題名　ISWI Newsletter - Vol. 4 No. 107
差出人　George Maeda

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* ISWI Newsletter - Vol. 4 No. 107                         24 October 2012 *
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*           I S W I  =  International Space Weather Initiative               *
*                          (www.iswi-secretariat.org)                        *
*                                                                            *
* Publisher:        Professor K. Yumoto, ICSWSE, Kyushu University, Japan  *
* Editor-in-Chief:  Mr. George Maeda, ICSWSE (maeda[at]serc.kyushu-u.ac.jp)*
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Attachment(s):
(1) "AWESOME 2012-10", 901 KB pdf, 6 pages.
(2) "AWESOME 2012-12", 768 KB pdf, 7 pages.
(3) "SARA_SpaceWeather" 974 KB pdf, 3 pages.

:   Re:
:   (1) Link for "2012 ISWI and MAGDAS School"
:   (for photos and lecture notes).
:   (2) Some AWESOME developments!
:   (3) SARA's contributions to Space Weather

Dear ISWI Participant:

There three news items today:

----------(1)
As briefly mentioned in "ISWI Newsletter" Volume 4, Number 102, the "2012 ISWI and MAGDAS School on Space Science" (hosted by LAPAN of Indonesia) was a great success. All the lecture notes and some event photos are now available at this website:
http://iswimagdas2012.dirgantara-lapan.or.id/program.html
Check it all out !!!

Please be informed that this ISWI school was No. 3.
(No. 1 was in Ethiopia two years ago, and No. 2 was in Slovakia last year; school reports for No. 1 and No. 2 can be found in the ISWI Newsletter archives.) This school is intended to be an annual event. School No. 4 will take place in Africa next year. Stay tuned to this newsletter for details.

----------(2)
The following note was received from Dr Morris Cohen of Stanford University. The two papers that he refers to are attached to this email (in the usual fashion). Note that AWESOME is one of the major ISWI instrument arrays. I am pleased to see his results today ! .... thank you Morris for sending this in.

: Hi George,
:
: I think it's time we spotlight a contribution from the AWESOME network.
:
: I'm attaching two papers that use the AWESOME network to discuss
: so-called "long recovery events". These are D-region ionospheric
: disturbances cause directly above powerful lightning strokes that

: can take many minutes to recover from. They are distinct because
: most ionospheric disturbances from lightning (known as "early VLF
: events") decay away within a couple minutes, with the exception of
: an apparently distinct class which last much longer. There have
: been two papers published in the past couple months that utilize
: the AWESOME/IHY/ISWI array to study these phenomenon.
: Here are the links:
:
: http://vlf.stanford.edu/sites/default/files/publications/2012-12.pdf
: http://vlf.stanford.edu/sites/default/files/publications/2012-10.pdf
:
: Thanks and I hope the Ecuador meeting went smoothly.
:
: Best,
:   -Morris
: Friday, 19 Oct 2012
: ____________________
: Dr. Morris B. Cohen
: Stanford University
: 350 Serra Mall, Room 315
: Stanford, CA 94305 USA

----------(3)
SARA (Society of Amateur Radio Astronomers) has become a regular
contributor to this newsletter. Attached as pdf is a short
report on their contributions to space weather. Consider joining
SARA as it is only 20 USD per year.

:   * * *

Please encourage your space weather colleagues and students to
subscribe to the ISWI Newsletter, which is now in its fourth year
of publication here at Kyushu University in beautiful Fukuoka
in southern Japan. This newsletter exists to circulate information
for the entire ISWI community.

Most respectfully yours,
:   George Maeda
:   The Editor
:   ISWI Newsletter

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 117, A08311, doi:10.1029/2012JA017567, 2012

Long recovery VLF perturbations associated with lightning discharges

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Received 26 January 2012; revised 28 June 2012; accepted 28 June 2012; published 10 August 2012.

[1] Long D-region ionospheric recovery perturbations are a recently discovered and poorly understood subcategory of early VLF events, distinguished by exceptionally long ionospheric recovery times of up to 20 min (compared to more typical ~1 min recovery times). Characteristics and occurrence rates of long ionospheric recovery events on the NWC transmitter signal recorded at Malaysia are presented. 48 long recovery events were observed. The location of the causative lightning discharge for each event is determined from GLD360 and WWLLN data, and each discharge is categorized as being over land or sea. Results provide strong evidence that long recovery events are attributed predominately to lightning discharges occurring over the sea, despite the fact that lightning activity in the region is more prevalent over land. Of the 48 long recovery events, 42 were attributed to lightning activity over water. Analysis of the causative lightning of long recovery events in comparison to all early VLF events reveals that these long recovery events are detectable for lighting discharges at larger distances from the signal path, indicating a different scattering pattern for long recovery events.

