The VLF fingerprint of elves: Step-like and long-recovery early VLF perturbations caused by powerful ±CG lightning EM pulses

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[1] Subionospheric VLF recordings are investigated in relation with intense cloud-to-ground (CG) lightning data. Lightning impacts the lower ionosphere via heating and ionization changes which produce VLF signal perturbations known as early VLF events. Typically, early events recover in about 100 s, but a small subclass does not recover for many minutes, known as long-recovery early events (LORE). In this study, we identify LORE as a distinct category of early VLF events, whose signature may occur either on its own or alongside the short-lived typical early VLF event. Since LORE onsets coincide with powerful lightning strokes of either polarity (±), we infer that they are due to long-lasting ionization changes in the uppermost D region ionosphere caused by electromagnetic pulses emitted by strong ± CG lightning peak currents of typically > 250 kA, which are also known to generate elves. The LORE perturbations are detected when the discharge is located within ~250 km from the great circle path of a VLF transmitter-receiver link. The probability of occurrence increases with stroke intensity and approaches unity for discharges with peak currents ≥ ~300 kA. LOREs are nighttime phenomena that occur preferentially, at least in the present regional data set, during winter when strong ± CG discharges are more frequent and intense. The evidence suggests LORE as a distinct signature representing the VLF fingerprint of elves, a fact which, although was predicted by theory, it escaped identification in the long-going VLF research of lightning effects in the lower ionosphere.

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1. Introduction

[2] Subionospheric very low frequency (VLF) signals are used to probe and investigate conductivity perturbations in the lower ionosphere caused by the impulsive coupling of quasi-electrostatic (QE) fields and electromagnetic pulses (EMP) generated by tropospheric lightning (e.g., see reviews by *Rodger* [2003] and *Inan et al*. [2010]). The most common class of lightning-induced VLF perturbations is known as *early* VLF events. These events occur in narrowband VLF signals only occasionally but always within a few milliseconds of a causative cloud-to-ground (CG) lightning flash, thus the term "early" signifies a direct lightning effect on the overlying upper atmosphere and ionosphere. They include two subcategories, the "early/fast" whose onset occurs within a few milliseconds, and the "early/slow" whose onset builds up gradually over 1 to 2 s, apparently because subsequent in-cloud lightning bursts are acting to create additional ionization after the initial causative CG flash [*Haldoupis et al*., 2006]. Early events are distinct from "lightning-induced electron precipitation (LEP)" VLF events, whose onset is delayed by ~1 s relative to their causative CG lightning discharge [e.g., see *Inan et al*., 2010]. Typical early and LEP events are characterized by recoveries typically lasting from a few tens of seconds to a couple of minutes.

[3] The early VLF events have been investigated for more than 20 years. Studies over the last several years in Europe, using the Stanford University AWESOME VLF receivers [*Cohen et al*., 2010] and optical observations of transient luminous events (TLE) such as sprites and elves [*Neubert et al*., 2005], established that nearly all sprites are accompanied with early events [*Haldoupis et al*., 2004, 2010], although some of them may occur without sprites, possibly because the latter went undetected [*Haldoupis et al*., 2010]. In addition, a close relation has been shown to exist between early/fast events and sprite halos [*Moore et al*., 2003]. These observations imply that typical early events have their origin in positive cloud-to-ground (+CG) discharges with large charge moment changes which are known to exclusively produce sprites and sprite halos via quasi-electrostatic fields in

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the mesosphere (see review by *Pasko et al*. [2012, and references therein]). The early event recovery times of several tens of seconds can be understood in terms of the electron density relaxation times at D region heights between about 65 and 80 km [*Haldoupis et al*., 2009].

[4] The present study deals with a new type of VLF events that were first recognized and reported by *Cotts and Inan* [2007]. These are also characterized by early onsets but have long recoveries lasting up to many minutes or are step-like events in which the signal does not recover to pre-event levels. Recently, *Salut et al*. [2012] provided additional data showing that these perturbations are attributed predominately to lightning discharges occurring over the sea, which are believed to be stronger than those over land. *Salut et al*. [2012] also observed that long-recovery events occur when the transmitter path passes as far as 250 km from the lightning, a larger distance than the typical early/fast event, which usually occur within 50–100 km of the lightning [*Johnson et al*., 1999]. *Cotts and Inan* [2007] relied on a modified D region chemistry model by *Lehtinen and Inan* [2007] to attribute the long recoveries as being due to long-lasting conductivity relaxation times of heavy ions in the lower D region. Based on this postulation, *Cotts and Inan* [2007] went further to suggest a relationship with “gigantic jets” which are huge upward discharges between the thundercloud top and the upper D region ionosphere [e.g., *Pasko et al*., 2002; *van der Velde et al*., 2010].

[5] Recently, *Haldoupis et al*. [2012] showed that these long-recovery VLF events occur in association with simultaneous elves and high-altitude sprites both triggered by very intense + CG lighting discharges. They introduced the term LORE, for “long-recovery early events,” and attributed them to long-lasting electron density enhancements in the uppermost D region ionosphere near 80 to 90 km which can affect subionospheric VLF propagation during nighttime.

[6] The present paper continues the work of *Haldoupis et al*. [2012]. In particular, there was a need to investigate a claim made by these authors, namely that LOREs occur overwhelmingly in correspondence to an “elve and sprite pair” rather than an elve or a sprite alone; this led them to postulate that LOREs result from a coupling process between the two phenomena which involves in-time sequence both lightning EMP and QE fields. The present study shows that LOREs originate from powerful CG discharges of either positive or negative (±) polarity, which implies that a strong lightning-induced EMP is the key behind LOREs; therefore, these phenomena are likely to occur always with an elve and not necessarily with an elve and sprite pair.

[7] Interestingly, the present results confirm for first time theoretical predictions published several years ago by *Rodger et al*. [1998, 2001] and reviewed later by *Rodger* [2003]. The agreement with theory is to be discussed in detail after the presentation of results.

2. Experimental Data

[8] The investigation of *Haldoupis et al*. [2012] was based on a single maritime thunderstorm that lasted 6 h and produced 50 TLEs, mostly sprites, several elve and sprite pairs (all accompanied by LOREs), and a gigantic jet, the first ever to be observed in Europe [*van der Velde et al*., 2010]. During its course, the storm produced several powerful + CG strokes with peak currents exceeding +200 kA; among them also was a huge +406 kA flash which generated a spectacular elve and a large sprite plus a LORE that lasted more than 30 min. Amazingly, this powerful and long-lasting storm did not generate any intense negative CG discharges (peak currents did not exceed −80 kA), which therefore did not allow a comparison with strong negative CG discharges. We overcome that shortcoming in the present study.

