JOURNAL OF GEOPHYSICAL RESEARCH: SPACE PHYSICS, VOL. 118, 1–11, doi:10.1002/2013JA019087, 2013

# On the relationship between lightning peak current and Early VLF perturbations

M. M. Salut,[1] M. B. Cohen,[2] M. A. M. Ali,[1,3] K. L. Graf,[4] B. R. T. Cotts,[5] and Sushil Kumar[6]

Received 5 June 2013; revised 6 September 2013; accepted 17 October 2013.

[1] Lightning strokes are known to cause direct heating and ionization of the *D* region, some of which are detected via scattering of VLF transmitter signals and are known as Early VLF events. The disturbed ionosphere typically recovers in many tens of seconds. New experimental evidence is presented demonstrating that the scattering pattern and onset amplitude of Early VLF events are strongly related to both the magnitude and polarity of causative lightning peak current. Observations of Early VLF events at nine Stanford VLF receiver sites across the continental United States are combined with lightning geolocation data from the National Lightning Detection Network (NLDN). During January and March 2011, NLDN recorded 7769 intense lightning discharges with high peak currents (>100 kA) generating 1250 detected Early VLF events. We show that the size of the scattered field due to the ionospheric disturbance increases with the peak current intensity of the causative lightning discharge. The most intense peak currents of >+200 and < –250 kA disturb VLF transmitter signals as far as ∼400 km away from the lightning stroke. Early VLF event detection probability also increases rapidly with peak current intensity. On the other hand, the observed VLF amplitude change is not significantly dependent on the peak current intensity. Stroke polarity is also important, with positive strokes being ∼5 times more likely to generate Early VLF disturbances than negative strokes of the same intensity. Intense positive cloud-to-ground lightning discharges, especially when occurring over the sea, are also more likely to produce Early VLF events with long recovery (many minutes).

**Citation:** Salut, M. M., M. B. Cohen, M. A. M. Ali, K. L. Graf, B. R. T. Cotts, and S. Kumar (2013), On the relationship between lightning peak current and Early VLF perturbations, *J. Geophys. Res. Space Physics*, *118*, doi:10.1002/2013JA019087.

## 1. Introduction

[2] "Early" VLF perturbations are changes to subionospheric very low frequency (VLF, 3–30 kHz) transmitter signals generated by direct impulsive coupling between lightning and the overlying ionosphere. These perturbations occur immediately (<20 ms) after the causative lightning discharges with an onset duration ranging from <20 ms up to 2 s [*Inan et al.*, 1988; *Haldoupis et al.*, 2006] followed by a comparatively slower relaxation of ionization back to ambient signal levels typically in 10–180 s [*Sampath et al.*, 2000]. Based on the onset duration of Early VLF perturbations, these events are divided into two subcategories: "Early/Fast" and "Early/Slow" events. "Early/Fast" VLF events possess a rise time of <50 ms [*Inan et al.*, 1988]; "Early/Slow" events display a longer rise time of up to 2 s [*Haldoupis et al.*, 2006].

[3] Lightning-induced electron precipitation (LEP) events are another class of subionospheric VLF perturbations. These events are created by the small fraction of lightning energy which leaks upward through the ionosphere and couples into the magnetosphere, where it propagates in the whistler mode. This whistler energy propagates either directly along the Earth's geomagnetic field lines in ducts [e.g., *Burgess and Inan*, 1993] or obliquely in the plasmasphere [e.g., *Johnson et al.*, 1999a; *Lauben et al.*, 2001], leading to indirect VLF perturbations by inducing electron precipitation. Precipitating energetic electrons collide with neutral particles in the upper atmosphere, producing an ionospheric disturbance which can perturb a subionospherically propagating VLF signal [e.g., *Helliwell et al.*, 1973; *Johnson et al.*,

[1]Department of Electrical, Electronics and Systems Engineering, Universiti Kebangsaan Malaysia, Selangor, Malaysia.
[2]School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia, USA.
[3]Institute of Space Science, Universiti Kebangsaan Malaysia, Selangor, Malaysia.
[4]Department of Electrical Engineering, Stanford University, Stanford, California, USA.
[5]Exponent Inc., Bowie, Maryland, USA.
[6]School of Engineering and Physics, University of the South Pacific, Suva, Fiji.

Corresponding author: M. M. Salut, Department of Electrical, Electronics and Systems Engineering, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Malaysia. (ashkanpoursalut@yahoo.com)


2169-9380/13/10.1002/2013JA019087

1999a]. These indirect lightning-induced VLF perturbations are characterized by a sudden change in amplitude and/or phase of the VLF probe signal occurring ~ 0.3–2.5 s after the causative lightning discharge with an onset duration (rise time) of ~0.5–2.0 s, and followed by a recovery duration of ~10–100 s [*Sampath et al.*, 2000]. *Cotts et al.* [2011] investigated the longitudinal dependence of LEP events together with the complicating effects of atmospheric backscatter in the precipitation process. LEP events have also been detected in satellite-based observations [e.g., *Inan et al.*, 1989].

[4] The physical mechanism and scattering pattern of Early VLF events have been a key topic of debate since they were discovered. *Inan et al.* [1993] proposed that Early/Fast VLF events are the signature of heating of the lower ionospheric electrons produced by intense electromagnetic pulses (EMPs) radiated from lightning discharges. *Taranenko et al.* [1993] numerically calculated conductivity modifications due to direct effects of lightning EMP in the *D* region ionosphere, which lead to the prediction of optical emission known as elves. Elves have been observed in association with Early VLF events [*Mika et al.*, 2006; *NaitAmor et al.*, 2010; *Haldoupis et al.*, 2012].

[5] *Inan et al.* [1996a] suggested that sustained quasi-electrostatic (QE) fields above an active thundercloud can also quiescently heat the lower ionospheric electrons as well as create sprite discharges. Sprite-producing lightning has frequently been observed in correlation with Early VLF events [e.g., *Haldoupis et al.*, 2004, 2010]. *Inan et al.* [1995] demonstrated that the vast majority of the causative lightning discharges of sprite-associated VLF events occur within ±50 km from the great circle path (GCP) between transmitter and receiver, exhibiting narrow-angle scattering and in the forward direction. On the other hand, *Dowden et al.* [1994, 1996] proposed that narrow ionization columns in sprites can produce Early VLF events at wide-angle scattering even in the backward direction. Extensive studies by *Marshall et al.* [2006] showed that backscattering from sprite occurred only for a very small number of cases. Furthermore, recent 3-D full-wave electromagnetic simulation results indicated that the backscattered VLF signal, due to lightning discharges, is too small to generate discernible Early VLF perturbations [*Lehtinen et al.*, 2010]. *Johnson et al.* [1999b] used Stanford-Holographic Array for Ionospheric Lightning receiver array to directly measure the size of the ionospheric conductivity-enhanced region associated with causative lightning discharges with peak current +18 to +52 kA and from –24 to –64 kA. Their measurements showed that Early VLF disturbances possess a lateral extent of ~90±30 km and displayed forward scattering patterns. The authors also suggested that the peak current of lightning discharges does not directly relate to the occurrence of Early VLF events. *Moore et al.* [2003] showed theoretically that the scattering pattern of Early/Fast events is consistent with scattering from sprite halos.

[6] Geometry of the lightning, transmitter, and receiver is also important in determining the scattering pattern and recovery duration of Early VLF events. *NaitAmor et al.* [2010, 2013] demonstrated experimentally that the transmitter frequency, the distance from transmitter to the perturbation, the distance from perturbation to the receiver, and the scattering angle are all important factors in the observed Early VLF event characteristics.

[7] A newly classified subset of Early VLF perturbations known as long recovery events, in which the ionosphere takes up to ~30 min to recover, was first studied by *Cotts and Inan* [2007]. Recently, *Salut et al.* [2012] observed that these long-recovery Early VLF events are mostly associated with lightning activity over the sea, but could not investigate the connection to polarity and peak current of for long recovery events due to lack of data for this time period. It has also recently been observed that peak currents of oceanic lightning are considerably higher than those of land lightning [*Said et al.*, 2013]. *Haldoupis et al.* [2012] reported observation of 10 long recovery events correlated with simultaneous sprites and elves triggered by intense cloud-to-ground (CG) lightning discharges with positive polarity. *Haldoupis et al.* [2013] observed that occurrence probability of long recovery events increases with peak current intensity and reaches unity for peak currents higher than ~ 300 kA.

