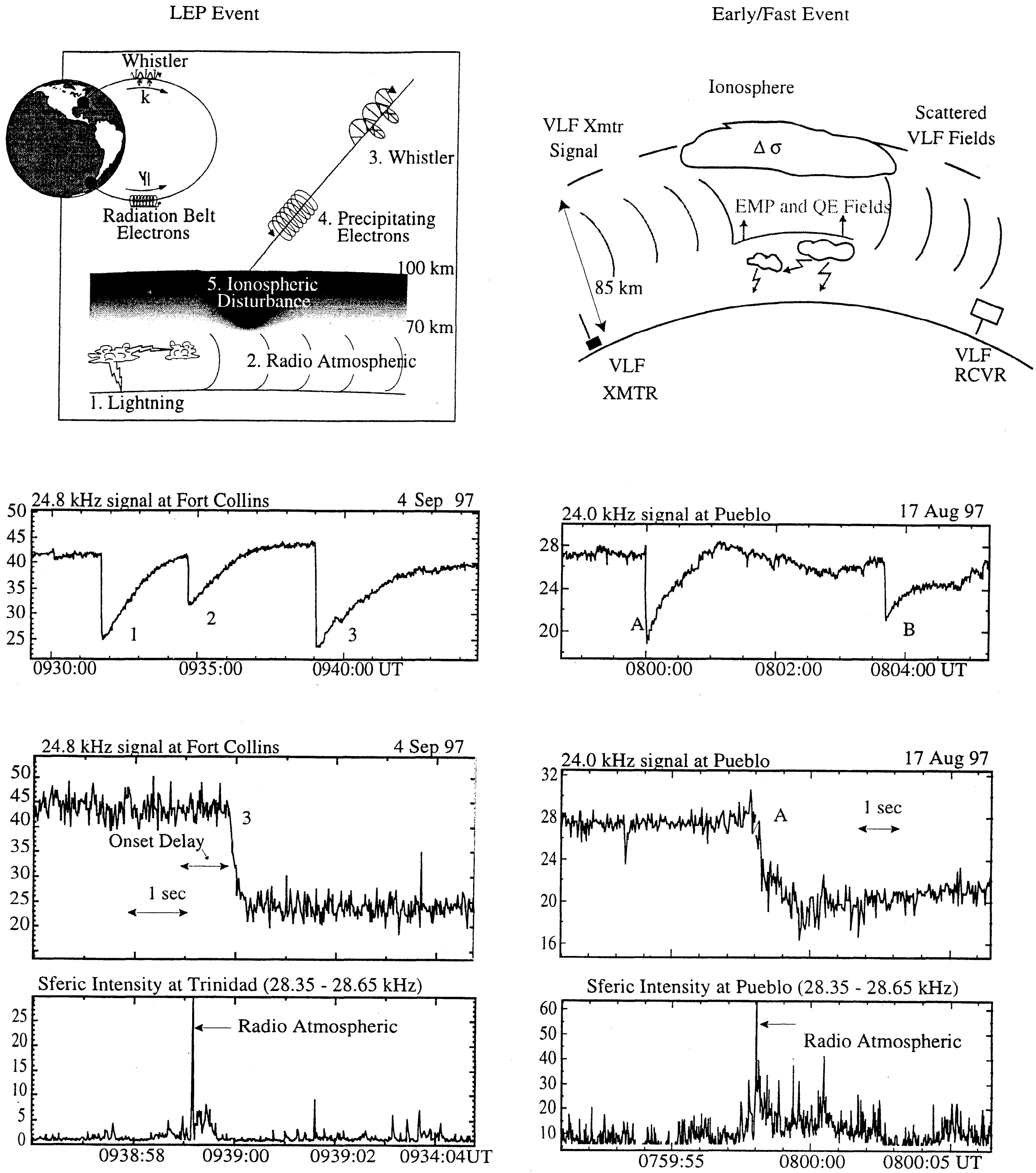

Figure 1. (top) The physical processes associated with lightning-induced early/fast and LEP event signatures are shown. (bottom) An example of (left) LEP event and (right) early/fast event with the associated sferics, as recorded by HAIL. Early/fast events are characterized by an event-onset within 20 ms after the associated sferic. LEP event onset occurs after a characteristic $\sim$ 1 s delay following the sferic occurrence.

events. We undertake a quantitative comparison of recovery signatures of early/fast and LEP events to shed more light on the physical nature of the ionospheric disturbances involved in the two classes of events.