[9] Here, we utilize VLF transmitter amplitude data recorded in Crete, Greece and concurrent lightning detection network (LINET) ± CG discharges of large peak currents (≥ ±200 kA) over Italy. LINET, which is described by *Betz et al*. [2004], provides the discharge position with an uncertainty of ~ 300 m, the occurrence time with an accuracy of microsecond, whereas the error in peak current intensity is less than 10%. The Crete VLF and Italian LINET data combination was chosen because several VLF links recorded in Crete had great circle paths (GCP) crossing through the Italian territory monitored by the LINET system. It should be noted that this large data set was not complemented by any concurrent TLE measurements since these were not available (except for those that have been included already in the single-event study of *Haldoupis et al*. [2012]). In the analysis, lightning records were considered during nighttime for the 12 month period from November 2009 to October 2010, during which time the VLF receiver in Crete operated fairly continuously. Early VLF perturbations during daytime are known to be rare, if ever present [*Inan et al*., 2010], so only nighttime events were considered.

[10] The lightning data is summarized in Figure 1, which also shows the GCPs of the VLF transmitter (Tx) and receiver (Rx) links used in the study. The narrowband VLF receiver is situated in Heraklion, Crete. Also shown in Figure 1 are the locations of five European transmitters (HWU-20.9 kHz and HWV-18.3 kHz both located in LeBlanc, Central France; DHO-23.4 kHz, Germany; GQD-22.1 kHz, UK; and NSC-45.9 kHz, Sicily) and their GCPs to Crete. These GCPs, along with the GCPs of the powerful NAA-24.0 kHz transmitter in Cutler ME, USA and the US Navy transmitter NRK, operating at 37.5 kHz in Keflavik, Iceland, also have been used here. The best suited Tx-Rx links for this study are the NAA-, HWU-, and HWV-Crete links which cross Italy and the center of the region monitored by the lightning detection system.

[11] The map in Figure 1 shows the locations of the 960 ± CG discharges considered in the analysis, which had very large peak currents (> ±200 kA), and thus representing a tiny subset (< 0.5 %) of the total number of ± CG recordings. Out of the 960 discharges, about 60% (582) were positive (red circles in Figure 1) and the rest 40% (378) negative (blue circles). This is in line with what is known to be valid in general, that is, large positive CG discharges are stronger and more frequent relative to their negative counterparts [*Rakov and Uman*, 2003].

[12] The histograms to the right of Figure 1 show how the positive and negative discharges are distributed with month (top) and peak current intensity (bottom). The great majority (~50 %) of these powerful lightning strokes occur during winter months (December–February) and only about 5%–10% during summer months (June–August). Interestingly, this contrasts with the overall total ± CG lightning activity

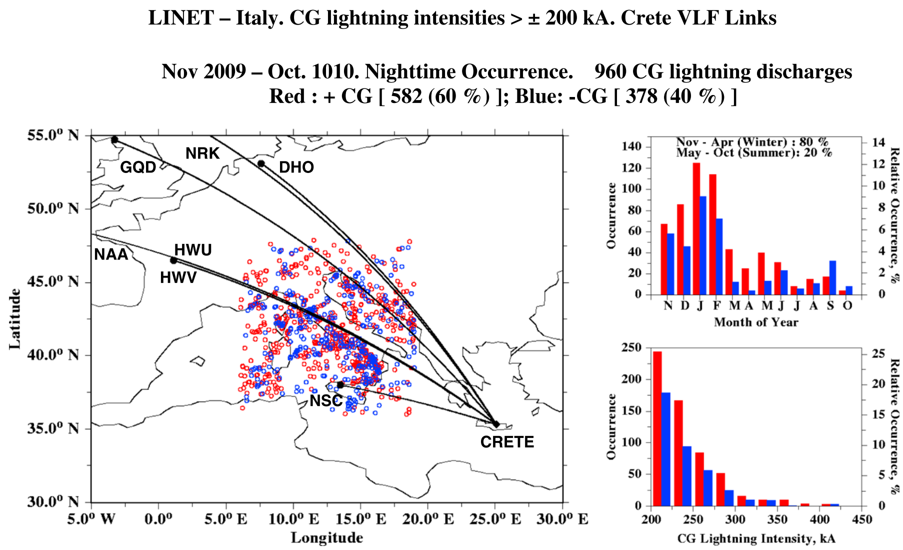

Figure 1. The map to the left shows the great circle paths (GCP) of various VLF transmissions to the Crete receiver and the locations of 960 ± CG lightning discharges with peak current > 200 kA, which were considered in the present study. To the right are histograms showing the occurrence distributions of positive (red) and negative (blue) CG lightning discharges per month (top) and peak current intensity (bottom).

(distributions are not shown here) which peaks in summer [see also *Christian et al*. 2003]. The histograms in the bottom panel show that the most powerful discharges with peak currents > 300 kA represent only a small fraction (~6.5 %) of the total number under consideration. Finally, the great majority of the high peak current discharges occur over the sea and/or near the coastline, mostly during winter months, a fact that certainly has a physical significance which is not yet well understood [e.g., *Said et al*. 2013]

3. Results

[13] The great variability in narrowband VLF recordings precludes the use of an automatic procedure for the detection of early events. Thus, we inspected visually the VLF amplitude time series data for all the VLF links shown in Figure 1, by selecting a proper time interval centered at the exact LINET time of a given discharge. This procedure was applied for each of the 960 ± CG strokes that have peak currents > ±200 kA. No VLF phase time series were considered in this statistical study. This was partly because VLF phases were often affected by interference and transmitter signal phase changes and mostly because the much more reliable signal amplitude data sufficed here for our purposes. The method of analysis identified quickly that LOREs associate with powerful EMPs which, as in the case of elves (e.g., see *Barrington-Leigh et al*. [2001] and review by *Pasko et al*. [2012]), are emitted by powerful CG discharges of either positive or negative polarity.

3.1. Step-like and Long-recovery Early VLF Events

[14] A common form of LORE is the "step-like LORE," easily discernible since it imprints itself sharply in the raw and filtered narrowband VLF recordings. It is illustrated in Figure 2 for both the raw data (top panel) and the low-pass filtered data (bottom panel); the latter being used routinely to depict the relatively short-living signatures of early/fast, early/slow, and LEP events; filtering is useful for better visual identification of early VLF events and creates no serious artifacts in the observed signatures. The raw signal contains both longer-term ionospheric perturbations, shaped by the complexity of subionospheric waveguide modal propagation effects and large-scale ionospheric disturbances, as well as high-frequency impulses caused by lightning-produced atmospherics, or sferics, of various intensities and origins. More specifically, narrowband VLF data, when analyzed with 50 Hz resolution, can have some impulses in the amplitude data as a result of large sferics. Since the time of each integration time is 20 ms, a powerful sferic (1 ms long) can have significantly more energy in a 200 Hz bandwidth than

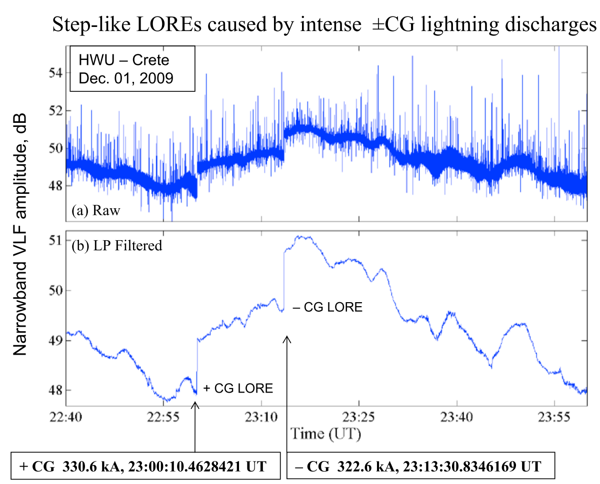

Figure 2. Characteristic examples of step-like long-recovery early VLF events (step-like LOREs) caused by a positive or a negative CG discharge of large peak current intensity. The step-like LORE event is identified to be a unique VLF signature that is imprinted strongly in the raw (top) and low-pass filtered (bottom) narrowband VLF signal amplitudes.