[8] In this paper, we measure the size of the scattering region associated with intense lightning discharges with high peak currents of >100 kA and investigate the connection between the peak current and the onset of Early VLF perturbation. We apply these analyses to both typical and long-duration Early VLF events.

## 2. Description of the Experiment

[9] The VLF data presented in this study were collected from January to March 2011 by nine Atmospheric Weather Electromagnetic System of Observation, Modeling, and Education (AWESOME) VLF receivers. Figure 1 shows the location of the VLF receivers, U. S. Navy VLF transmitters, and the causative lightning discharges of some featured Early VLF events presented later. The VLF receivers are located at nine Stanford University stations in Bermuda (BE), Las Vegas, New Mexico (LV), Sheridan, Montana (SH), Taylor, Indiana (TA), Siena College, New York (SI), Walsenburg, Colorado (WA), and three receivers in Oklahoma (designated north, east, and west; ON, OE, and OW, respectively). The receivers record the amplitude and phase of the NAA (24.0 kHz, Maine), NAU (40.75 kHz, Puerto Rico), NLK (24.8 kHz, Washington), NML (25.2 kHz, North Dakota), and NPM (21.4 kHz, Hawaii) VLF transmitters. The instrumentation of the data recording system at each site is described by *Cohen et al.* [2010]. The receivers each consist of a pair of orthogonal crossed-loop antennas to detect wideband radio waves as weak as a few fT/rt-Hz in both the East-West and North-South magnetic planes. A preamplifier located near the antennas passes the broadband VLF signal in range of 0.3–47 kHz. The signal then is digitized at 100 kHz using GPS timing (<100 ns error) and recorded on a computer. The phase and amplitude of narrowband signals at specific frequencies are demodulated and recorded with 20 ms time resolution [*Cohen et al.*, 2010; *Johnson*, 2000]. The data are posted to Stanford University automatically via internet.

[10] Data from the National Lightning Detection Network (NLDN) provide the time, location, polarity, and peak current of lightning strokes for CG lightning flashes [*Cummins et al.*, 1998] and are used to determine the location of each Early VLF event. NLDN consists of 150 low-frequency

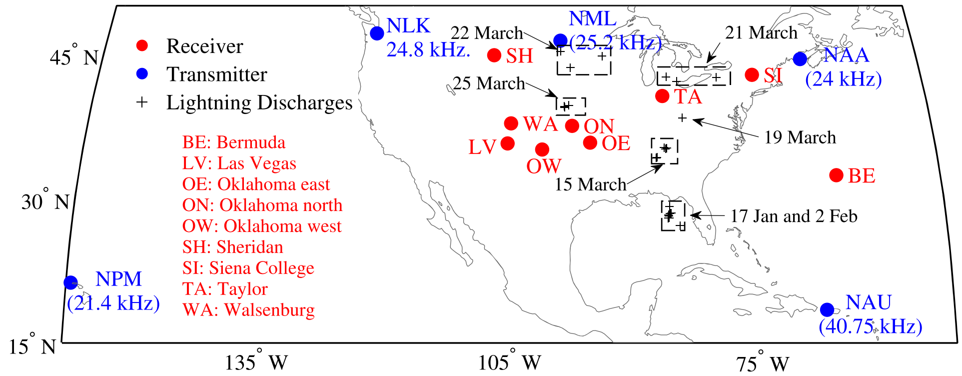


**Figure 1.** Geographic locations of five U.S. naval VLF transmitters, nine AWESOME VLF receivers, together with the causative lightning discharges occurred on 17 January, 2 February, and 15, 19, 21, 22, and 25 March 2011.

sensors across the continental USA, with a CG stroke detection efficiency of ~90%. To distinguish Early VLF events from indirect ionospheric disturbances such as lightning-induced electron precipitation [*Peter and Inan*, 2004], high time resolution analysis was made to measure the time delay between the causative lightning flashes and the onset of all lightning-associated VLF perturbations. The onset of Early VLF events was time-aligned (<20 ms) with the causative lightning flashes, whereas LEP events possess an onset delay of 0.3 to 2.5 s following the lightning return stroke. We therefore excluded all LEP events from this study.

[11] In this study, we used every NLDN-located stroke with peak amplitude above 100 kA from January to March 2011 as a starting point, searched in the collected narrowband data for any available transmitter-receiver path that passes within 400 km of the event, and restricted the search to nighttime events. We then analyzed each event, noting which had associated Early VLF events, as well as the associated Early VLF event properties (e.g., onset duration, amplitude, and recovery time). There were certainly a large number of Early VLF events generated by strokes weaker than 100 kA, but we restrict this study to intense strokes above 100 kA for the purposes of searching a long period of time without being overwhelmed by the number of events to examine. Setting these criteria resulted in more than 18,000 possible events in 3 months. This compiled database forms the basis of this study. We first present a number of case studies, followed by large scale statistics.

## 3. Results

### 3.1. Case Studies

[12] We now present five case studies to investigate the scattering pattern and onset amplitude of Early VLF events associated with intense lightning discharges (>100 kA). We define the term "typical peak current lightning" to mean CG discharges with magnitude between 0 and 100 kA, "large peak current lightning" to the discharges between 100 and 200 kA; and "very large peak current lightning" to the discharges higher than 200 kA. In addition, we refer to each of the Early VLF signal perturbations observed in correlation with a lightning discharge as an "event." Since multiple VLF signals pass through any given region, each of them may simultaneously detect an Early VLF event, and thus multiple events may be observed for a single lightning discharge.

#### 3.1.1. The 21 March 2011 Case

[13] *Johnson et al.* [1999b] measured the size of the ionospheric disturbance region for Early/Fast VLF events associated with peak discharge currents <100 kA by monitoring the NAA transmitter signal at nine Stanford VLF stations. The authors suggested that typical lightning discharges can affect the conductivity of the lower ionosphere with a lateral extent of ~90±30 km. In this case study, we monitor the NAA transmitter signal recorded by five Stanford VLF stations to measure the size of the ionospheric scattering region for large and very large peak current discharges (>100 kA). On 21 March 2011, NLDN located lightning from a vast storm over New York and Michigan. NLDN recorded 202 large and 14 very large peak current lightning discharges from this storm. These powerful discharges were correlated with 106 Early VLF amplitude events on the NAA signal recorded at Walsenburg, Taylor, and Oklahoma VLF sites. Figure 2 shows the corresponding VLF signatures of the amplitude events produced by three intense lightning discharges of +104, –235, and +206 kA NLDN peak currents, respectively. At 02:17:56 and 07:04:29 UT, NLDN measured +104 and –235 kA peak current lightning strokes time-coincident with nine amplitude perturbations on the NAA transmitter signal recorded at Walsenburg, Taylor, and Oklahoma VLF sites. These two high peak current discharges perturbed the VLF signal within 225–280 km of the causative lightning strokes. At 09:40:10 UT, NLDN recorded a +206 kA peak current discharge (C). This very large peak current lightning stroke was correlated with four large ($\gtrsim$ 2 dB) amplitude changes on the NAA signal. The VLF amplitude perturbations correlated with lightning A–C started immediately (<20 ms) after the causative NLDN discharges, and reached full perturbation levels in <50 ms. It is evident from Figure 2 that high peak current lightning stroke can affect the conductivity of the lower ionosphere at much larger lateral extent than typical lightning discharges as reported by [*Johnson et al.*, 1999b].