Citation: 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.

1. Introduction

[2] The intense electromagnetic pulse (EMP) radiated from powerful cloud-to-ground (CG) lightning discharges can couple directly into the lower ionosphere, producing transient localized *D*-region conductivity changes. This conductivity change perturbs the subionospheric propagation of Very Low Frequency (VLF, 3–30 kHz) transmitter signals through the region, producing detectable early/fast events on the VLF signal. These events are triggered within <20 ms ('early') after the causative lightning impulse with a <20 ms onset duration ('fast') [*Inan et al.*, 1988] followed by a slower relaxation of ionization to undisturbed levels in 60–180 s [*Sampath et al.*, 2000]. *Haldoupis et al.* [2006] demonstrated a new category of early events with comparatively longer onset duration (~1–2 s; 'slow') with similar recovery signatures. The gradual risetime of these events implied cumulative ionization generated by consecutive intracloud lightning discharges. These consecutive discharges appeared as clustered sferics in their broadband measurements. These events were labeled as 'early/slow' events. The term 'Early VLF events' applies to both early/fast and early/slow VLF events, to emphasize the small onset delay associated with direct coupling of the lightning electromagnetic energy to the lower ionosphere. Also, it has been shown that sprites are very often, if not always, associated with early VLF events [*Haldoupis et al.*, 2004, 2010].

[3] Recently, *Cotts and Inan* [2007] catalogued a new category of early VLF events with unusually long enduring recoveries of up to ~20 min, and suggested these long recovery events may be consistent with gigantic jets. *Lehtinen and Inan* [2007] proposed a new chemistry model for the stratosphere/lower ionosphere, and attributed the observation of early VLF events with long lasting 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. *van der Velde et al.* [2010] were the first to report a pellucid correlation between a gigantic jet event initiation and an early VLF event, although the recovery time was obscured by a subsequent sprite.

[4] *Cotts and Inan* [2007] classified three distinct types of long recovery events based on the recovery rates in amplitude and phase back to their ambient levels. Type 1 events display long amplitude recovery while the phase recovery resembles that of a typical early event (<200 s). Type 2 events exhibit long recovery signatures on both amplitude and phase. In type 3, or 'step-change', events the perturbed

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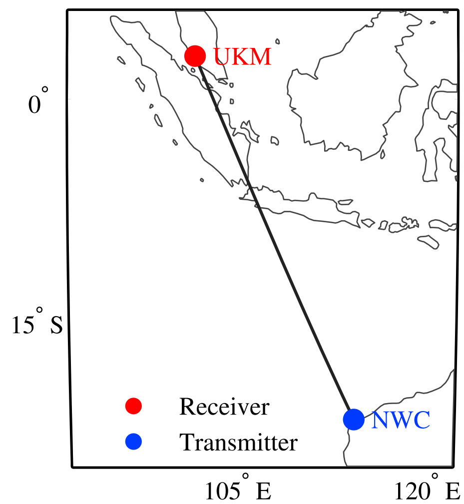

Figure 1. Geographic map showing the locations of the NWC transmitter, VLF receiver and the GCP.

signal fails to recover to its ambient conditions. A typical step-change early VLF event endures for 200 s [*Kumar et al.*, 2008; *Inan et al.*, 1996]. One suggested cause of the long recovery times is substantial ionization of heavy ions at lower altitudes (<50 km) [*Glukhov et al.*, 1992; *Pasko and Inan*, 1994] induced by gigantic jet events [*Lehtinen and Inan*, 2007].

[5] In this paper, we present a large new catalog of long recovery early VLF events observed at Universiti Kebangsaan Malaysia (UKM), on the VLF NWC signal. Long recovery events were studied previously by *Cotts and Inan* [2007] by monitoring multiple all-sea-based and all-land-based signal paths. The authors found that these events occur more often over the water-based signal paths. However, due to the lack of lightning location information, *Cotts and Inan* [2007] were unable to determine the scattering pattern of long recovery events, and were unable to distinguish the effect of the lightning location along the path, which is known to significantly affect the perturbed ionospheric signature [*NaitAmor et al.*, 2010]. The NWC to UKM path traverses over both ocean and land regions, providing further insight into the geographical distribution of long recovery events, and for the first time correlates the events with lightning discharge locations to investigate their VLF scattering patterns.