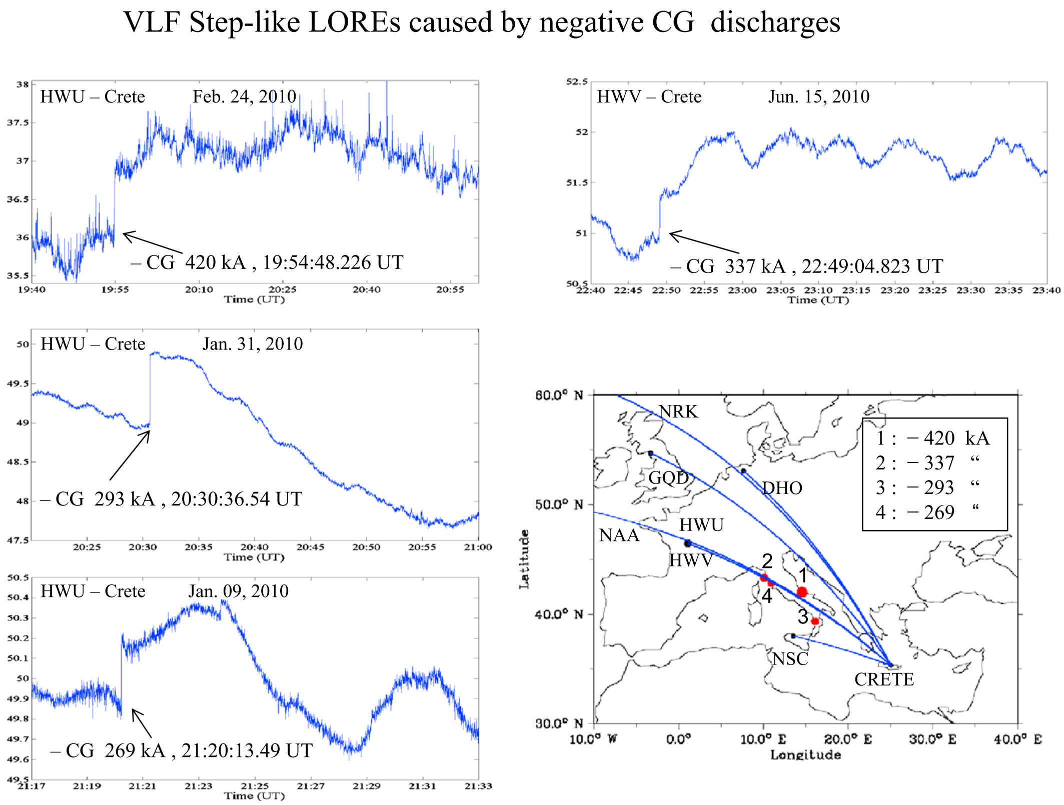

Figure 3. Typical examples of step-like LORE events caused by powerful negative CG discharges located near the GCPs of the observing VLF Tx-Rx links. Intense CG discharges are known to radiate strong electromagnetic pulses, which can reach the upper D region ionosphere to excite optical emissions (elves) and produce electron heating and ionization changes.

the VLF transmitter had. As such, there will be a sharp spike, lasting one sample point, whenever a lightning stroke occurred close to the instrument. For the purposes only of visual clarity, we display the data here after applying a 5 point median filter, which removes sharp outliers caused by sferic energy overwhelming the transmitter signal.

[15] Shown in Figure 2 are two typical examples of step-like LORE events; the first is caused by a positive CG stroke with +330 kA peak current followed ~13 min later by a second event which is initiated by a powerful CG discharge of opposite polarity, −322 kA peak current. The VLF perturbation is in both cases characterized by a positive step-like increase in signal amplitude which shows no imminent recovery in contrast to typical early/fast, early/slow, and also LEP events. The step-like LORE perturbation tends to offset the signal amplitude from its pre-event level for fairly long times. The amplitude steps are ~1.0 dB, but in general, they can range from a fraction of decibels to several decibels. The perturbation amplitudes were not analyzed here, as they are affected in a complex way by many factors [*Marshall et al.*, 2010] including the causative peak current intensity and the distance of discharge location relative to a VLF link GCP [*NaitAmor et al.*, 2010], the VLF transmitter signal characteristics (e.g., power and frequency), complex waveguide modal propagation and scattering geometry effects [*Poulsen et al.*, 1993], and ambient ionospheric conditions, whose effects on the signal amplitude are not easily quantified.

[16] Figure 3 shows four examples of long-recovery early events initiated by large peak current negative CG lighting strokes, plotted here for the Tx-Rx link in which the lightning-induced perturbation was clearly identified. The step-like disturbances in the top two panels that offset the signal for long time correspond to very intense – CG discharges having peak currents of −420 kA (left) and −337 kA (right). The other two panels below also show step-like perturbations caused by weaker (but still very large) negative discharges of −293 kA and −269 kA peak current, respectively. The map to the right shows the corresponding – CG discharge locations relative to the GCPs of the VLF links monitored in Crete. Although not shown in Figure 3, we stress that the step-like early events were not detected by all three links, that is the NAA-, HWU-, and HWV-Crete links, despite that the causative discharges occurred close to their GCPs which are almost identical. Also, the events went totally undetected by the remaining links that have GCPs passing far away from the stroke locations. This demonstrates that a proper transmitter-event-receiver geometry is required in order to observe a LORE and that the lightning properties alone are not always sufficient to generate an observed LORE, even if the transmitter-receiver path passes very close to the event.