The physical nature of ionospheric disturbances involved in early/fast events and whether they act as forward or isotropic scatterers has been a topic of debate in recent years [*Inan et al.,* 1996d; *Dowden et al.,*

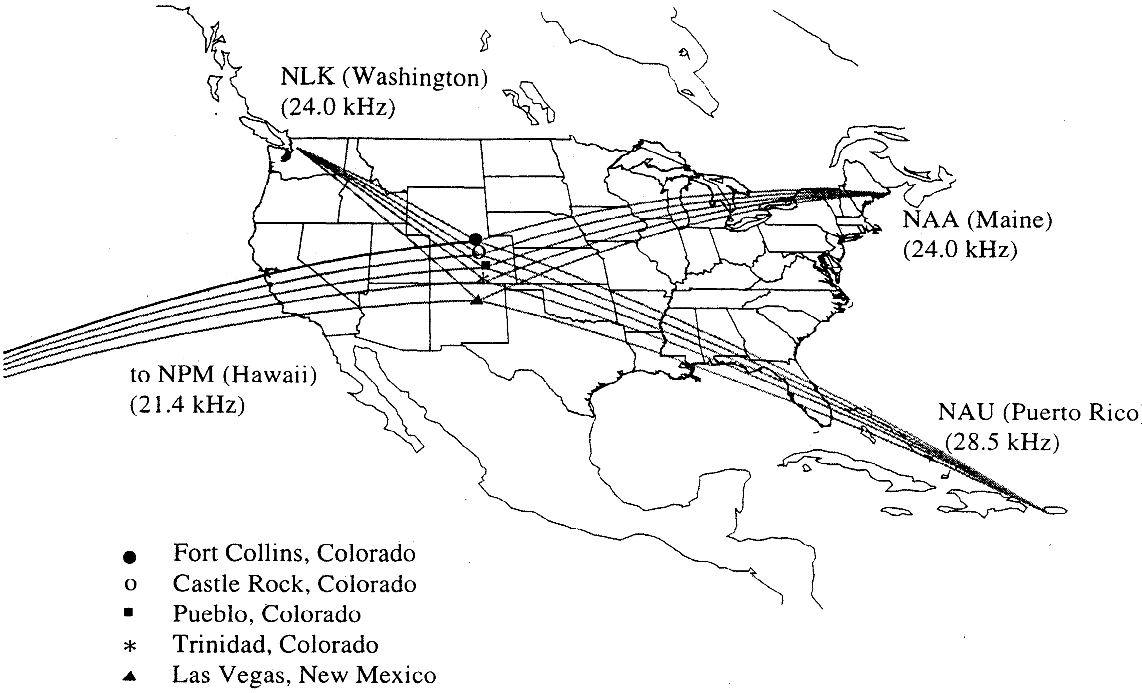

Figure 2. Map showing the VLF HAIL receiver locations in New Mexico and Colorado. For the summer of 1997, the HAIL receivers tracked the 24.0-KHz NAA transmitter from Maine. The lines connecting the transmitters and the receivers indicate the great circle paths.

1996; *Johnson et al.,* 1999]. In this paper, a quantitative study of occurrence statistics of early/fast events is undertaken which provides further insight on the scattering properties of the associated ionospheric disturbances.

2. Description of Experiment and Measurements

The VLF data analyzed in this study were acquired by the five HAIL receivers shown in Figure 2, during the summer of 1997. From north to south, the receiver locations are Fort Collins, Castle Rock, Pueblo, Trinidad (all in Colorado), and Las Vegas (New Mexico). The HAIL receivers measured amplitude and phase from three VLF transmitters located in Maine, Hawaii, and Washington. For this study, only events seen on the NAA signal as observed at HAIL sites were analyzed, with the associated great circle paths covering the midwestern thunderstorm activity. Data were typically acquired nightly during 0100 -1300 UT. The VLF receivers were synchronized to GPS to provide a stable time and phase reference. The data set consisted of high-resolution digital recordings (50-Hz sampling rate for VLF amplitude and 10-Hz rate for VLF phase) on all the transmitter signals monitored.

For the purposes of this paper, we define a VLF event to be a VLF amplitude change greater than 0.3 dB and/or phase change greater than 3 deg, lasting for longer than 10 s, typically (but not always) followed by recovery to preevent levels. The detection threshold is determined by the background VLF radio atmospheric noise levels. In most cases, the event does not return to preevent levels due to longer term background trends, possibly driven by midlatitude precipitation or other nighttime ionospheric conductivity variations. Hence, while measuring the recovery times and recovery patterns, the signals were visually extrapolated to preevent or would have been (in the absence of event) levels. For consistency, all recovery time and recovery pattern measurements, as well as amplitude and phase measurements, were visually made on time-averaged (over 0.64 s) data, displayed with consistent scale.

The National Lightning Detection Network (NLDN) uses a nationwide network of lightning sensors incorporating direction finding or time of arrival techniques to locate individual cloud-to-ground (CG) flashes and to record the first stroke peak current, polarity and number of strokes [*Orville,* 1991]. The low time resolution (1 s) NLDN data were used to determine the exact location of individual lightning flashes. However, the time resolution of the NLDN data in hand was not sufficient to differentiate between early/fast and LEP event onset delays after lightning flash occurrence. Hence early/fast and LEP event identification was made by time aligning the VLF event with the associated sferic recorded with high time resolution in our own data, consistent with previous data analysis techniques [e.g., *Inan et al.,* 1993, 1996a]. Early/fast event onsets were time aligned (i.e., within data resolution of 20 ms) with sferics, while