#### 3.1.2. The 22 March 2011 Case

[14] On 22 March 2011, over 12,131 CG flashes were recorded by the NLDN network between 0330 and 1100 UT, occurring from 41°–46°N to 95°–105°W. Of these 12,131 CG discharges, 83 (0.68%) were large peak current

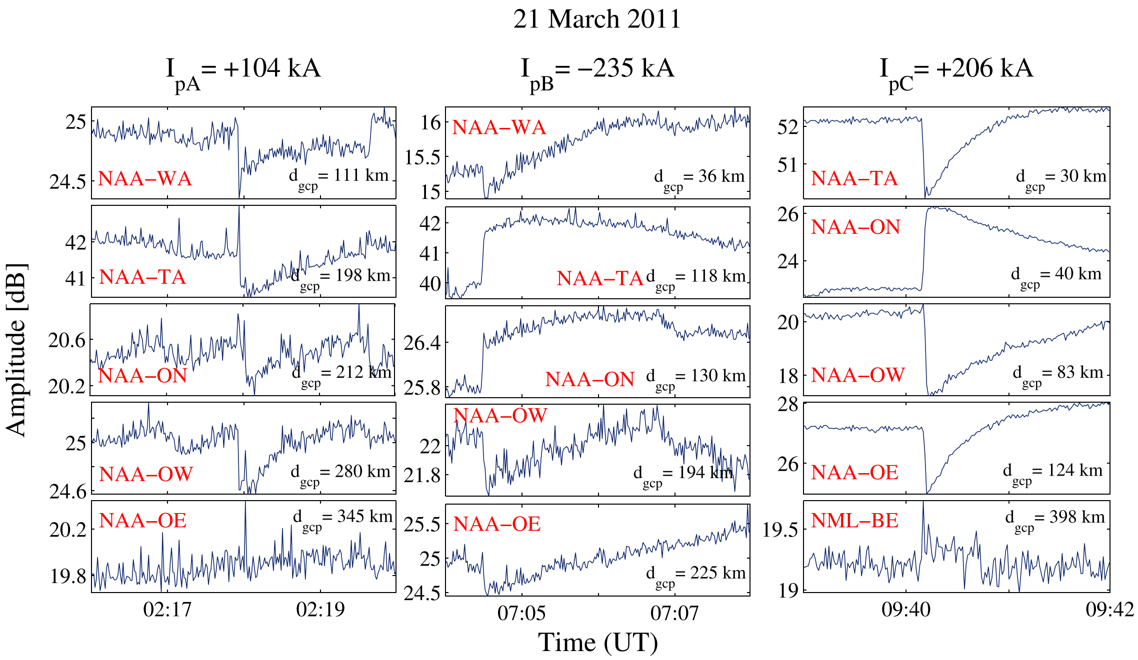


**Figure 2.** Early VLF perturbations observed on the NAA VLF transmitter signal and recorded at five Stanford VLF sites. These events are correlated with NLDN-measured +104, –235, and +206 kA peak currents. The lateral distance between the GCPs and the causative NLDN flashes are shown in each panel link.

discharges and six (0.05%) were very large peak current discharges. A total of 98 Early VLF events were detected on the NML signal received at Taylor, Oklahoma sites, Walsenburg, and Sheridan. Of these 98 amplitude events, 39 were correlated with large peak current lightning discharges, and 17 were correlated with very large peak current CG discharges. For each very large peak current CG discharge, at least one of the available VLF probe signals exhibited a correlated VLF amplitude perturbation. Figure 3 shows the corresponding VLF signatures of the events produced by a very large (D) and two large (E, F) peak current NLDN discharges. Lightning discharges D, E, and F took place over North and South Dakota and Minnesota, and were located within 100 to 350 km of the NML VLF transmitter. These observations show that large and very large peak current lightning strokes can produce forward scattering Early VLF signal perturbations when the causative lightning discharge occurs within ∼400 km of the VLF signal GCP, a much larger distance than previously reported [*Johnson et al.*, 1999b]. Thirty-five Early VLF events were detected in correlation with typical lightning discharges, while the causative lightning discharges of seven events were not detected. Since NLDN detection efficiency is low for low peak current strokes ($I_p$ <5 kA) and increases significantly for peak discharge currents >15 kA [*Cummins et al.*, 1998], we considered these events as typical Early/Fast generating lightning discharges. Throughout our analysis, we also observed that the vast majority of typical lightning discharges perturb the VLF signal when occurring within ∼50 km of the signal GCP.

### 3.1.3. The 15 March 2011 Case

[15] A thunderstorm on 15 March 2011 from 0500 to 0730 UT located in northern Alabama and southern Tennessee was correlated with five Early amplitude events on the NAU-SH signal. The storm was located ∼2100 and 2600 km from the Sheridan receiver and the NAU transmitter, respectively. The causative lightning discharges of the five Early VLF events had peak current higher than +100 kA. The NAU to Sheridan GCP was located west of the causative lightning discharges. We used the NAU-TA signal paths to the east and the NAA-OE signal paths to the north to bound the size of the ionospheric scattering regions associated with these high peak current CG discharges. On that day, data for Oklahoma North and West VLF stations were missing due to equipment malfunction. Figure 4 shows three snapshots of the amplitude signal perturbations detected on 15 March 2011. NLDN recorded two very large peak current lightning discharges (G and H) at 05:18:01 and 05:22:16 UT. These very large peak current lightning created two large amplitude changes (∼+5 dB) on the NAU signal recorded at Sheridan that recovered in ∼5 min. However, the VLF perturbation produced by these two lightning appeared as two small amplitude changes (∼0.2–0.4 dB) on the NAA-OE signal followed by relatively shorter recovery duration. Unfortunately, the NAU signal recorded at Taylor receiver was contaminated by numerous large sferic bursts during this time.

[16] The onset of Early VLF events (I) was time-aligned with two successive lightning discharges with peak currents +117 and +125 kA that occurred at 07:01:04.19122 and 07:01:04.19123 UT. These two successive large peak current lightning discharges perturbed the VLF signals within 393 km of the causative lightning strokes, generating ∼0.3–0.8 dB amplitude perturbations on NAA and NAU transmitters signals. At 07:03:52 UT, NLDN measured a +282 kA peak current lightning time-coincident with ∼ +3 dB amplitude change on the NAU-SH signal followed by a prolonged ∼ 13 min recovery. However, the events

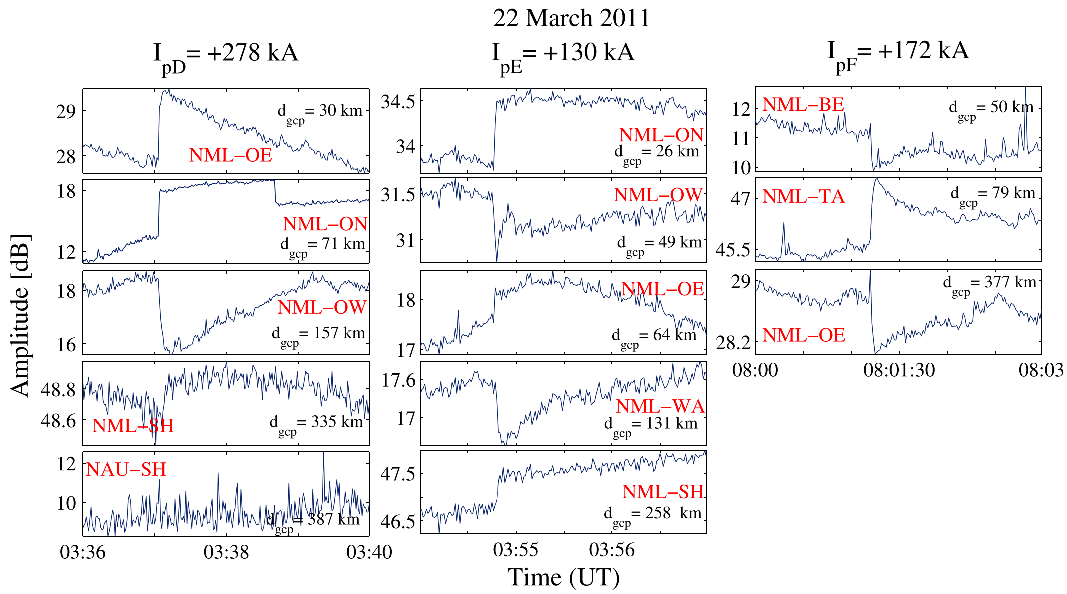


**Figure 3.** The VLF signatures of 12 Early VLF amplitude events observed on 22 March 2011, coincident with three strong +CG discharges of +278, +130, and +172 kA peak currents. The events were detected on NML VLF signal. The peak current intensity of the causative lightning discharges and their distances from each VLF signal path are labeled in each plot. It is evident from the figure that high peak current lightning strokes can produce Early VLF signal perturbations when the causative lightning discharge occurs within ~400 km of the VLF signal GCP.

detected on the NAU to Taylor and NAA to Oklahoma east exhibited significantly smaller amplitude perturbations followed by shorter recoveries. Similarly, a +143 kA NLDN peak current created ~ 2.0, 0.4, and 0.2 dB perturbations on the VLF probe signals at distance of 287, 348, and 389 km, respectively.