[17] All amplitude steps in Figure 3 are positive, ranging from about 0.5 to 2.0 dB. They have onsets coincident with their causative discharges and offset the signal for long times, that is, from many minutes to more than an hour as shown in the upper two panels. It is important to note that the very great majority (>95%) of step-like LOREs are of positive polarity (amplitude increases). This signature is similar with examples presented by *Cotts and Inan* [2007] and events

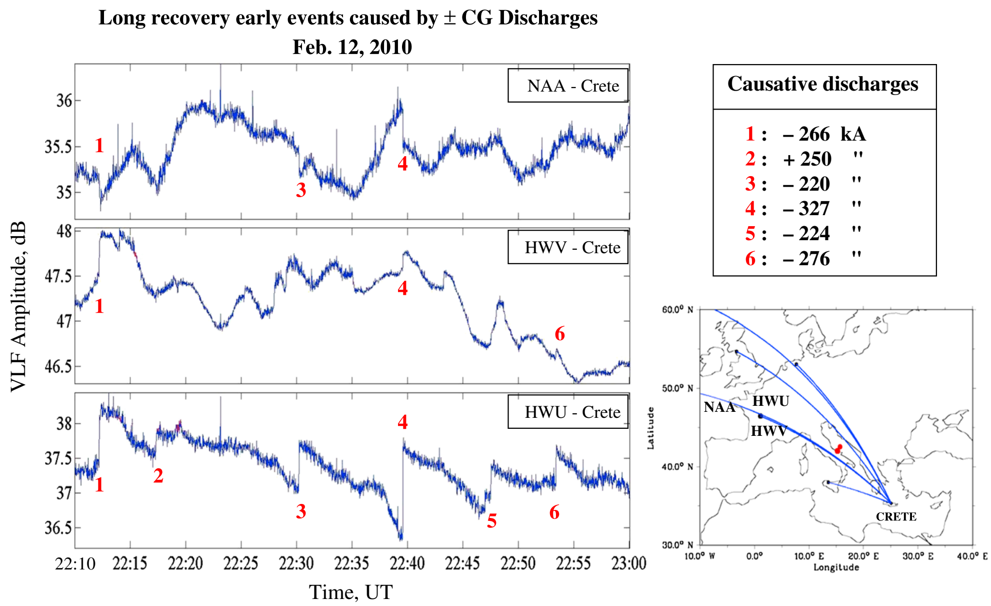

Figure 4. VLF LOREs caused by negative or positive CG discharges of high peak current, generated in sequence by a localized storm during an hour. Most of the VLF perturbations here appear to recover gradually to pre-onset levels contrary to the step-like cases that show no imminent recovery, as the case here for event 4 in the signal of the NAA-Crete link shown in the top panel.

reported by *Haldoupis et al*. [2012] which, in the latter case, were caused by large + CG discharges. In past studies, examples of step-like LOREs were published first by *Inan et al*. [1988, Figure 17], *Inan et al*. [1996, Figure 6], and *Dowden et al*. [1997, Figure 2e], but these were at that time not identified to be of specific importance.

[18] Figure 4 shows more examples of long-recovery early events, most of which are not "step-like" since they recover gradually back to pre-onset levels. All events shown in this figure are observed during a localized storm which occurred over the central east coastline of Italy. The VLF data shown are from the NAA-, HWV-, and HWU-Crete links. There are six events shown in Figure 4 (numbered form 1 to 6), all initiated by the strongest CG discharges detected during this, 50 min., time interval. The exact peak currents are given to the right and include five strong negative CG discharges with peak currents ranging from −224 to −327 kA, and one + CG discharge of +250 kA. It is important to stress again that these events are not observed in all three links shown in Figure 4, despite that all their Tx-Rx GCPs are spatially coincident. The six LOREs, which were all depicted in the HWU-Crete signal shown in the bottom panel, have amplitudes ranging from about 0.5 to 1.5 dB and gradual recoveries, ranging from several to many minutes. Their perturbation polarity is predominantly positive, except for events 1, 3, and 4 in the upper panel of the NAA-Crete link, which are negative.

[19] Having established that the LORE may occur in association with lightning of either polarity, we now distinguish the LORE signature from that of typical early events. Figure 5 shows 1 h recordings during a maritime storm which occurred near the central-west Italian coastline and produced high peak current discharges of only positive polarity (+CG). Shown in the upper three panels are narrowband VLF signal amplitude recordings for the NAA-, HWU-, and HWV-Crete links, with the corresponding ± CG lightning discharges plotted as sequential vertical lines in the lower panel. As seen, the storm produced several intense positive + CG discharges with peak currents > +100 kA which initiated either early/fast events (which, as discussed in the introduction, have been shown to be associated with sprites and sprite halos) or both early/fast and step-like LORE events. This latter combination was triggered only by the strongest positive discharges having +400 and +274 peak currents.

[20] As seen in Figure 5, there are at least seven + CG discharges with peak currents ranging from +102 to +400 kA, all producing typical early/fast events, characterized by narrow peaks and relatively short recoveries of ~1 min. They are mostly detected in the NAA- and/or HWU-Crete links but not the HWV-link. On the other hand, the strongest discharge of +400 kA produced a step-like LORE that was observed in all three links under consideration; however, the HWU link in the middle panel observed a composite early VLF signature in which an early/fast perturbation is clearly present in addition with a long-lasting step-like LORE perturbation, both having the same onset triggered instantly by the +400 kA discharge. The same composite signature is seen for the second stronger discharge of +274 kA in both the HWU and NAA links. We attribute the composite early/fast and step-like LORE signature to the combined effects of QE and EMP fields affecting different portions (altitudes) of the D region ionosphere. In this case, the likely QE and EMP fields are in association with the charge moment change and peak current intensity of the same + CG discharge, respectively.

3.2. Occurrence Characteristics

[21] In the following, we use the term LORE for all events, that is, the step-like with no clear recovery and those which show a long-duration (more than ~ 5 to 10 min) recovery. For the available 582 + CG and the 378 –CG nighttime discharges with peak currents > ±200 kA, there

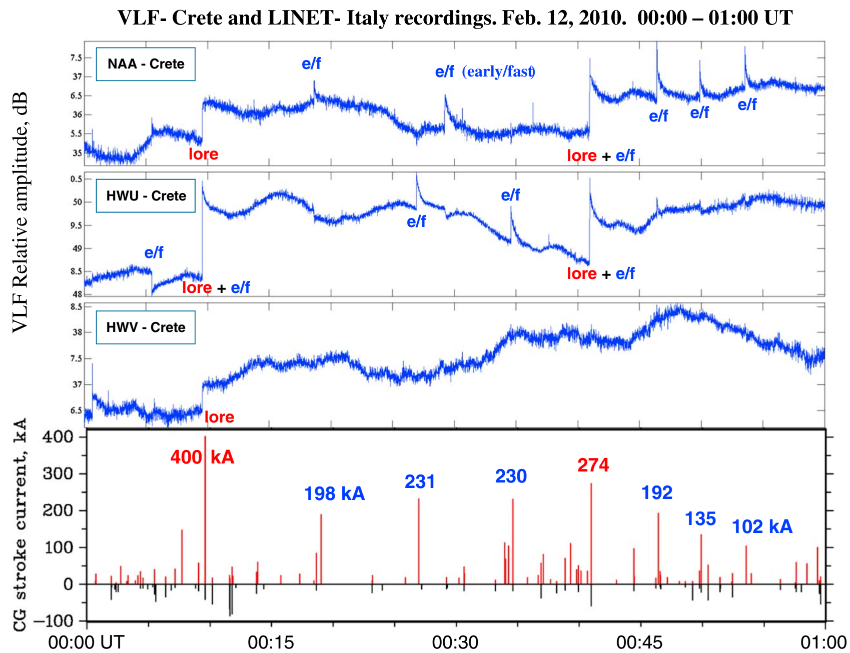

Figure 5. Examples of concurrent onset early/fast and step-like LORE perturbations both caused by positive CG discharges of large peak currents. This combination, met here for the strongest +400 kA and +274 kA discharges, can lead to a characteristic composite VLF signature which is attributed to the ionospheric effects of quasi-electrostatic and electromagnetic pulsed fields occurring in relation with the same causative + CG discharge.

were 230 + CG (40%) and 110 – CG (30%) that produced LOREs that have been detected, which means that a LORE was observed by at least one VLF link. In this respect, about 35% of the total 960 ± CG discharges with peak currents >200 kA produced LOREs that have been observed. The smaller percentage (30%) of LOREs initiated by – CG discharges relative to 40% of positive ones is likely because positive strokes with very large peak currents are more frequent and more intense than negative ones [*Rakov and Uman*, 2003].