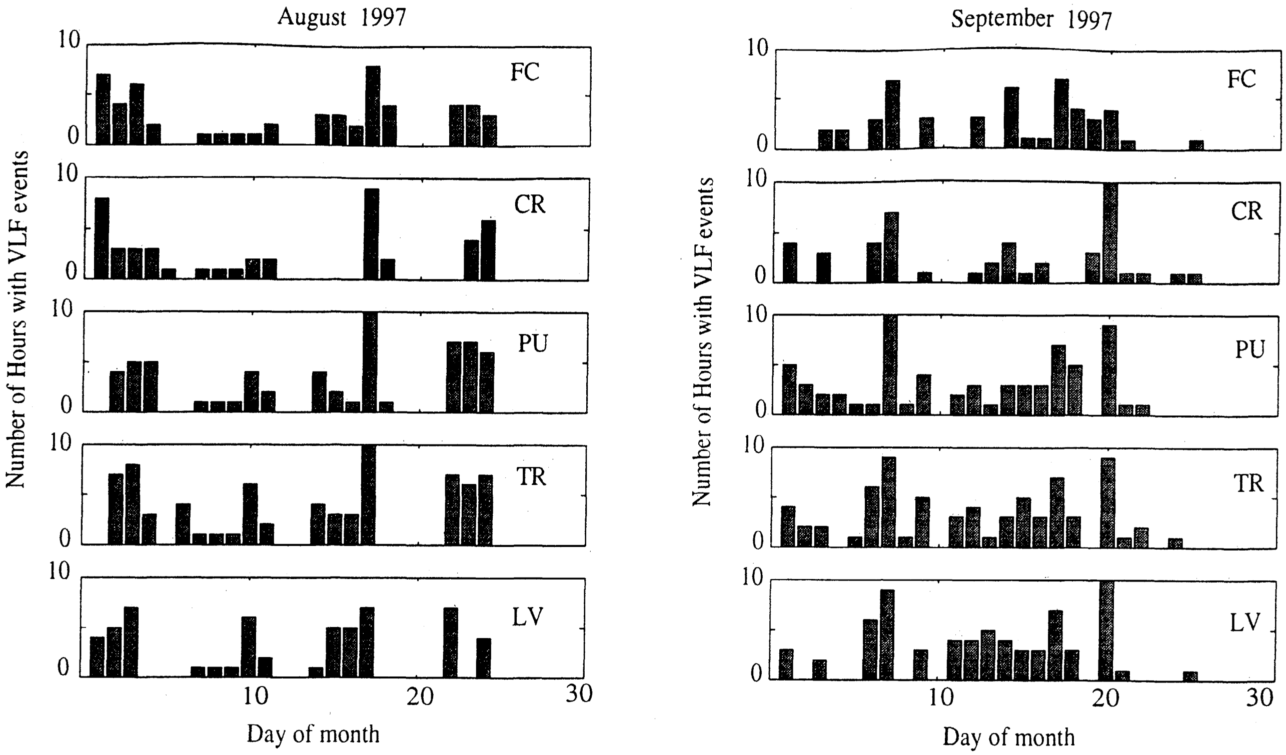

Figure 3. This plot shows the daily variation of the duration of VLF event occurrence during the August and September 1997. We selected 10 good days (August 2,3,17,and 24 and September 4,6,7,9,17, and 20) for detailed analysis. During these days, the HAIL receivers recorded lightning-associated subionospheric VLF perturbation for several hours.

the LEP event onsets had a characteristic delay of 300 ms to 1 s following the corresponding sferic occurrence. (See Figure 1 for an example recording of LEP and early/fast event with sferic occurrence.) Sferics were recorded as impulses in the VLF frequency band at 28.5 kHz, which was originally designed to detect the amplitude of a VLF transmitter, but which in the absence of the transmitter signal (the NAU transmitter changed its operating frequency) provided an excellent measure of sferic energy. In some (relatively few) cases, noise levels in the data precluded the identification of the VLF event type on the basis of onset delays; such cases were excluded from data analysis.

The data set obtained during the summer of 1997 consist of a large number of VLF events. The daily variation of the duration of event occurrence during the 2 months of August and September 1997 is shown in Figure 3. Detailed analysis of each event from this enormous data set in order to determine whether it was an early/fast or LEP event was deemed prohibitive. For our study, we selected 10 active days (August 2,3,17, and 24 and September 4,6,7,9,17, and 20), constituting a set of events which exhibited the range of characteristics of the complete data set and spanning the 2-month period. We note that this selection was made solely on the basis of statistics observed on Figure 3, which shows that during these 10 days, the HAIL receivers recorded many VLF events due to lightning-induced ionospheric disturbances, over prolonged periods of time.