[17] We observe in this case study that very large peak current lightning discharges, in comparison to large peak current discharges, are associated with longer recovery duration. Also, the VLF perturbations observed on the NAA-OE signal path are significantly smaller than those detected on the NAU to Sheridan VLF path. This disparity can be attributed to the geometry of the causative lightning, transmitter, and receiver as described by *NaitAmor et al.* [2010]. Finally, we note that these high peak current lightning discharges can produce forward scattering Early VLF signal perturbations when the causative lightning discharge occurs within ~400 km of the affected VLF signal paths.

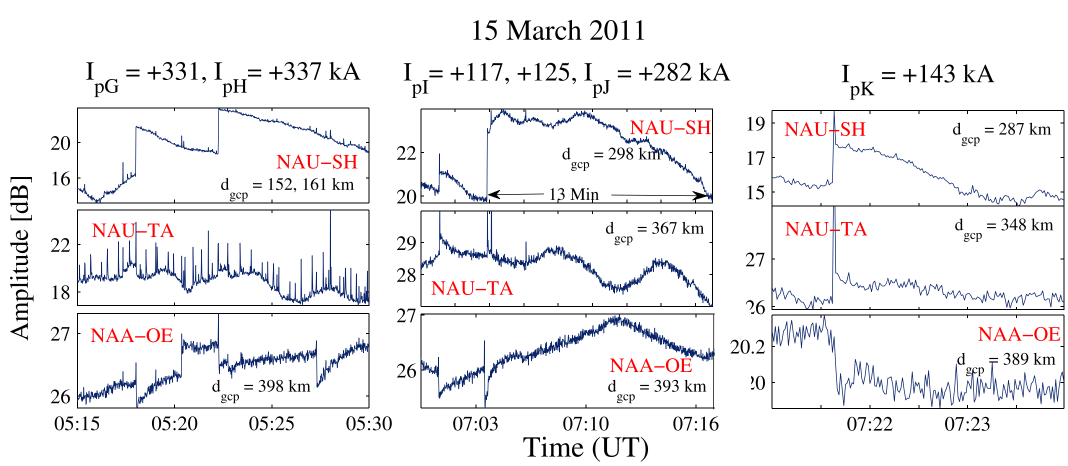


**Figure 4.** Early VLF events observed on 15 March 2011 between 0500 and 0730 UT. The lightning discharges responsible for these events had peak current magnitude above +100 kA. These high peak current discharges generated five large amplitude perturbations on the NAU-SH path with amplitude perturbations ranging from ~0.8 to 5 dB and several smaller sharp amplitude changes on the NAU-TA and NAA-OE signal paths ~0.2–0.4 dB in amplitude. It is evident from the figure that Early VLF events caused by high peak current lightning discharges can be observed when the disturbance region is ~400 km from the GCP.

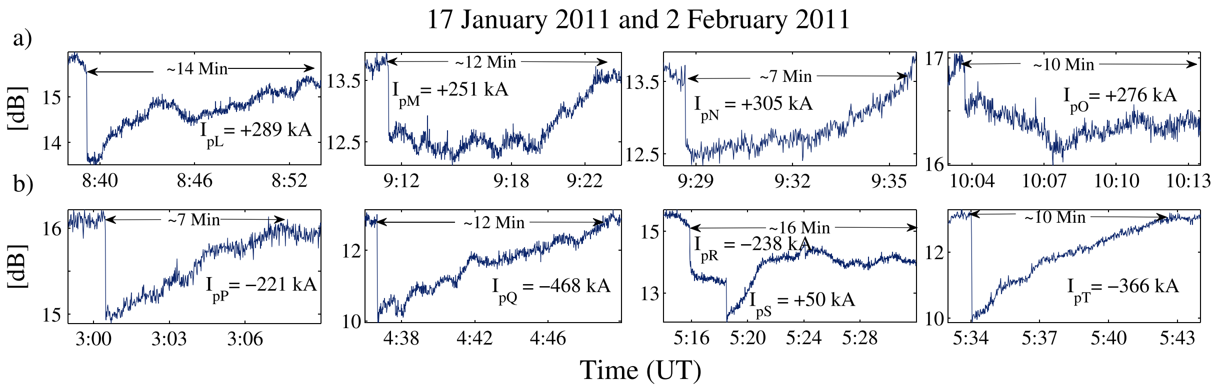


**Figure 5.** (a) The amplitude of the NAU signal observed in Las Vegas on 17 January 2011 between 0830 and 1030 UT exhibited three VLF signatures of Early VLF events with long-enduring recoveries. The onset of the long recovery signal perturbations was time-correlated with very large peak current +CG discharges over the water. (b) Early VLF events with prolonged recoveries observed on 2 February 2011 on the NAU VLF transmitter signal recorded at Las Vegas associated with NLDN-measured –221, –468, –238, and –366 kA peak currents over the water.

We could not identify any Early VLF perturbations on the NAA-WA signal, whose GCP was >400 km from the intense lightning discharges.

#### 3.1.4. The 17 January 2011 Case

[18] In previous case studies, we presented Early VLF event characteristics associated with large and very large peak current lightning discharges over land areas. Recently, *Cotts and Inan* [2007], *Salut et al.* [2012], and *Kumar and Kumar* [2013] reported that Early VLF events exhibiting exceptionally long recovery times of up to 30 min are predominantly associated with oceanic lightning activity. However, due to the lack of lightning peak current information, they were unable to investigate the correlation between lightning peak current intensity and the occurrence of long recovery events. Here we present Early VLF ionospheric disturbances generated by very large peak current lightning discharges over the sea. On 17 January 2011, NLDN network located a positive lightning storm over Gulf of Mexico, and four Early VLF events were detected on the NAU transmitter signal recorded at Las Vegas. Due to equipment malfunction, data for Oklahoma VLF stations are not available for this date. Figure 5a shows the VLF signatures of the four amplitude events observed on that day. All events exhibit long recoveries ranging from ~7 to 14 min. High-resolution analysis reveals that the onset of the events is time-coincident with four powerful cloud-to-sea discharges of +289, +251, +305, and +276 kA NLDN peak currents, respectively. The causative lightning of the events were located approximately midway along the NAU-LV GCP, ~2000 km from the Las Vegas receiver and ~2200 km from the NAU transmitter. We also note that at 08:51:49 UT, another very large peak current (+289 kA) lightning occurred within 44 km from the VLF signal path which did not produce a detectable (>0.2 dB) perturbation on the NAU-LV signal.

[19] Similarly, a negative lightning storm on 2 February 2011 over the same geographic region was correlated with 4 long recovery Early VLF events observed on the NAU signal received at Las Vegas. The events were triggered by four very large peak current lightning discharges. Figure 5b shows 4 VLF signature of long recovery amplitude perturbations observed on 2 February 2011. The VLF data presented here suggest that very large peak current cloud-to-sea discharges have a strong tendency to create long-lasting ionization enhancements on the overlying ionosphere, producing long recovery Early VLF perturbations.

### 3.2. "Near-Receiver" Events

[20] In previous sections, we presented observations of Early VLF events occurring far ($\gtrsim$ 1000 km) from the receivers. Results indicated that high peak current lightning strokes can produce forward scattering Early VLF signal perturbations when the causative lightning discharge occurs within ~400 km of the VLF signal GCP. The scattering pattern of Early VLF events occurring near (~500 km) the receiver has been more open to interpretation. *Dowden et al.* [1996] suggested that narrow ionization columns in sprites can produce backscattering Early VLF events when they occur within 500 km of the receiver while *Inan et al.* [1995] and *Haldoupis et al.* [2004] reported exclusively forward scattering of VLF signals in correlation with sprite discharges. *Mika et al.* [2005] demonstrated that ~5% of the sprites that occurred within 100–200 km of the receiver had corresponding VLF backscattered-like perturbations. The authors suggested that these backscattered-like Early VLF events were generated due to overlapping of the ionospheric-disturbed region over the receiver. *Marshall et al.* [2006] quantitatively investigated the correlation between sprites and Early VLF perturbations. The authors identified nine VLF events (out of over 250 sprites) that occurred >280 km from the receivers and exhibited perturbations in the backward direction. Since sprites have been observed in association with Early events when they occur within 100 km of the VLF signal path, *Marshall et al.* [2006] considered those nine events as VLF backscatter perturbations.