[22] During the course of the analysis, it became clear that the LORE detection or occurrence depends on the peak current intensity of the causative discharge in addition to its location relative to the Tx-Rx GCP of a VLF link. Figure 6 shows how the LORE-causative ± CG discharge locations are distributed relative to the GCPs of the observing VLF

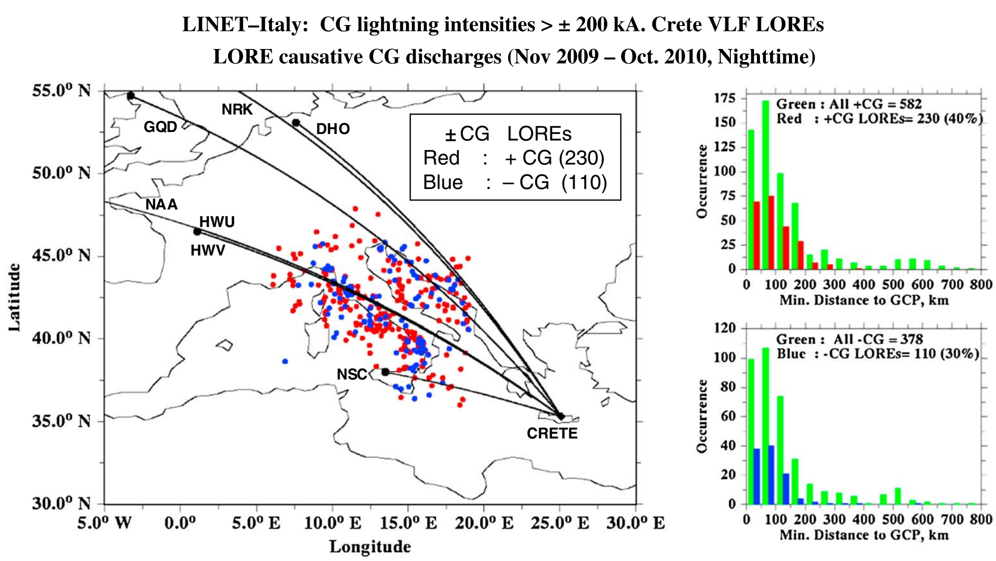

Figure 6. The map in the left is the same as in Figure 1 but now includes only the ± CG discharges which are LORE causative. They tend to cluster within a distance of ~300 km about the VLF link great circle paths. The histograms to the right show how the LORE-causative ± CG discharges, relative to the total number of discharges, are distributed with their distance to GCPs.

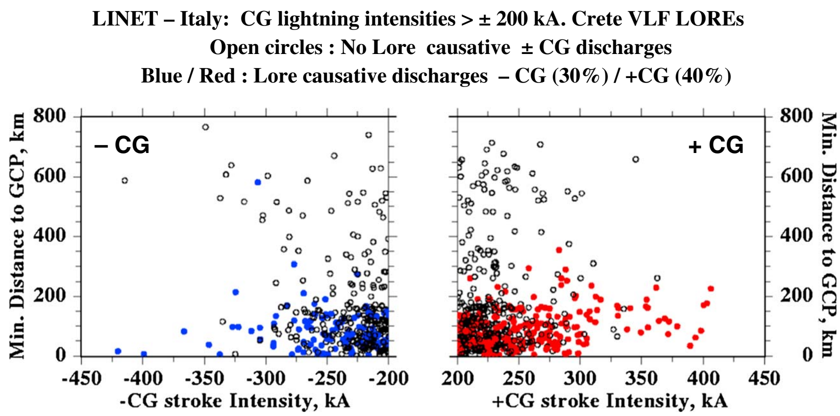

Figure 7. Scatter plots of negative (left) and positive (right) CG discharges for LORE-causative (blue/red) or not causative (black). In the *x* axis is the discharge peak current intensity. In *y* axis is the discharge location minimum or nearest distance to the VLF transmitter-receiver GCPs shown in Figure 1 or 6. See text for more details.

links. Comparison of the map in Figure 6 with that in Figure 1, where all (960) ± CG discharges are plotted, shows that only the discharges clustered around the GCPs, within a distance of about ± 300 km, generated LOREs that have been detected.

[23] To better quantify the effect of discharge location on the observation of LORE events, we computed the minimum distance from the lightning location to each of the GCPs shown in Figure 1, to produce the histograms shown to the right of Figure 6. These histograms show the total number of discharges available (green color) and the LORE-causative discharges, using red color for positive (top plot) and blue for negative (bottom plot). As seen, the great majority of ± CG discharges that produced LOREs have distances to a GCP which are < 250 km. Also, the probability of LORE detection approaches zero if a ± CG discharge is located at a distance greater than ~300 km from all GCPs. This characteristic distance is 3 to 4 times larger than the ~50 to 100 km needed for a VLF link to detect an early/fast event [*Johnson et al.*, 1999], which implies that the LORE-related ionospheric disturbances are much more extended compared to those in relation with early/fast events. This is in agreement with *Salut et al.* [2012], which found that LOREs are observed over a wider distance (up to 250 km) above the causative lightning flash than ordinary early VLF events.

[24] Figure 7 is an *x-y* scatter plot for all CG available, as well as for the LORE-causative + CG (230) and – CG (110) discharges. The plot shows the nearest distance to a GCP (*y* axis) as a function of lightning peak current (*x* axis). The information needed for inspecting Figure 7 is given in its header and the color-coded points in the scatter plot. As shown in Figure 7, LORE detection is favored by the combination of large discharge current intensities and short distances to a VLF link GCP, which is mostly less than ~250 km. Figure 7 also shows that ± CG discharges with very large peak currents, (> ±300 kA), are very likely to produce a LORE if they occur within a 250 km zone about a Tx-Rx GCP. On the other hand, seen in Figure 7 are a large number of strong ± CG discharges which may not produce a LORE that is detected even though they are located relatively near the Tx-Rx GCPs and within the zone of ~250 km mentioned above. This, combined with the fact that an event may not be detectable by all links that have similar GCPs, means that there are more reasons involved in LORE generation and/or VLF detection, such as the path geometry, as discussed by *Nait Amor et al.* [2010]. This observation indicates that the requirement for a large peak current intensity and a short distance of discharge location to GCP is a strong contributing factor in the observation of LORE events, but this by itself is not a sufficient criterion for LORE detection. This matches a similar conclusion reached by *Haldoupis et al.* [2010] for the early/fast event occurrence in relation with sprites.