3. Recovery Signatures: LEP Versus Early/Fast Events

The observed 10-100 s of VLF signatures of LEP events have been quantitatively interpreted in terms of recombination and attachment processes in the nighttime D region, by means of which the enhanced secondary ionization produced by LEP bursts decays back to ambient levels [*Glukhov et al.*, 1992; *Pasko and Inan*, 1994]. Until recently, the observed recovery times of early/fast events were also attributed to similar return to ambient levels of enhanced secondary ionization [*Inan et al.*, 1996b]. However, in the context of the new mechanism recently suggested by *Inan et al.* [1996c], involving the quiescent heating of the lower ionosphere by thundercloud fields, early/fast events are not due to secondary ionization enhancements and the observed recovery is instead attributed to the reestablishment of thundercloud charge and associated electric fields leading to changes in heating levels of ambient ionospheric electrons. Thus a quantitative comparison of the recovery signatures of these two different types of events, namely, LEP and early/fast, is now in order and is undertaken in this section.

3.1. Data Analysis

For an accurate measurement of recovery patterns of VLF events recorded by HAIL receivers, we analyzed the VLF data in the following manner. We started by

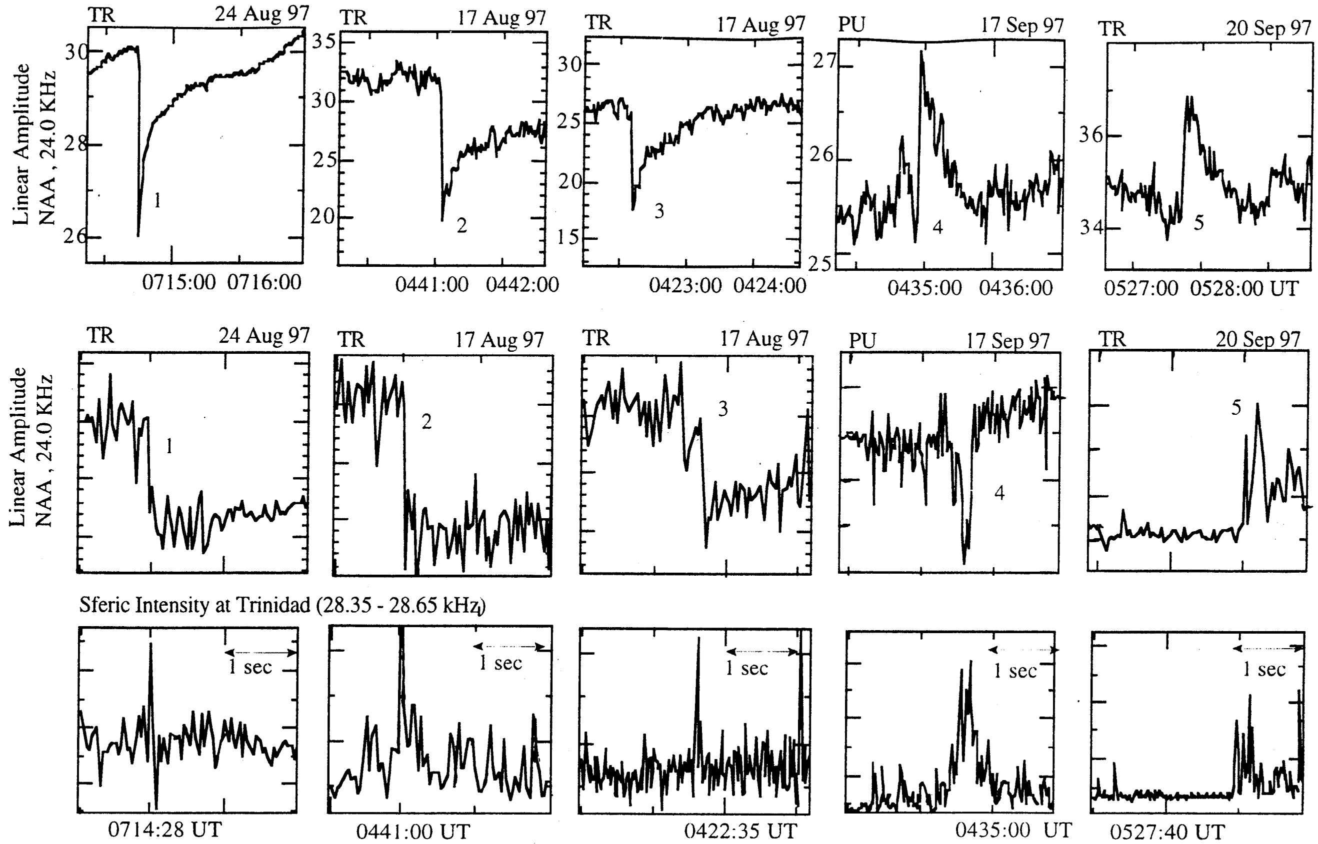

Figure 4. (Top) Typical early/fast events (averaged over 0.64 s) used for recovery pattern analysis. (middle) The corresponding high resolution versions of these events. (bottom) The associated sferics.

randomly selecting from the original data set, 48 LEP events and 74 early/fast events, that had an amplitude change of greater than 0.5 dB. It should be noted that these events were not selected from a continuous period of time in one single day but were randomly selected from the 10 days referred to in the previous section.