2. Instrumentation and Observations

[6] The VLF data presented here consist of the amplitude and phase of the NWC transmitter signal (21.8°S, 114.1°E; 19.8 kHz), as recorded by the Stanford-AWESOME receiver installed at UKM, Malaysia (2.55°N, 101.46°E) in 2009 and 2010. The Stanford-AWESOME receiver at UKM, described by *Cohen et al.* [2010], consists of two orthogonal crossed loop antennas to collect wideband magnetic fields as weak as a few fT/rt-Hz in both the North–South and East–West directions. The detected signal is bandpass filtered between 0.3–47 kHz and sampled at 100 kHz using GPS timing (<100 ns error). The amplitude and phase of narrowband signals at specific frequencies are demodulated and recorded at 50 Hz time resolution. The VLF receiver was distributed as part of the International Heliophysical Year (IHY) and United States Basic Space Science Initiative (UNBSS) [*Scherrer et al.*, 2008]. Data from the GLD360 network [*Said et al.*, 2010] and World Wide Lightning Location Network (WWLLN) [*Dowden et al.*, 2002] provide the time and location of each lightning strike along the transmitter-receiver great circle path (GCP). Comparing the timing of observed VLF events with lightning strikes recorded in the GLD360 and WWLLN data determines the location of the lightning discharge associated with each long recovery event. Neither GLD360 (~40–60% detection efficiency, 1–4 km accuracy) nor WWLLN (few % detection efficiency, 15–20 km accuracy) are able to detect all lightning discharges, so a causative discharge location cannot always be determined.

[7] Figure 1 shows the location of the NWC transmitter, VLF receiver and the GCP. NWC to UKM signal path is part-sea-based and part-land-based, providing a single VLF link to explore occurrence characteristics of long recovery events, whereas previous observation [*Cotts and Inan*, 2007] utilized multiple VLF paths with different frequencies (28.5, 40.75 kHz NAU and 24 kHz NAA) to investigate these events. Monitoring multiple VLF transmitters for studying the recovery signatures of the lightning-associated perturbations may create ambiguities due to the different ionospheric reflection height for each of these signals. *Mika et al.* [2006] observed that the recovery durations of the VLF events identified on the 18.3 kHz signal were significantly shorter than those detected in the 24.0 and 37.5 kHz signals. Also, *Kumar et al.* [2008] reported that early/fast VLF events observed on NWC signal exhibit faster recovery rates than those detected in the 21.4 kHz NPM.

[8] Most of the VLF data presented in this study were acquired during 83 active nights in October–December 2009 and April–December 2010. A total of 403 early VLF events were detected on the NWC signal received in UKM, Malaysia, and 48 of these events exhibited a long recovery (defined here as >200 s). The events were detected by visual inspection of the recorded VLF signal. We considered a detection threshold of ~0.2 dB for amplitude and ~2 degree for phase based on typical noise levels.

[9] The characteristics of the identified long recovery events are analogous to those reported by *Cotts and Inan* [2007], possessing three different long recovery signatures. Figure 2 displays examples of each of the three types of observed long recovery events. Figure 2a presents a Long-amplitude/short-phase recovery perturbation (Type 1). The amplitude of Event A displays a negative polarity perturbation of ~2 dB followed by a long recovery signature to undisturbed level in ~22 min, whereas the phase signature recovers in ~3 min like a typical early event. The expanded record of Event A (Figure 2b) shows a high resolution view of the amplitude signal event onset which coincides with a lightning discharge in the vicinity of the GCP. Event B of Figure 2c displays a large amplitude and phase perturbation on the VLF signal followed by a long recovery to pre-event level in both the amplitude and phase (Type 2). The expanded windows in Figure 2d show the high resolution (20 ms) examination of Event B within a ±5 second interval of the event onset, as well as a 12-point median filter (red line). The second immediately following the event onset (marked by the red dashed rectangle in Figure 2d) clearly