#### 3.2.1. The 25 March 2011 Case

[21] We now present data related to thunderstorm activity on 25 March 2011 to examine the scattering pattern of near-receiver Early VLF events in association with powerful CG discharges. On that day, NLDN network recorded 2818 lightning discharges, occurring from 36°–41°N to 95°–105°W. From these 2818 lightning discharges, 47 were

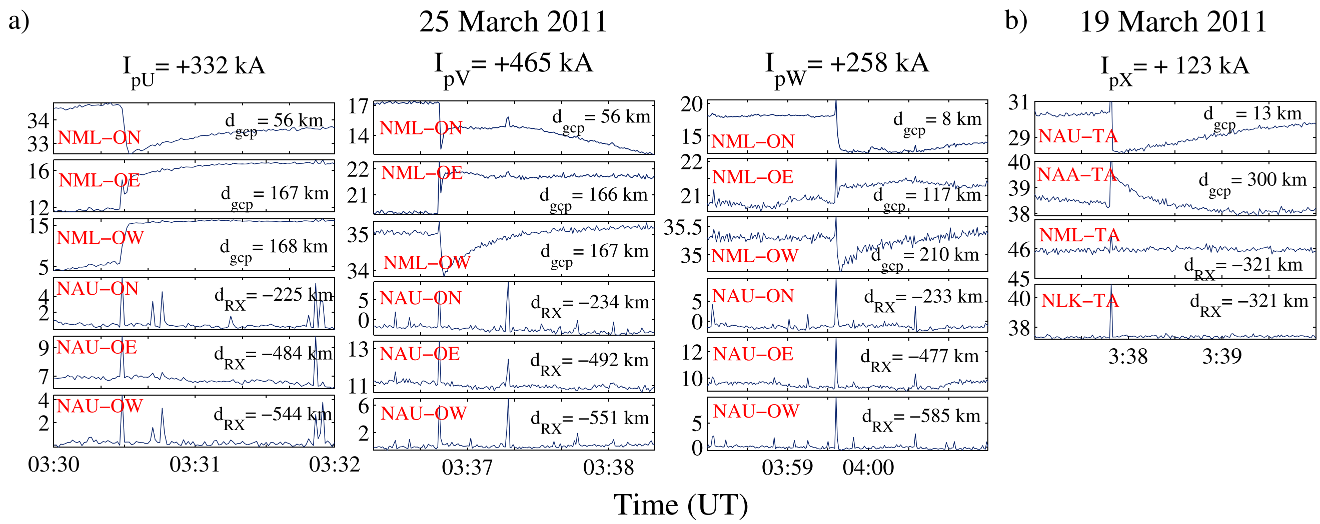


**Figure 6.** (a) Multiple VLF signatures of amplitude perturbations observed on 25 March 2011 in association with three very large peak current +CG lightning discharges ranged from +258 to +465 kA. A one-to-one correlation between these very large peak current +CG discharges and VLF forward scatter events was found. (b) A +123 kA peak current on 19 March 2011 occurred near ($d_{Rx}$= 321 km) Taylor VLF receiver. This large peak current lightning perturbed the NAA and NAU VLF signals, indicating forward scattering Early VLF signal perturbations, but it could not perturbed the NML and NLK signals located in backward directions.

large peak current discharges and five were very large peak current discharges. These intense lightning occurred near ($d_{Rx}$= $\sim$200–600 km) the Oklahoma VLF receivers, unlike the previous three case studies where the causative lightning was located far ($\gtrsim$ 1000 km) from the VLF receivers. We used the NML transmitter signal to detect forward scatter VLF perturbations and the NAU signal to investigate for possible backscattering. Figure 6a shows the VLF signatures of nine amplitude perturbations observed on this date, together with the peak currents of the causative lightning discharges and the distance from that lightning discharge to the VLF signal GCP for each event. We used "+" and "–" signs to show the forward and backward directions relative to the VLF receivers, respectively. Numerous large amplitude perturbations (up to $\sim$10 dB) on the NML signal were detected. On the other hand, none of these discharges, not even the powerful +CG discharges, could perturb the NAU signal recorded at Oklahoma stations. Since the causative lightning discharges on this date were located past the receiver relative to the NAU-Oklahoma probe signal GCPs, detection of an Early VLF event on any of these signals would have suggested backscatter and very wide-angle scattering. We also note that NLDN measured a –275 kA peak current at 04:46:36.7 UT that did not produce any detectable VLF perturbations.

[22] Figure 6b provides another example of near-receiver Early VLF events. On 19 March 2011, NLDN recorded a large peak current lightning discharge located 321 km from Taylor station. This large peak current +CG discharge created two large (1.3 and 2.6 dB) forward scattering Early VLF events on the NAU and NAA signals; no VLF backscatter perturbations on the NML and NLK signals were observed. Our observations are consistent with *Inan et al.* [1996b], *Haldoupis et al.* [2004], and simulation results of *Lehtinen et al.* [2010], indicating that the backscattered VLF signal is generally too small to generate discernible Early VLF perturbations even for very large peak current lightning discharges.

### 3.3. Peak Current Polarity

[23] Having examined the relationship between lightning current and Early VLF event properties on a case study basis, we now proceed with a statistical analysis of many events. In this paper, we have investigated the scattering pattern and occurrence rates of Early VLF events produced by intense lightning discharges through the use of multiple VLF signal paths. From Figures 3, 4, and 6, we noted a one-to-one correlation between very large peak current +CG lightning flashes and Early VLF perturbations, consistent with forward scattering with the transmitter paths at large distances (up to $\sim$400 km) from the lightning discharge. Figure 5 illustrates that both positive and negative very large peak current cloud-to-sea lightning discharges can create Early VLF events with prolonged recovery duration (>500 s).

[24] The peak current of the lightning stroke affects three components of the ionospheric disturbance and observed Early VLF event: (1) the apparent size of the scattering region, (2) the occurrence rate, and (3) the recovery duration. To quantify the effect, we examined the disturbances associated with all 7769 NLDN-recorded CG flashes with peak currents >100 kA and located within 400 km of a VLF probe signal GCP in North America for dates between 1 January and 2 February 2011 and from 1 to 25 March 2011. The VLF events were detected by visual inspection of the recorded data. We applied a detection threshold of $\sim$0.2 dB for amplitude signal perturbation based on typical noise levels. Table 1 shows distributions of the high peak current lightning flash density, number of VLF signal paths analyzed, and Early VLF perturbations detected. The total number of negative large peak current lightning

**Table 1.** Distribution of Early VLF Events as a Function of the Peak Current Magnitude of the Causative Lightning Discharges From 1 January to 2 February 2011 and From 1 to 25 March 2011

| Lightning Peak Current (kA) | Lightning Discharges | Number of VLF Links | Total Events | Occurrence Probability |
|---|---|---|---|---|
| –150< I < –100 | 3951 | 14580 | 179 | 1.2% |
| –200< I < –150 | 718 | 2583 | 66 | 2.6% |
| –250< I < –200 | 154 | 510 | 30 | 5.9% |
| I < –250 | 51 | 146 | 21 | 14.4% |
| TOTAL | 4874 | 17819 | 296 | 1.7% |
| +100< I < +150 | 2062 | 7694 | 419 | 5.4% |
| +150< I < +200 | 567 | 2084 | 263 | 12.6% |
| +200< I < +250 | 175 | 698 | 159 | 22.8% |
| I > +250 | 91 | 365 | 113 | 31% |
| TOTAL | 2895 | 10841 | 954 | 8.8% |

outnumbered positive flashes by a ratio of 1.7. However, this ratio dropped to 0.56 for peak current of >250 kA.