The 48 LEP and 74 early/fast events selected had well-defined exponential recovery patterns. Events with unusual recovery patterns (such as a step-like recovery or a recovery time less than 10 s) were very rare in occurrence and were excluded from analysis. Figure 4 and Figure 5 provide examples of typical early/fast and LEP events, with associated sferics, that were used for recovery pattern measurement. It should be noted that there is an $\sim$ 1 s delay between LEP event onset and sferic occurrence. In contrast, early/fast event onset occur within 20 ms of sferic occurrence. For each of the selected events, the amplitude levels at times 0, 5, 10, 20, 60, 120, 180, 240, and 300 s were measured, where $t = 0$ corresponds to the time of event onset. The amplitude values at these sample points were used to generate a plot of the recovery pattern of the VLF event. The events were normalized (to the initial event amplitude) and time averaged over 0.64 s to maintain consistency in data analysis. Samples were taken more often immediately after the event onset in order to capture the typically more rapid changes in amplitude during initial part of the recovery. Examples of recovery patterns of VLF events so generated are shown in Figure 6a. It should be noted that in order to avoid bias in data, multiple observations of the same VLF event recorded at different receiver locations were not included. Figure 6b displays the same data in a somewhat different format, showing the percentage of events which recovered back to a given fraction of the normalized amplitude change at different time instances of recovery. Figure 6c shows the statistically averaged early/fast and LEP event signatures and Figure 6d shows the histogram of recovery times to ambient levels.

3.2. Results

Results of our analysis show the subtle but distinct differences between recovery patterns of early/fast and LEP events. The normalized amplitude distribution of early/fast and LEP events at different time snapshots (during recovery), as illustrated in Figure 6b, clearly exhibits the differences between the recoveries.

A majority of early/fast events exhibit a rapid initial recovery during the first 20 s following the onset, when compared to LEP events. The latter exhibits a much slower recovery to preevent levels during this same time period. For example, at time 5 s, less than 10% of LEP events had normalized amplitudes less than 0.8 (indicating slower recovery), while more than 80% of