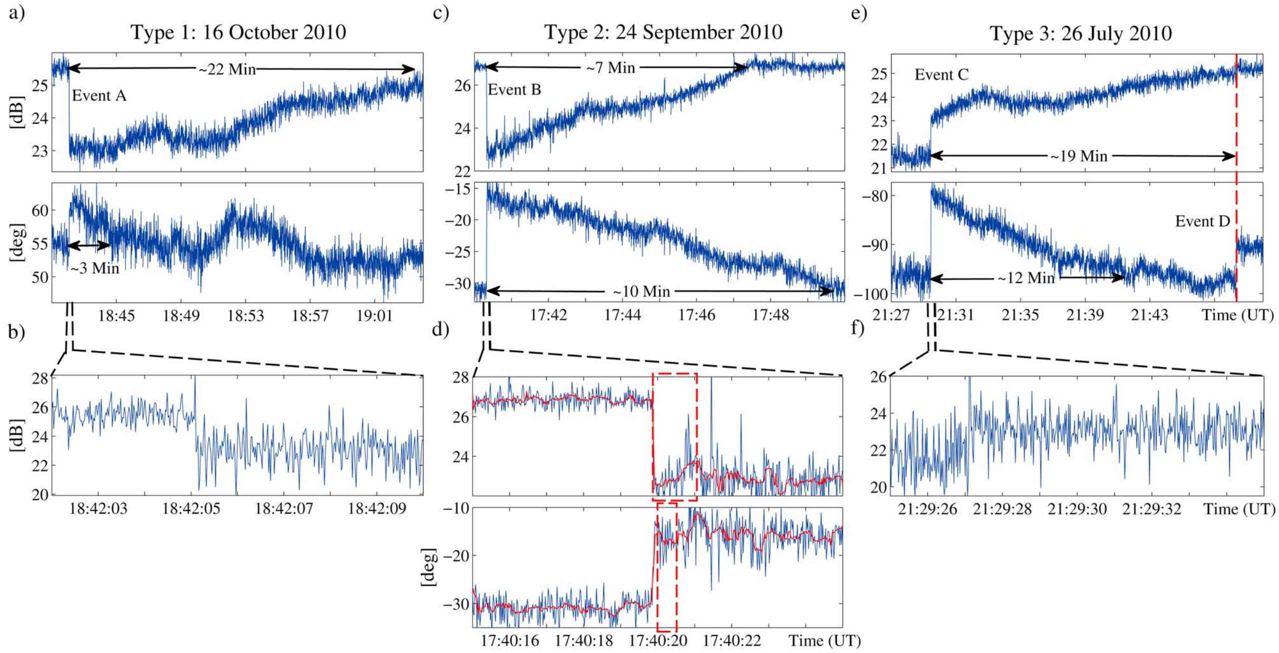

Figure 2. An example of a long recovery event of each type. (a) A type 1 long recovery event observed on 16 October 2010, referred to as Event A. (b) High resolution (20 ms) analysis of Event A. (c) A type 2 long recovery event observed on 24 September 2010, referred to as Event B. (d) An expanded view of the event onset with the initial rapid partial recovery highlighted in each plot. (e) A typical long enduring step-change event observed on 26 July 2010. There are two onset events occurring 19 min apart, these events are labeled C and D. (f) The onset of Event C.

displays an exponential rapid initial partial recovery. GLD360 and WWLLN did not record any lightning flashes precisely coinciding with this event onset, but WWLLN did detect a significant number of CG discharges near this time due to an active oceanic storm overlying the path. This suggests the approximate location of the causative discharge near the GCP. Event C of Figure 2e exhibits a lengthy step-change event (Type 3) whose amplitude perturbation does not recover to ambient levels, while the large perturbed phase signal recovers back to the ambient levels in ∼12 min. The impulsive sferic shown in Figure 2f is time-correlated with a lightning discharge recorded by WWLLN. Furthermore, occurrence of a powerful lightning discharge near the GCP produced the ∼0.2 dB and 6 degree perturbation which is labeled as Event D.