[25] The data in Table 1 show an overall occurrence rate of ~4.4% for Early VLF events produced by peak current >100 kA. *Salut et al.* [2012] reported 403 Early VLF events in association with 478495 lightning flashes, occurring within 350 km of the VLF signal path. Comparing our statistical results to the 0.08% presented in *Salut et al.* [2012] supports the notion that the initiation of Early VLF events is strongly dependent on the peak current of lightning discharges, with the larger peak current lightning analyzed here showing a much larger occurrence rate of Early VLF events. Furthermore, it has been observed that even among intense lightning discharges, those with higher peak currents are more likely to generate Early VLF events. We observe a ~3.4% occurrence rate for large peak lightning, whereas this value was six times higher for very large peak current NLDN discharges.

[26] To investigate the relation between lightning peak current and the size of the scattering region, Figure 7 presents the distribution of Early VLF events as a function of the causative lightning peak current and the distance from flash location to the VLF signal GCP. Given that our observations were consistent with forward scatter and did not suggest backscatter or wide-angle scattering, the distance from the lightning flash location to the VLF signal GCP provides an estimate of the minimum lateral extent of the ionospheric disturbance. We would further expect the Early VLF event occurrence rate in each case to correlate with the magnitude and/or occurrence rate of an ionospheric disturbance. We see that the apparent size of the ionospheric disturbance grows larger for larger peak currents. The results of Figure 7 suggest that higher peak current lightning discharges can more frequently perturb VLF transmitter signals as far as ~400 km away from the lightning stroke.

[27] Figure 8 shows distribution of recovery duration of Early VLF events as a function of the peak current of the causative lightning discharges. A total of 1250 Early VLF perturbations were identified, and 90 of these perturbations exhibited a long recovery (defined here as >200 s). Of the 296 Early VLF events correlated with negative lightning discharges, only 20 events displayed a long recovery signature. Of the 954 Early VLF events time-correlated with positive high peak current lightning strokes, 70 events exhibited recoveries longer than 200 s. We also note that from the 90 long recovery events, 64 events recovered within 500 s, and 26 events displayed recovery duration of >500 s. Results indicate that the vast majority of Early VLF events with recovery duration greater than 500 s detected during this period of January and March 2011 were correlated with sea-based lightning discharges. Of the 26 unusually long recovery events (>500 s), 21 events were located over water and five events occurred over land areas. So these unusually long recovery events can be caused by lightning occurring over land, but they are detected far more frequently in correlation with lightning occurring over sea. Furthermore, we have observed that as the peak current of CG lightning increases, the occurrence rate of Early VLF events with long-enduring recovery increases, in agreement with *Haldoupis et al.* [2013].

[28] Figure 9a shows the absolute amplitude change associated with all large and very large Early-generating lightning discharges during 1 January to 2 February and 1 to 25 March 2011. The vast majority of the events had amplitude changes between 0.2 and 0.8 dB. We note that very large peak discharge currents are more often associated with large amplitude change (> 1 dB). Figure 9b shows the scatterplot of amplitude perturbations associated with all detected Early

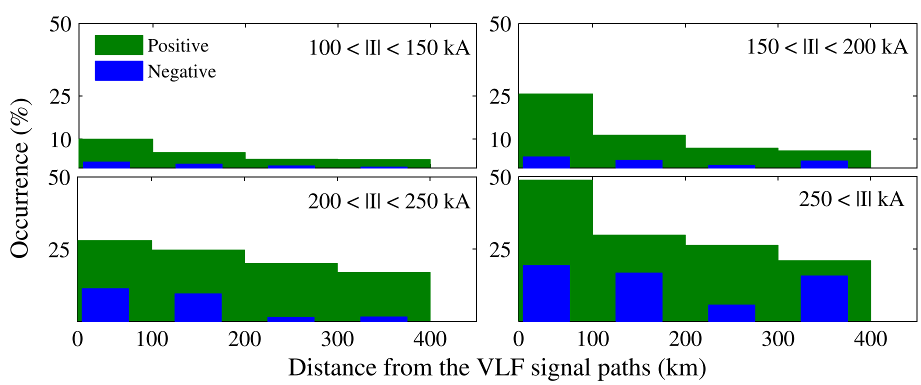


**Figure 7.** Probability of generating an Early VLF events as a function of the peak current magnitude of the causative lightning discharges and distance of stroke location from the VLF signal paths, for data between 1 January to 2 February 2011 and from 1 to 25 March 2011. It is evident from the figure that the apparent size of the ionospheric disturbance grows larger for larger peak currents.

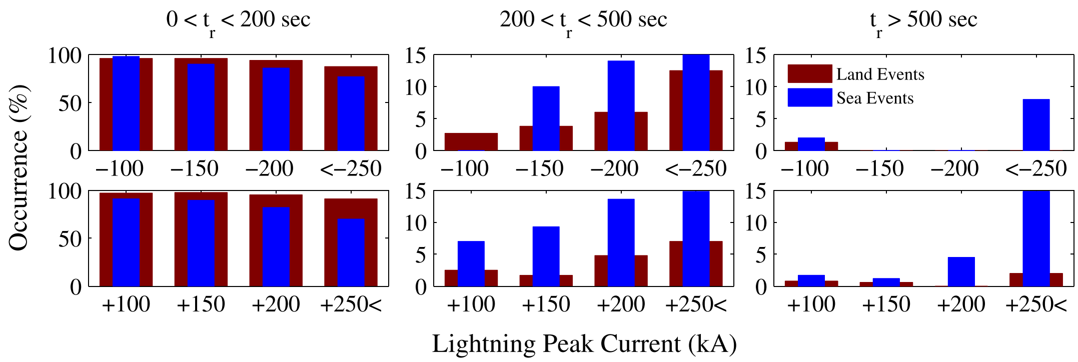


**Figure 8.** Distribution of peak current of the causative lightning discharges as a function of the recovery duration ($t_r$) of Early VLF events. The figure shows that as the peak current of lightning increases, the occurrence rate of Early VLF events with long-enduring recovery increases.

VLF events, together with a linear regression and correlation coefficient analysis. The correlation coefficient between amplitude perturbations and lightning peak current for these 1250 Early VLF events is $r$ = 0.17, which suggests a weak positive correlation. This matches our physical intuition, as a larger peak current is more likely to produce a greater ionospheric disturbance and subsequently a larger perturbation to a probe signal. The reason it is not a stronger correlation is likely due in part to the importance of scattering geometry (scattering angle, distance to receiver, etc.), which should affect the amplitude perturbation but we did expect to be uncorrelated with lightning peak current. Also note that this analysis considers only detected events for large and very large peak current lightning. Table 1 shows that the occurrence rate of detectable Early VLF events clearly increases for larger peak currents, but the correlation analysis here shows that among those detected events, there exists only a weak correlation between lightning peak current and the magnitude of the observed probe signal perturbation.

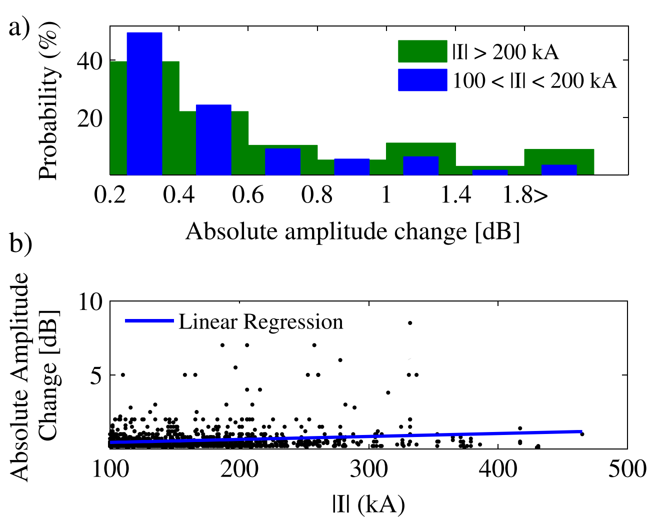


**Figure 9.** (a) Distribution of amplitude change in decibel associated with Early VLF events. (b) The scatterplot of amplitude perturbations associated with all detected Early VLF events, together with a linear regression and correlation coefficient analysis.