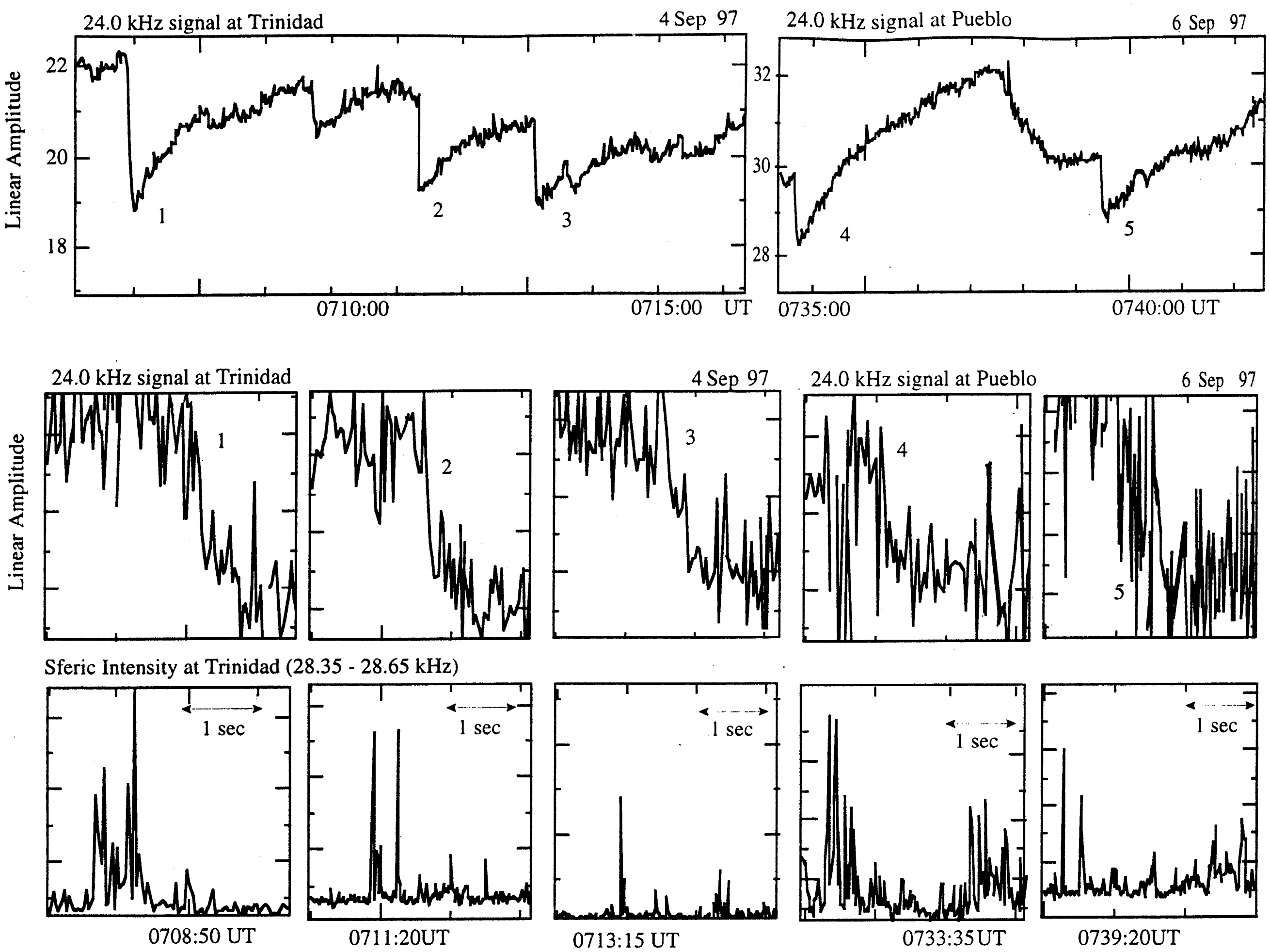

Figure 5. (Top) Typical LEP events (averaged over 0.64 s) used for recovery pattern analysis. (middle) The corresponding high resolution versions of these events. (bottom) The associated sferics. Note the characteristic onset delay (100ms to 1 s) following the sferic.

early/fast events had normalized amplitudes less than 0.8 (indicating rapid recovery). Similarly, at time 20 s, more than 90% of LEP events and fewer than 15% of early/fast events had normalized amplitudes greater than 0.5.

About 60 s after the onset (when the events are in the later stages of recovery), the amplitude distributions of LEP and early/fast events appear more similar. The time duration (60 s) after which the recovery rates for the two types of VLF signatures appear similar is dependent on the total recovery time to preevent levels. From Figure 6 c, the total recovery time for LEP events is roughly between 120 and 180 s while that for the early/fast events is between 60 and 240 s.

For only a small fraction of events analyzed, the LEP and early/fast recovery patterns were similar during the entire period of recovery.

To better illustrate this subtle difference in the recovery patterns, we have plotted the statistically averaged recovery signatures of early/fast and LEP events in Figure 6d. It can be seen that on average, early/fast events exhibit a rapid initial recovery during the first 20 s following the onset, when compared to LEP events.

To determine whether the characteristics of early/fast recovery patterns analyzed above were dependent on the particular data set chosen, we analyzed 34 successive early/fast events from August 17, and 22 successive early/fast events from August 3. These events were recorded by the receiver located in Trinidad and showed similar characteristics to the ones observed from the original set of 74 early/fast events.

The difference in recovery patterns between the two types of events in the first 20 s of recovery indicates that lightning-induced ionospheric disturbances associated with early/fast and LEP events may have different physical mechanisms as their root cause. The experimental evidence of a distinct physical nature of the ionospheric disturbance is consistent with the recent theoretical suggestions [*Inan et al.*, 1996c] which attributes the recovery of early/fa-st events to the reestablishment of thundercloud charge immediately after a lightning discharge, a process fundamentally different than the chemical recovery of enhanced secondary ionization.

The recovery pattern of LEP events has been attributed to secondary ionization produced by lightning-induced precipitation of radiation belt electrons [e.g.,