[25] Figure 8 better quantifies some of the points made above. It displays the occurrence distributions of LORE-causative CG discharges relative to the total number of CG lightning discharges, all occurring within a 300 km zone about the GCPs, representing ~88% of the total number of 960 discharges under consideration. The curves in Figure 8 show the relative occurrence rate, defined as the percent ratio of LORE-causative to the total CG discharges, for both positive (top plot) and negative (bottom plot) lightning discharges. The most important result here is the increase of relative LORE occurrence (or detection) rate with increasing discharge peak current intensity. The probability of LORE occurrence is about 20% to 30% for discharge peak currents ±250 kA and increases with increasing peak current, gradually approaching 100% for currents greater than 350 kA (keeping in mind of course that the statistical sample is rather small for these very large peak current discharges).

[26] We finish the results presentation with an additional observation regarding the seasonal dependence of LORE occurrence rate. The monthly distribution of intense ± CG discharges shown in Figure 1 indicates that LOREs occur overwhelmingly during winter; note that this is valid for the region under consideration and may not be valid worldwide. Out of the 960 ± CG discharges identified during the period from November 2009 to October 2010 under consideration, about 78% (746) occurred during the winter period from November to April and the rest, 22% (214), during the summer interval from May to October. A first look at the relative LORE occurrences during these two 6 month periods differ significantly, that is, 45% (34%) of positive (negative) CG discharges producing LOREs for the winter period, as compared to 17% (14%) for the summer period. The large

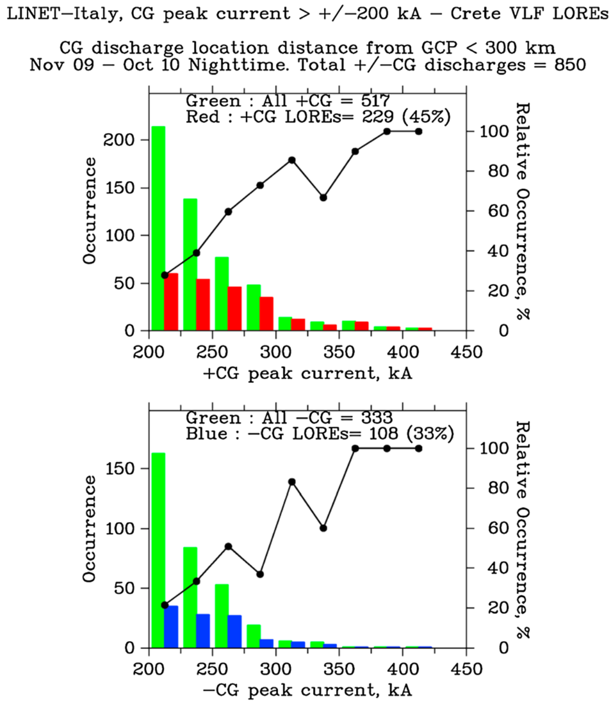

Figure 8. The plots here illustrate statistically that the probability of LORE occurrence (or detection) increases with ± CG peak current intensity if the causative discharge is located within a distance of ~300 km to a VLF link great circle path.

differences in the relative occurrence rate of LOREs between winter and summer may be attributed, at least partly, to the fact that ± CG discharges with peak currents >200 kA are on average more intense in winter (mean is ~243 kA) than in summer (mean is ~232 kA). This attribution, however, should be treated as tentative since there is need for a more detailed study on this matter.

4. Discussion

[27] The present results clarify and supplement the work on LOREs of *Haldoupis et al*. [2012], which relied on a single storm that gave only + CG discharges of high peak current and happened to produce LOREs in connection with elve and sprite pairs. Here we establish that LOREs can be caused equally well by either a positive or negative CG discharge of intense peak current. Given that a sprite has its origin in positive CG discharges of large charge moment change (e.g., *Cummer and Lyons* [2005] and the recent review by *Pasko et al*. [2012]), the present findings are important because they point to the origin of LOREs to be in strong lightning EMP fields impacting the upper D region ionosphere. This implies that the postulation of *Haldoupis et al*. [2012] that LOREs may relate to a coupling process which involves both EMP and QE fields acting upon the ionospheric plasma in sequence, is likely not correct.

[28] The lightning-induced EMP effects on the nighttime ionosphere have been studied theoretically and simulated numerically in several papers, e.g., see recent paper by *Marshall* [2012] and references therein. In all studies, the EMP effects are confined to altitudes higher than ~80 and include excitation of optical emissions, known as elves, and ionization changes induced by the heated ambient electrons under the EMP field action. The ionization changes include both electron density increases ($+\Delta N_e$) by ionization impact at altitudes higher than ~85 km and electron density decreases ($-\Delta N_e$) by electron attachment processes at altitudes lower than ~85 km [e.g., see *Taranenko et al*., 1993]. Actually, the role of a powerful lightning EMP in the generation of momentary airglow emissions in the uppermost D region and lower E region between about 85 and 105 km was predicted theoretically before the discovery of elves [*Inan et al*., 1991; *Taranenko et al*., 1993]. Elves are now established as being the TLE fingerprint of either positive or negative CG discharges emitting strong EMPs which impact onto the uppermost D region and the lower E region ionosphere.

[29] As in the case of elves which were predicted to exist prior to their discovery, there are references in the literature predicting that strong lightning EMPs producing elves should also be associated with a unique VLF signature in subionospheric narrowband VLF transmissions. For example, in his review, *Rodger* [2003] discussed the potential of large VLF perturbations accompanying elves by referring to theoretical predictions of strong lightning EMPs producing long-lasting ionization increases at high D region altitudes near the nighttime VLF reflection heights (~ 85 to 90 km). *Rodger* [2003] further postulated that elve-related VLF perturbations should exist and went on to suggest that "the relaxation of such perturbations to pre-event levels would be expected to be extremely slow due to the long lifetimes of electrons at elves-altitudes" and that "such perturbations would likely appear as sudden step-like changes in received (VLF) amplitude and phase signals without a clear relaxation signature." It is astonishing that such predictions made ~15 years ago are now confirmed by the experimental findings of the present study, particularly the detection and identification of the step-like LORE as the dominant type of VLF perturbations associated with powerful lightning EMPs.

[30] Although there were no systematic concurrent TLE measurements for the present study, the findings here indicate that LOREs are the VLF counterpart of elves, since elves are well known to be caused by powerful ± CG lightning EMPs. This claim was verified by the single storm study of 12 December 2009 made by *Haldoupis et al*. [2012] where very intense + CG discharges were always accompanied with elves, and in that case, with sprites as well. Also, the present results confirm the validity of the statement "elves were always accompanied by large amplitude VLF perturbations" made by *Fukunishi et al*. [1996] in the first observational paper on elves, where they referred on concurrent, but never published, narrowband VLF observations.