## 4. Discussion

[29] By analyzing thousands of high peak current lightning discharges, our study provides the first opportunity to assess the potential size and scattering pattern of large and very large peak current lightning discharges. Previous studies considered scattering from all lightning discharges or from a selected few high peak current discharges. Since <100 kA NLDN peak current lightning represents ~98% of all lightning discharges, previous studies that considered all lightning discharges were mostly analyzing these lower peak currents. Past experimental observations indicated that the causative lightning discharges of Early VLF events were located within 50 km of the affected VLF signal paths and that signal perturbations were dominated by forward scattering effects. *Johnson et al.* [1999b] reported that lightning discharges with peak current < 60 kA can affect the conductivity of the lower ionosphere with ~90±30 km lateral extent. Our results in Figure 7 suggest that higher peak current lightning strokes can more frequently produce forward scattering Early VLF events when the causative lightning discharge occurs at larger distances of up to ~400 km of the VLF signal GCP. *Rodger et al.* [2001] suggested that EMPs with peak discharge currents higher than 95 kA can dramatically (~100% or greater) increase the lower ionospheric electron density. Moreover, *Rodriguez et al.* [1992] estimated that the widths of the heated and ionized regions due to EMPs from intense lightning discharges ($E_{100}$= 20 V/m) at half-maximum values to be 200 and 90 km, respectively, and to increase to 440 and 260 km for a $E_{100}$= 40 V/m pulse. *Moore et al.* [2003] attributed Early VLF events to the combination of the lightning EMP and QE fields which can directly affect the conductivity of the *D* region of the ionosphere. Noting that QE fields likely only generate ionization changes with 20–50 km lateral extent [*Pasko et al.*, 1995], we attribute the large lateral extent of the ionospheric region to the conductivity enhancements induced by lightning EMP.

[30] Table 1 shows that the occurrence rate of Early VLF events increases with peak current intensity of the causative lightning discharges. Since lightning-EMP intensity is directly related to the peak current of CG lightning discharges, the strong correlation between the occurrence of Early VLF perturbations and lightning peak current further supports the explanation that the lightning-EMP process plays a major role in the generation of direct VLF

disturbances. The ∼5 times higher Early VLF event occurrence rate for +CG discharges in comparison to negative flashes can be explained by the difference in durations of positive and negative CG lightning discharges. *Berger et al.* [1975] reported that +CG strokes have durations of 25 μs to 2 ms, with a median of 230 μs; whereas –CG flashes have durations of 30 to 200 μs, with a median of 75 μs. Longer discharge duration can suggest higher charge transfer after the +CG return stroke, leading to the formation of a stronger QE fields above the thunderstorm region with 20–50 km lateral extent which can heat the overlying ionosphere. QE fields are other important factors in addition to the lightning EMP for initiation of Early VLF events occurring near the VLF signal paths. Therefore, our higher Early VLF event occurrence rate for +CG strokes is qualitatively consistent with the lightning-EMP process as well as QE fields acting as the causative physical mechanism for disturbing the ionosphere.

[31] Lightning peak current, polarity, and location are also important factors in the recovery duration of Early VLF events. The 73% of the observed Early VLF events with recovery duration of >500 s were correlated with intense +CG lightning strokes as opposed to negative, and 81% were correlated lightning occurring over sea as opposed to over land. Two mechanisms have been proposed for long-enduring density enhancements in the ionosphere. *Haldoupis et al.* [2012] reported correlation between unusually long recovery Early VLF events and very intense +CG lightning discharges that generated elve emissions followed by column sprites. *Rodger* [2003] suggested that EMP emitted from large peak current lightning discharges can generate a long-lasting ionization in the lower ionosphere. Sprite discharges can also affect the density of the ionosphere for 100 to 1000 s [*Sentman et al.*, 2008; *Gordillo-Vazquez*, 2008]. *Lehtinen and U. S. Inan* [2007] proposed a new chemistry model for the stratosphere/lower ionosphere and attributed the observation of Early VLF perturbations with unusually long enduring recoveries (∼ $10^3$–$10^4$ s) to the persistent ionization of positive and negative ions at altitudes below 50 km induced by a gigantic jet. However, due to the vast area of observation and lack of optical recordings, we were not able to investigate relation between long recovery VLF events and gigantic jets and sprite-elve pairs. The geographic distribution of long recovery events observed in this paper is consistent with the occurrence of elves and gigantic jets reported by *Chen et al.* [2008] and *Said et al.* [2013].

## 5. Conclusion

[32] We investigated scattering pattern and occurrence rates of Early VLF perturbations in association with high peak current lightning discharges (>100 kA). We observed that the peak current magnitude of the causative lightning discharges strongly affects the scattering pattern, recovery duration, and occurrence rate of Early VLF events. Analysis indicated that the apparent size of the scattering region increases with the peak current intensity of the lightning discharges up to ∼400 km in radius, consistent with the expected geometry of the ionospheric region affected by intense EMPs [*Rodriguez et al.*, 1992]. We also observed that the occurrence rates of Early VLF events increased rapidly with the peak current magnitude of the causative lightning discharges. Results suggest that polarity of the causative lightning discharges is another important factor that affect the onset and recovery duration of Early VLF events. Occurrence probability of long recovery events and Early VLF perturbations produced by intense +CG lightning discharges is ∼3 to 5 times higher than their negative counterparts. We also found that the induced amplitude change is not directly related to the peak current intensity.

[33] **Acknowledgments.** We are grateful to Stanford University VLF research group, notably Umran Inan for establishment of AWESOME Global Network and providing VLF data used in this research. The authors wish to thank NLDN network for providing the lightning location data. M.M. Salut was supported during this research by the UKM fellowship.

[34] Robert Lysak thanks the reviewers for their assistance in evaluating this paper.

## References

Berger, K., R. B. Anderson, and H. Kroninger (1975), Parameters of lightning flashes, *Electra*, *80*, 223–237.

Burgess, W. C., and U. S. Inan (1993), The role of ducted whistlers in the precipitation loss and equilibrium flux of radiation belt electrons, *J. Geophys. Res.*, *98*(A9), 15,643–15,665.

Chen, A. B., et al. (2008), Global distributions and occurrence rates of transient luminous events, *J. Geophys. Res.*, *113*, A08306, doi:10.1029/2008JA013101.

Cohen, M. B., U. S. Inan, and E. W. Paschal (2010), Sensitive broadband ELF/VLF radio reception with the AWESOME instrument, *IEEE Trans. Geosci. Remote Sens.*, *48*(1), 3–17, doi:10.1109/TGRS.2009.2028334.

Cotts, B. R. T., and U. S. Inan (2007), VLF observation of long ionospheric recovery events, *Geophys. Res. Lett.*, *34*, L14809, doi:10.1029/2007GL030094.

Cotts, B. R. T., U. S. Inan, and N. G. Lehtinen (2011), Longitudinal dependence of lightning-induced electron precipitation, *J. Geophys. Res.*, *116*, A10206, doi:10.1029/2011JA016581.

Cummins, K. L., M. J. Murphy, E. A. Bardo, W. L. Hiscox, R. B. Pyle, and A. E. Pifer (1998), A combined TOA/MDF technology upgrade of the U.S. National Lightning Detection Network, *J. Geophys. Res.*, *103*(D8), 9035–9044, doi:10.1029/98JD00153.

Dowden, R. L., C. D. D. Adams, J. B. Brundell, and P. E. Dowden (1994), Rapid onset, rapid decay (RORD), phase and amplitude perturbations of VLF subionospheric transmissions, *J. Atmos. Terr. Phys.*, *56*(11), 1513–1527.

Dowden, R. L., J. B. Brundell, W. A. Lyons, and T. E. Nelson (1996), Detection and location of red sprites by VLF scattering of subionospheric transmissions, *Geophys. Res. Lett.*, *23*(14), 1737–1740.

Gordillo-Vazquez, F. J. (2008), Air plasma kinetics under the influence of sprites, *J. Phys. D: Appl. Phys.*, *41*, 234016, doi:10.1088/0022-3727/41/23/234016.

Haldoupis, C., M. Cohen, B. Cotts, E. Arnone, and U. Inan (2012), Long-lasting D-region ionospheric modifications, caused by intense lightning in association with elve and sprite pairs, *Geophys. Res. Lett.*, *39*, L16801, doi:10.1029/2012GL052765.