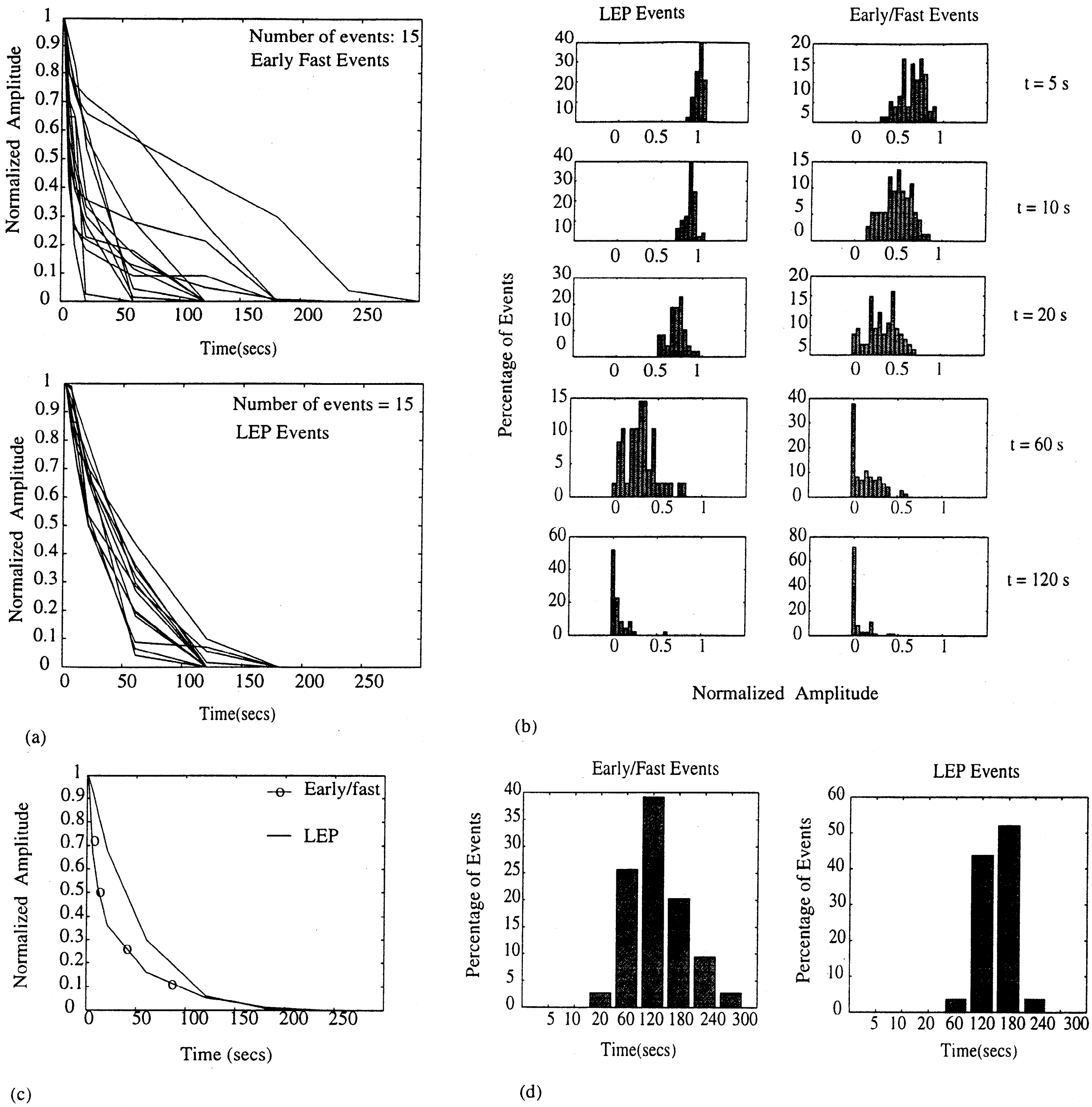

Figure 6. Early/fast events exhibit a faster rate of recovery to preevent levels during the first 20 s, when compared to LEP events. (a) Example recovery patterns measured from the data set. (b) Histogram of early/fast and LEP event amplitudes during the various stages of recovery. (d) Statistically averaged recovery pattern of LEP and early/fast events. (c) Comparison of recovery times of early/fast and LEP events to preevent levels.

Pasko and Inan, 1994 and references therein]. Since a small fraction of early/fast events have recovery patterns similar to LEP events, it is possible that a subset of early/fast events are caused by secondary ionization produced by lightning EMPs [*Inan et al.,* 1996b], or strong quasi-electrostatic fields producing sprites [*Inan et al.,* 1995; *Pasko et al.,* 1994].

4. Occurrence Properties of Early/Fast Events

The physical nature of ionospheric disturbances involved in early/fast events and whether they act as forward or isotropic scatterers, has been a topic of debate in recent years. According to *Poulsen et al.* [1993b], scattering from typical ionospheric disturbances in LEP events is confined to within ±20° of the forward direction of VLF signal path, a fact also confirmed with experimental work [*Lev-tov et al.,* 1996]. Experimental work on early/fast events indicates that the ionospheric disturbances involved in these events act as forward scatterers with events preferentially occurring on paths which are within ±50 km of the causative lightning [*Inan et al.,* 1993; 1996a; *Johnson et al.,* 1999], that is inconsistent with the hypothesis of *Dowden et*

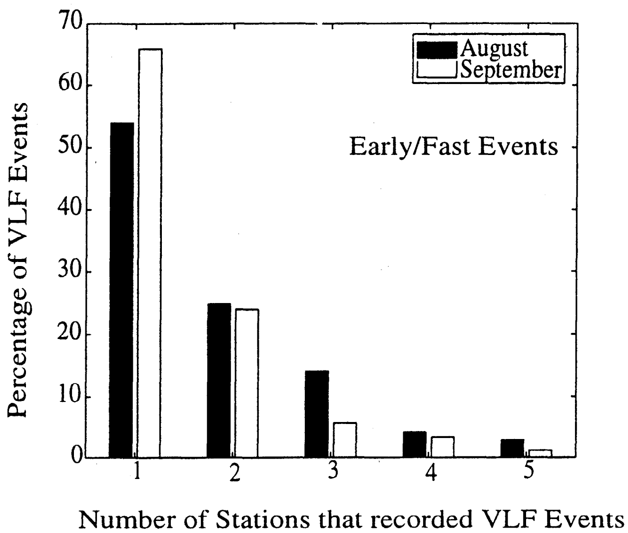

Figure 7. Spatial distribution of VLF events recorded by adjacent stations. It can be seen that on average the same VLF event is recorded by two adjacent HAIL receivers separated by ~ 170 km. This implies that the VLF amplitude pattern width measured by HAIL receivers is ~ 240 km (170 + 35 + 35 km). The above experimental observation, when interpreted in the light of VLF diffraction pattern [*Chen et al.,* 1996], suggests that lightning-induced ionospheric disturbances act as forward scatterers.

al. [1994] that early/fast events are due to isotropic scattering of VLF waves from ionization columns of a few kilometers in lateral extent. If ionospheric disturbances were isotropic scatterers, early/fast VLF signal perturbations should be observed even when the CG lightning is far away from the perturbed signal path. The proximity requirement of CG lightning from the great circle path (for early/fast events) thus provides strong evidence against *Dowden*'s [1994] argument. A quantitative study of occurrence statistics of early/fast events as observed at multiple sites sheds further light on this property.