[31] The key property that is unique to the LORE signature and needs to be understood is their long recoveries. In considering this property, however, we need to stress that the observations identified basically two LORE categories, that is, those which recover gradually to pre-event levels within times of several minutes to many minutes and step-like events which have very slow or no imminent relaxation phase. It is also important to stress that there are often LORE events which display both types simultaneously at different VLF links, that is, a clear gradual recovery to pre-event signal levels in one link, whereas another link observes a

step-like perturbation which does not have a clear recovery (e.g., see in Figure 5 the event triggered by the +400 kA stroke; also such a clear case was presented and discussed by *Haldoupis et al*. [2012, Figures 2 and 3]). Naturally, an important implication here is that the two LORE categories, which apparently possess different recovery properties, relate to different physical processes that require more research and quantitative modeling in order to be understood. Since this is beyond the scope of the present paper, we offer below here in brief only some qualitative ideas for their interpretation.

5. Possible Physical Mechanisms

[32] We postulate, based also on *Rodger*'s [2003] suggestions, that LORE events with gradual recoveries are likely due to EMP-driven impact ionization increases in the uppermost D region (~85 to 90 km) and the subsequent generation of ionospheric disturbances there. These disturbances may reach down to VLF reflection heights to forward scatter the incident VLF signal which then can be superimposed on the direct signal at the receiver to produce a LORE-type perturbation. In this case, the VLF perturbation amplitude recovers according to the relaxation rate of the elevated electron density. At uppermost D region heights, the electron density relaxation is predominantly due to molecular dissociative recombination, which, as shown by *Rodger et al.* [1998, 2001], is a relatively slow process there that can easily account for the observed LORE recovery times of approximately 5 to 20 min, depending on the assumed altitude and the absolute level of the elevated electron density.

[33] With respect to the step-like events which do not recover to pre-onset levels, apparently, these could relate to a longer-lasting modification in the upper D region ionosphere caused also by the same powerful lightning EMP that causes ionization increases above ~85 km which relax slowly within several to many minutes. Our data cannot by itself provide a clue as to what is happening in the step-like cases; thus, we hypothesize on the following idea as a possible interpretation.

[34] According to all theoretical-lighting EMP models [e.g., *Taranenko et al*., 1993; *Rowland et al*., 1996; *Marshall et al*., 2008; *Marshall*, 2012], the only significant EMP effect on upper D region ionization, other than electron production by impact above 85 km, is electron density depletion due to electron attachment at altitudes below about 80 to 85 km. This electron depletion below combined with the increase in ionization above causes a sudden sharpening of the upper *D* region electron density profile near 85 km, which in turn, may have a remarkable effect on VLF propagation signals. As discussed by *Inan et al*. [1993], a sharpening in electron density profile may act as a good reflector that increases the reflection coefficient for all waveguide VLF modes. This, combined with a reduced absorption for the signal along its path below the reflection height, can lead to step-like amplitude increases of the direct signal at the receiver. This anticipation could very well be in connection with the observed step-like LORE events which nearly always show a positive amplitude jump. In addition, these events may associate with large horizontal disturbances, comparable in extent to those of elves (say 200 to 500 km), which may act as effective VLF reflectors. As for the absence of recovery in step-like LOREs, this can be explained if we accept the premise that electron detachment is indeed a very slow process during nighttime in the upper D region, contrary to daytime when sunlight detaches the electrons rapidly. This is to say that after a massive attachment of electrons which is imposed instantly by a powerful lightning EMP during nighttime at altitudes below 85 km, there is nothing particular to detach them fast from the negative ions; thus, the electron depletions live much (say 1–2 h) than electron recombination above 85km (from several to many minutes). Some justification for the existence of long detachment times during night is provided by *Glukhov et al*. [1992] who used a four constituent electrochemical model. Although the above interpretation ideas remain uncertain at present, it is worth proving or disproving their validity with more research, particularly more detailed modeling studies, a task that we plan to take up in the near future.

[35] Finally, we comment briefly on the absence of LOREs during daytime. In general, daytime early VLF events are difficult to be generated in the upper D region, apparently because QE and EMP fields are heavily attenuated in the presence of elevated daytime D region electrical conductivities. Also, even if a powerful EMP had somehow reached the uppermost D region to generate ionization by impact, such perturbations in electron density could not be detected because VLF reflection heights are lowered down during daytime to about 70 km. On the other hand, a powerful EMP is very unlikely to generate ionization changes near the daytime lower VLF reflection heights, mainly because the electron mean free path there is too small in order for the electrons to gain sufficient energy to trigger impact ionization production. One, however, may not exclude entirely the possibility of momentary electron density depletions due to attachment at heights as low as 70 km by extremely powerful EMPs during daytime, which then, and in principle, might be detected by subionospheric VLF waves, a point that also deserves future consideration.

6. Summary of Key Findings

[36] The present study, which relied on a large data set of narrowband VLF recordings and intense CG lightning discharges, identified the LORE as a distinct signature from early VLF events, rather than the tail end of a probabilistic distribution of recovery times. The term "long-recovery early event" (LORE) is used to describe the signature in general. The term "step-like LORE," which is launched here to describe abrupt narrowband VLF amplitude perturbations with either very long or no clear recovery, constitutes the dominant subcategory of the LORE events. The key findings are summarized as follows.

[37] 1. LOREs are long-lasting VLF perturbations which occur in relation with long-lived ionospheric modifications generated, in the uppermost D region, by EMPs emitted from powerful CG lightning discharges of either positive or negative polarity.

[38] 2. In most cases, the VLF signal level is offset in a step-like fashion showing no imminent or very slow recovery; less frequently, the event may have a clear gradual recovery to pre-onset levels. Often, the recovery time associated with these events is superimposed on slowly varying ionospheric conditions which may sometimes mask the event duration.

[39] 3. LORE onset amplitudes range from a fraction of dB to several dB and are overwhelmingly positive, that is, the VLF signal amplitude increases; this is nearly always true for step-like LOREs.

[40] 4. The LORE occurrence/detection is favored strongly when ± CG discharges have very large peak currents (say ±250 kA) and occur within 200–300 km (say < 250 km) from the GCP of a transmitter-receiver VLF link.

[41] 5. The combination of a strong CG peak current discharge and a short distance of discharge location to a GCP increases the likelihood for LORE detection, but these conditions may not be always sufficient.

[42] 6. LORE-causative ± CG discharges represent a very small subset, less than about ~0.5% of the total number of lightning discharges.

[43] 7. LOREs are observed during nighttime when VLF reflection heights reach the uppermost D region heights and preferentially during winter when intense ± CG discharges are more frequent and carry higher peak currents. Since the associated ionization changes occur at higher altitudes (> 80 km), LOREs last longer because the electrochemical recovery times there are slower due to lower neutral densities.