[10] Figure 3 displays histograms of amplitude and phase changes associated with all early VLF events detected on the NWC signal received at UKM. We detect amplitude and phase perturbations as high as ∼−4.4 dB and 23 degree respectively. The majority of the VLF events displayed amplitude perturbations between −1.5 and +1.5 dB and phase perturbations between −10 and +10 degrees. To estimate the size of the region affected by early and long recovery events, we measured the lateral distance of the causative lightning of all VLF events from the signal path. Figure 4a shows the locations of the lightning responsible for all detected early VLF perturbations. Figure 4b shows that the causative lightning discharges of 259 of the 355 early VLF events occur within 100 km of the GCP from the transmitter to receiver, and are thus associated with narrow-angle scattering for our geometry. This 73% rate is consistent with past studies [*Inan et al.*, 1996; *Johnson et al.*, 1999]. In the other 96 events, the causative lightning discharges were situated 100–350 km from the GCP, implying wide-angle scattering. Figure 4c and 4d show the locations and lateral distance of the lightning discharges for the long recovery events. Only 44% of the long recovery events correlate with lightning discharges within 100 km of the GCP; the lightning responsible for the other 27 long recovery events were 100–350 km from the signal path. We should also note that the causative lightning for all our observed VLF events

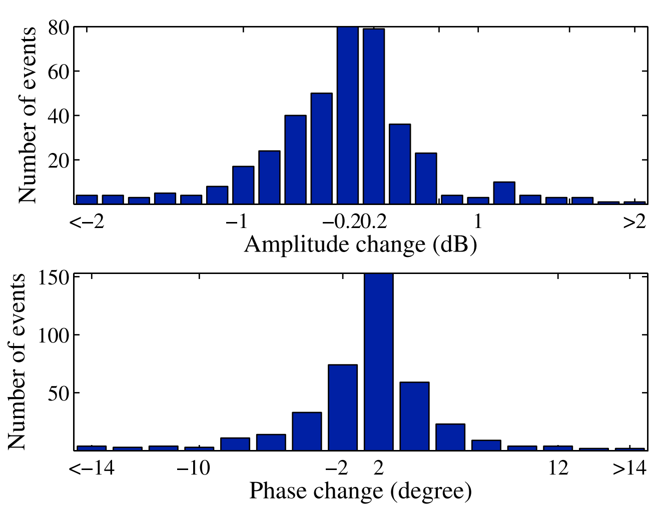

Figure 3. Histograms of the amplitude and phase perturbations associated with all early VLF events.