Haldoupis, C., M. Cohen, E. Arnone, B. Cotts, and S. Dietrich (2013), The VLF fingerprint of elves: Step-like and long-recovery early VLF perturbations caused by powerful ±CG lightning EM pulses, *J. Geophys. Res. Space Physics*, *118*, 5392–5402, doi:10.1002/jgra.50489.

Haldoupis, C., N. Amvrosiadi, B. R. T. Cotts, O. A. van der Velde, O. Chanrion, and T. Neubert (2010), More evidence for a one-to-one correlation between sprites and early VLF perturbations, *J. Geophys. Res.*, *115*, A07304, doi:10.1029/2009JA015165.

Haldoupis, C., R. J. Steiner, A. Mika, S. Shalimov, R. A. Marshall, U. S. Inan, T. Bosinger, and T. Neubert (2006), "Early/slow" events: A new category of VLF perturbations observed in relation with sprites, *J. Geophys. Res.*, *111*, A11321, doi:10.1029/2006JA011960.

Haldoupis, C., T. Neubert, U. S. Inan, A. Mika, T. H. Allin, and R. A. Marshall (2004), Subionospheric early VLF signal perturbations observed in one-to-one association with sprites, *J. Geophys. Res.*, *109*, A10303, doi:10.1029/2004JA010651.

Helliwell, R., J. P. Katsufrakis, and M. Trimpi (1973), Whistler-induced amplitude perturbation in VLF propagation, *J. Geophys. Res.*, *78*, 4679–4688.

Inan, U. S., A. Slingeland, V. P. Pasko, and J. V. Rodriguez (1996b), VLF and LF signatures of mesospheric/lower ionospheric response to lightning discharges, *J. Geophys. Res.*, *101*(A3), 5219–5238.

Inan, U. S., D. C. Shafer, W. P. Yip, and R. E. Orville (1988), Subionospheric VLF signatures of nighttime D region perturbations in the vicinity of lightning discharges, *J. Geophys. Res.*, *93*(A10), 11,455–11,472.

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., M. Walt, H. D. Voss, and W. L. Imhof (1989), Energy spectra and pitch angle distributions of lightning-induced electron precipitation: Analysis of an event observed on the S81-1 (SEEP) satellite, *J. Geophys. Res.*, *94*, 1379–1401.

Inan, U. S., T. F. Bell, V. P. Pasko, D. D. Sentman, E. M. Wescott, and W. A. Lyons (1995), VLF signatures of ionospheric disturbances associated with sprites, *Geophys. Res. Lett.*, *22*(24), 3461–3464.

Inan, U. S., V. P. Pasko, and T. F. Bell (1996a), Sustained heating of the ionosphere above thunderstorms as evidenced in "early/fast" VLF events, *Geophys. Res. Lett.*, *23*, 1067–1070.

Johnson, M. P. (2000), VLF imaging of lightning-induced ionospheric disturbances, PhD thesis, Stanford Univ., Stanford, Calif.

Johnson, M. P., U. S. Inan, and D. S. Lauben (1999a), Subionospheric VLF signatures of oblique (nonducted) whistler-induced precipitation, *Geophys. Res. Lett.*, *26*(23), 3569–3572.

Johnson, M. P., U. S. Inan, S. J. Lev-Tov, and T. F. Bell (1999b), Scattering pattern of lightning-induced ionospheric disturbances associated with early/fast VLF events, *Geophys. Res. Lett.*, *26*(15), 2363–2366, doi:10.1029/1999GL900521.

Kumar, S., and A. Kumar (2013), Lightning-associated VLF perturbations observed at low latitude: Occurrence and scattering characteristics, *Earth Planets Space*, *65*, 25–37, doi:10.5047/eps.2012.05.019.

Lauben, D. S., U. S. Inan, and T. F. Bell (2001), Precipitation of radiation belt electrons induced by obliquely propagating lightning-generated whistlers, *J. Geophys. Res.*, *106*, 29,745–29,770.

Lehtinen, N. G., and U. S. Inan (2007), Possible persistent ionization caused by giant blue jets, *Geophys. Res. Lett.*, *34*, L08804, doi:10.1029/2006GL029051.

Lehtinen, N. G., R. A. Marshall, and U. S. Inan (2010), Full-wave modeling of "early" VLF perturbations caused by lightning electromagnetic pulses, *J. Geophys. Res.*, *115*, A00E40, doi:10.1029/2009JA014776.

Marshall, R. A., U. S. Inan, and W. A. Lyons (2006), On the association of early/fast very low frequency perturbations with sprites and rare examples of VLF backscatter, *J. Geophys. Res.*, *111*, D19108, doi:10.1029/2006JD007219.

Mika, A., C. Haldoupis, R. A. Marshall, T. Neubert, and U. S. Inan (2005), Subionospheric VLF signatures and their association with sprite observed during Eurosprite-2003, *J. Atmos. Sol. Terr. Phys.*, *67*, 1580–1597.

Mika, A., C. Haldoupis, T. Neubert, R. R. Su, H. T. Hsu, R. J. Steiner, and R. A. Marshall (2006), Early VLF perturbations observed in association with elves, *Ann. Geophys.*, *24*, 2179–2189.

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.

NaitAmor, S., M. A. AlAbdoadaim, M. B. Cohen, B. R. T. Cotts, S. Soula, O. Chanrion, T. Neubert, and T. Abdelatif (2010), VLF observations of ionospheric disturbances in association with TLEs from the EuroSprite-2007 campaign, *J. Geophys. Res.*, *115*, A00E47, doi:10.1029/2009JA015026.

NaitAmor, S., M. B. Cohen, B. R. T. Cotts, H. Ghalila, M. A. AlAbdoadaim, and K. Graf (2013), Characteristics of long recovery early VLF events observed by the North African AWESOME Network, *J. Geophys. Res. Space Physics*, *118*, 5215–5222, doi:10.1002/jgra.50448.

Pasko, V. P., U. S. Inan, Y. N. Taranenko, and T. F. Bell (1995), Heating, ionization and upward discharges in the mesosphere, due to intense quasi-electrostatic thundercloud fields, *Geophys. Res. Lett.*, *22*(4), 363–368.

Peter, W. B., and U. S. Inan (2004), On the occurrence and spatial extent of electron precipitation induced by oblique nonducted whistler waves, *J. Geophys. Res.*, *109*, A12215, doi:10.1029/2004JA010412.

Rodger, C. J. (2003), Subionospheric VLF perturbations associated with lightning discharges, *J. Atmos. Sol. Terr. Phys.*, *65*, 591–606, doi:10.1016/S1364-6826(02)00325-5.

Rodger, C. J., M. Cho, M. A. Cliverd, and M. J. Rycroft (2001), Lower ionospheric modification by lightning-EMP: Simulation of the night ionosphere over the United States, *Geophys. Res. Lett.*, *28*(2), 199–202.

Rodriguez, J. V., U. S. Inan, and T. F. Bell (1992), D region disturbances caused by electromagnetic pulses from lightning, *Geophys. Res. Lett.*, *19*(20), 2067–2070.

Said, R. K., M. B. Cohen, and U. S. Inan (2013), Highly intense lightning over the oceans: Estimated peak currents from global GLD360 observations, *J. Geophys. Res. Atmos.*, *118*, 6905–6915, doi:10.1002/jgrd.50508.

Salut, M. M., M. Abdullah, K. L. Graf, M. B. Cohen, B. R. T. Cotts, and S. Kumar (2012), Long recovery VLF perturbations associated with lightning discharges, *J. Geophys. Res.*, *117*, A08311, doi:10.1029/2012JA017567.

Sampath, H. T., U. S. Inan, and M. P. Johnson (2000), Recovery signatures and occurrence properties of lightning-associated subionospheric VLF perturbations, *J. Geophys. Res.*, *105*, 183–192, doi:10.1029/1999JA900329.

Sentman, D. D., H. C. Stenbaek-Nielsen, M. G. McHarg, and J. S. Morrill (2008), Plasma chemistry of sprite streamers, *J. Geophys. Res.*, *113*, D11112, doi:10.1029/2007JD008941.

Taranenko, Y. N., U. S. Inan, and T. F. Bell (1993), The interaction with the lower ionosphere of electromagnetic pulses from lightning: Excitation of optical emissions, *Geophys. Res. Lett.*, *20*, 2675–2678, doi:10.1029/93GL02838.