4.1. Data Analysis

The HAIL system consists of five receivers placed on a linear array constituting a strip hologram [*Chen et al.*, 1996]. This geometry makes it possible to use the statistics of early/fast event signatures recorded simultaneously on multiple receivers to infer the size, location, and scattering properties of the corresponding ionospheric disturbances.

Figure 7 illustrates the spatial distribution of early/fast events recorded on multiple adjacent receivers during the summer of 1997. Figure 7 was obtained as follows. Early/fast events were first identified by time aligning the VLF event with the associated sferic recorded with high time resolution, consistent with previous experimental techniques. The number of adjacent receivers which recorded the same event were noted. This procedure was repeated for all the early/fast events in the data set to yield the spatial distribution shown in Figure 7. We emphasize that our data set has an inherent time resolution of 20 ms, whereas that of *Dowden et al.* [1994] is 400 ms. The 1:20 difference in time resolution is important in establishing the simultaneity between the causative sferics and the event onsets. In our analysis, the simultaneity of occurrence (within 20 ms) of the sferic and event onset is the only means of identifying these events as "early," distinct from LEP events, in which the perturbation onset is expected to be delayed with respect to the causative sferic by ~ 300 ms. Moreover, 100% of our events are accompanied by sferics occurring within 20 ms of event onset. This is in sharp contrast to the *Dowden et al.* [1994] experiment, where the association with sferics is made on a statistical basis and only 60% of the events have associated sferics.

4.2. Results and Discussion

To interpret the results of Figure 7, it important to note the following experimentally established facts and their implications.

It is well known from past experimental data that the midwestern region of the United States is a region of high lightning activity. The HAIL receivers were positioned so that a majority of these lightning disturbances occurred at distances quite far away from the transmitter and receiver locations. This allows us to use VLF far field diffraction theory [*Chen et al.*, 1996] in interpreting results.

It has been established from past work that early/fast events are detected only when the causative lightning discharges are located within ±50 km of the great circle propagation path, a fact confirmed by prior experimental results [*Inan et al.*,1993, 1996a].

The VLF diffraction theory dictates that if the ionospheric disturbances were indeed caused by ionization columns of few kilometers in lateral extent, they would act as isotropic scatterers. This would imply that VLF events would in general be observed on many of the HAIL receivers, leading to a nearly uniform spatial distribution of VLF events recorded on all five receivers. However, Figure 7 clearly shows that the distribution of VLF events on the five stations to be far from being uniform. On the average, a VLF event is recorded only on two adjacent receivers (which are ~ 170 km apart). The average amplitude pattern width [*Chen et al.*, 1996] of VLF signatures on the HAIL array extends to ~ 240 km (170 + 35 + 35 km).

The experimentally determined ±50 km proximity requirement of CG lightning with respect to the great circle path and the experimentally determined average amplitude pattern width of ~ 240 km, when interpreted in the light of VLF diffraction pattern [*Chen et al.,* 1996], suggests that the transverse extent of the disturbance size must be much greater than few tens of kilometers. Smaller disturbance sizes (e.g., 2-3 km ionization columns), as proposed by *Dowden et al.* [1994]

are not likely since they would produce an amplitude pattern width spanning the whole length of HAIL receivers (due to isotropic scattering), which is clearly not the case.

5. Summary

We have presented an analysis of the recovery signatures and occurrence properties of lightning-associated subionospheric VLF perturbations recorded by HAIL array during the summer of 1997. The HAIL array comprises of five VLF receivers located at $\sim$ 170 km spacing in Colorado and New Mexico, constituting a strip hologram [*Chen et al.,* 1996]. For this study, only events seen on the NAA signal as observed HAIL sites were used for data analysis because the associated great circle paths cover the midwestern thunderstorm activity. The two different types of events, so-called early/fast and LEP [*Inan et al.,* 1996a] are distinguished respectively by the lack or presence of a few 100 ms delay between VLF event onsets and causative lightning discharges.

Analysis of recovery signatures of the two types of events indicate subtle but distinct differences in the recovery rates to preevent levels. A majority of early/fast events were found to exhibit a more rapid initial recovery to preevent levels during the first 20 s of recovery, when compared to LEP events. This experimental evidence indicates that the physical nature of the ionospheric disturbance involved in the two classes of events are different, consistent with a recent theoretical suggestion [*Inan et al.,* 1996c]. An analysis of occurrence properties on multiple adjacent station revealed that ionospheric disturbances act largely as forward scatterers, and not as isotropic scatters.

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