[44] 8. Very powerful positive CG discharges can produce both an early/fast and a step-like LORE, therefore forming by superposition a composite VLF signature; this is likely coming from the combination of lightning QE and EMP fields acting at different altitudes in the upper *D* region ionosphere.

[45] 9. The evidence overwhelmingly suggests that LORE is a unique signature that represents the VLF counterpart, or the VLF fingerprint, of elves. This is a new finding which has been predicted to occur regularly but somehow escaped experimental identification in the long-going research of VLF studies of lightning effects in the ionosphere.

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References

Barrington-Leigh, C. P., U. S. Inan, and M. Stanley (2001), Identification of sprites and elves with intensified video and broadband array photometry, *J. Geophys. Res.*, *106*, 1741.

Betz, H.-D., K. Schmidt, P. Oestinger, and M. Wirz (2004), Lighting detection with 3-D discrimination of intracloud and cloud-to-ground discharges, *Geophys. Res. Lett.*, *31*, L11108, doi:10.1029/2004GL019821.

Christian, H. J., et al. (2003), Global frequency and distribution of lightning as observed from space by the Optical Transient Detector, *J. Geophys. Res.*, *108*(D1), 4005, doi:10.1029/2002JD002347.

Cohen, M. B., U. S. Inan, and E. W. Paschal (2010), Sensitive broadband ELF/VLF radio reception with the AWESOME instrument, *IEEE Trans. on Geoscience and Remote Sensing*, *48*(1), 3–16, doi:10.1109/TGRS.2009.2028331.

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.

Cummer, S. A., and W. A. Lyons (2005), Implications of lightning charge moment changes for sprite initiation, *J. Geophys. Res.*, *110*, A04304, doi:10.1029/2004JA010812.

Dowden, R. L., J. B. Brundell, and C. J. Rodger (1997), Temporal evolution of very strong Trimpis observed at Darwin, Australia, *Geophys. Res. Lett.*, *24*, 2919–2422, doi:10.1029/97GL02357.

Fukunishi, H., Y. Takahasi, M. Kubota, K. Sakanoi, U. S. Inan, and W. A. Lyons (1996), Elves: Lightning-induced transient luminous events in the lower ionosphere, *Geophys. Res. Lett.*, *23*, 2157–2160, doi:10.1029/96GL01979.

Glukhov, V., V. Pasko, and U. Inan (1992), Relaxation of transient lower ionospheric disturbances caused by lightning-whistler-induced electron precipitation, *J. Geophys. Res.*, *97*, 16,951–16,979.

Haldoupis, C., Neubert, T., Inan, U. S., Mika, A., Allin, T. H., 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.

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., A. Mika, and S. Shalimov (2009), Modeling the relaxation of early VLF perturbations associated with transient luminous events, *J. Geophys. Res.*, *114*, A00E04, doi:10.1029/2009JA014313.

Haldoupis, C., N. Amvrosiadi, B. R. T. Cotts, O. A. 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.*, *125*, A07304, doi:10.1029/2009JA015165.

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.

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

Inan, U. S., T. F. Bell, and J. V. Rodriguez (1991), Heating and ionization of the lower ionosphere by lightning, *Geophys. Res. Lett.*, *18*(4), 705–708.

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., A. Slingeland, V. P. Pasko, and J. V. Rodriguez (1996), VLF and LF signatures of mesospheric/lower ionospheric response to lightning discharges, *J. Geophys. Res.*, *101*, 5219–5238, doi:10.1029/95JA03514.

Inan, U. S., S. A. Cummer, and R. A. Marshall (2010), A survey of ELF/VLF research of lightning-ionosphere interactions and causative discharges, *J. Geophys. Res.*, *115*, A00E36, doi:10.1029/2009JA014775.

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

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.

Marshall, R. A. (2012), An improved model of the lightning electromagnetic field interaction with the D-region ionosphere, *J. Geophys. Res.*, *117*, A03316, doi:10.1029/2011JA017408.

Marshall, R. A., U. S. Inan, and T. W. Chevalier (2008), Early VLF perturbations caused by lightning EMP-driven dissociative attachment, *Geophys. Res. Lett.*, *35*, L21807, doi:10.1029/2008GL035358.

Marshall, R. A., U. S. Inan, and V. S. Glukhov (2010), Elves and associated electron density changes due to cloud-to-ground and in-cloud lightning discharges, *J. Geophys. Res.*, *115*, A00E17, doi:10.1029/2009JA014469.

Moore, C. R., C. P. Barrington-Leigh, and 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 EuroSprite-2007 campaign, *J. Geophys. Res.*, *115*, A00E47, doi:10.1029/2009JA015026.

Neubert, T., et al. (2005), Co-ordinated observations of transient luminous events during the EuroSprite2003 campaign, *J. Atmos. Sol-Terr. Phys.*, *67*, 807–820.

Pasko, V. P., M. A. Stanley, J. D. Mathews, U. S. Inan, and T. G. Wood (2002), Electrical discharge from a thundercloud top to the lower ionosphere, *Nature*, *416*, 152–154, doi:10.1038/416152.

Pasko, V. P., Y. Yair, and C.-L. Kuo (2012), Lightning related transient luminous events at high altitude in the Earth's atmosphere: Phenomenology, mechanisms and effects, *RSpace Sci. ev.*, *168*, doi:10.1007/s11214-011-9813-9.

Poulsen, W. L., U. S. Inan, and T. F. Bell (1993), A multiple-mode three-dimensional model of VLF propagation in the earth-ionosphere waveguide in the presence of localized D-region disturbances, *J. Geophys. Res.*, *98*, 1705–1717.

Rakov, V. A., and M. A. Uman (2003), *Lightning: Physics and Effects*, Cambridge University Press, New York.
Rodger, C. J. (2003), Subionospheric VLF perturbations associated with lightning discharges, *J. Atmos. Sol.-Terr. Phys.*, *65*, 591–606.
Rodger, C. J., O. A. Molchanov, and N. R. Thomson (1998), Relaxation of transient ionization in the lower ionosphere, *J. Geophys. Res.*, *103*, 6969–6975.
Rodger, C. J., M. Cho, M. A. Cliverd, and M. J. Rycroft (2001), Lower ionosphere modification by lighting-EMP: Simulation of the nighttime ionosphere over the United States, *Geophys. Res. Lett.*, *28*, 199–202.
Rowland, H. L., R. F. Fernsler, and P. A. Bernhardt (1996), Breakdown of the neutral atmosphere in the D-region due to lightning driven electromagnetic pulses, *J. Geophys. Res.*, *101*, 7935.
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.
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 (1993), *Geophys. Res. Lett.*, *20*, 2675–2678.
van der Velde, O. A., J. Bor, J. Li, S. A. Cummer, E. Armone, F. Zannotti, M. Fullekrug, C. Haldoupis, S. NaitAmor, and T. Farges (2010), Multi-instrument observations of a positive gigantic jet produced by a winter thunderstorm in Europe, *J. Geophys. Res.*, *115*, D24301, doi:10.1029/2010JD014442.