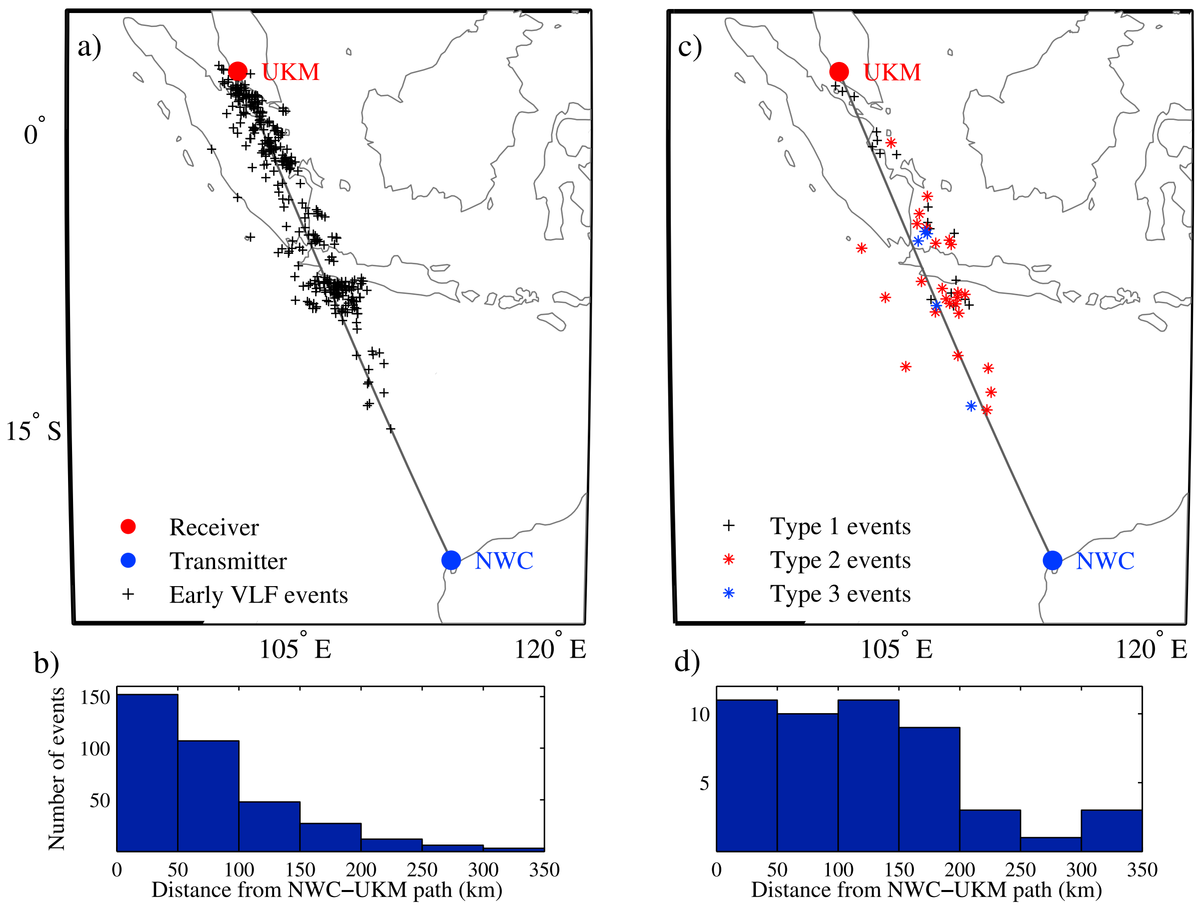

Figure 4. (a) Map shows the locations of the causative lightning discharges associated with early VLF events. (b) Distribution of the lateral distance of the causative lightning of early VLF event from the signal path. (c) Map of the lightning flashes time-correlated with the onset of long recovery events. The black crosses and red and blue asterisks indicate the location of the lightning responsible for Type 1, 2 and 3 long recovery events respectively. (d) Distribution of the lateral distance of the causative lightning of long recovery events from the GCP.

occurred within ~350 km of the GCP, which is consistent with the size of optical emissions observed during elves [*Inan et al.*, 1997].

[11] To investigate the geographic distribution of long recovery events, we divided all observed events into two subsets: land events and sea events. Since thunderstorm cells may be tens of km wide, Land events are classified as those events that occur over land and within 20 km of the coastline, otherwise the event is classified as a sea event. The causative lightning discharges of 8 events (16.7% of the total long recovery observations) were not identified. It is possible that the causative lightning discharges in these cases were simply not detected by the GLD360 and WWLLN, whose CG detection efficiencies are estimated at about 40–60% and a few percent, respectively. Even in these cases, however, the lightning detection networks located active storms overlying the path during the events. All 8 of the unidentified events coincide exclusively with oceanic storms overlying the GCP, so they were each classified as sea events. Table 1 shows the total number of early VLF events over the sea and land areas as well as the percentage of events which exhibit the recovery duration of >200, 540 and 1000 sec. An overwhelming majority (87%) of the observed >200 sec long recovery events correlate with lightning discharges located over the sea. This occurred despite the observation that lightning discharges along the signal path occur mostly over land areas rather than over the sea, with an average ratio of ~4:1. In particular, as the recovery time gets longer, the tendency for the event to be over the sea increases. The distribution of the causative lightning locations for each of these event types is presented in Table 2. Type 1 and Type 2 events were the more prevalent cases, and Type 3 events were much rarer.

3. Discussion

[12] We investigated characteristics and occurrence rates of long recovery events in association with lightning discharges. There is general agreement between our observed long recovery events and those presented by *Cotts and Inan* [2007], including three distinct recovery signatures, and a sporadic rapid (~0.5–1 s) initial partial recovery observed in some cases. The recent chemistry model of stratospheric/lower-ionospheric altitude proposed by *Lehtinen and Inan* [2007] suggests that gigantic jet discharges are able to produce early/fast perturbations on subionospheric VLF signals

Table 1. Distribution of the Lightning Located Within ~350 km of the GCP and All Early VLF Events Observed on the NWC Signal Received in UKM, Malaysia

Lightning Location	Lightning Flashes	Total Events	Recovery t_r < 200 s	Recovery 200 s ≤ t_r < 540 s	Recovery 540 s ≤ t_r <1000 s	Recovery t_r ≥ 1000 s
Sea	100144	231	53%	83%	87%	100%
Land	378351	172	47%	17%	13%	0%
Total	478495	403	355	23	15	10

with prolonged recoveries in range of $\sim 10^3$–10^4 s. They classified such long recovery signatures into two stages. The initial stage exhibits a fast recovery which endures for a few seconds due to the attachment detachment of electrons as illustrated in red dashed rectangular in Figure 2d. This initial stage, however, may not be observable in VLF data (e.g., Figure 2b) due to the high electric field induced by gigantic blue jets [*Lehtinen and Inan*, 2007]. This initial rapid recovery is followed by a lengthy recovery stage produced by the process of the mutual neutralization of negative and positive ions at lower altitudes (<50 km) which can persist for tens of minutes.

[13] The causative lightning of long recovery events were located on the average at larger distances from the GCP relative to the distances of typical early VLF events. Results of Figure 4a and 4b indicate that the majority of early VLF event-associated lightning are located near the signal path, whereas Figure 4c and 4d clearly show that long recovery early VLF events do not follow this distribution. We should also note that this larger scattering pattern observed in long recovery events may imply different physical mechanism or origin.

[14] The causative lightning of all VLF events are separated into land and sea subsets, as presented in Tables 1 and 2, due to the strong discrepancy in sea/land lightning occurrence rates and properties. This strong discrepancy is based on a substantial difference in sea/land thermal characteristics. During daytime, land surface temperature becomes higher than oceans, producing stronger updraft intensity, and this lead to dominance of lightning flash rate density over land areas [*Williams and Stanfill*, 2002; *Williams et al.*, 2004]. However, the average peak current of oceanic CG lightning appears to be stronger than their land counterpart due to the higher conductivity of the oceanic salt water relative to land surface [*Seity et al.*, 2000; *Füllekrug et al.*, 2002]. *Chen et al.* [2008] observed that lightning discharges with peak current higher than 80 kA occur 10 times more prevalent over the sea than land; whereas lightning flash rates in average is 10 times lower over the sea than over land areas [*Christian et al.*, 2003]. Also, we should note that lightning activity in general along the GCP from the NWC transmitter to the receiver, was much more prevalent over land areas than over the sea, according to the GLD360 and WWLLN measurements. By analysis of the geographical distributions of the 48 long recovery events, we have determined that 42 events occurred over the sea while only 6 events occurred over land and within ~20 km of the coastline. However, the collection of 403 early VLF events in general does not exhibit this trend. Since the ground conductivity does not affect the recovery signature of the early VLF event, the connection between the sea/land location and the recovery is likely a function of the type of lightning event that triggers the ionospheric disturbance, one that is more prevalent over water.

[15] Gigantic jets have been classified into three different types based on their morphological evolution and spectral properties [*Chou et al.*, 2010]. *van der Velde et al.* [2010] reported the first correlation between a positive polarity type 3 gigantic jet initiation and a −2 dB amplitude perturbation observed on narrowband VLF signal monitored at Stanford-AWESOME network in Tunisia. Unfortunately, the occurrence of a sprite triggered by a powerful +CG lightning right after the event onset disturbed the recovery signature and produced another −2 dB perturbation. The low occurrence rate of gigantic jets is the main difficulty in establishing the correlation between different types of long recovery events and gigantic jets. Therefore, to investigate the feasible relation between gigantic jets and long recovery events, we compare the statistical results of Table 1 with the occurrence rates of gigantic jets from past works. *Chen et al.* [2008] reported 13 gigantic jets recorded by ISUAL during a three year survey, with 69% observed over sea and 30% over land and coastal areas. Also, *Su et al.* [2002, 2003] reported observations of TLEs around Taiwan using ground campaigns in 2002 and 2003. The authors indicated that all gigantic jets (6 events) were attributed to oceanic storms. Since *Lehtinen and Inan* [2007] postulated recovery durations of $\sim 10^3$–10^4 s for early VLF events associated with gigantic jets, we compare this gigantic jet distribution to the distribution of our observed events with recovery duration ≥1000 s. Long recovery events with duration of ≥1000 s occur exclusively over the sea. This geographic distribution indicates that unusually long recovery events are associated predominantly with oceanic thunderstorm activities which lend support to the suggestion that long recovery VLF events may be consistent with the occurrence of gigantic jets.

4. Conclusion

[16] We presented characteristics and the occurrence properties of long recovery VLF perturbations in association with lightning discharges. The long enduring recoveries observed in certain early VLF events can be attributed to the lengthy process of the mutual neutralization of negative and positive ions at altitudes below 50 km which persist up to

Table 2. Distribution of Each of the Three Long Recovery Event Types Associated With Lightning Flashes Over the Sea, Coast, and Land[a]

Lightning Location	Type 1	Type 2	Type 3
Sea	12	25	5
Land	6	0	0
Total	18	25	5

[a]Type 1 exhibits long recovery in amplitude only, type 2 exhibits long recovery in amplitude and phase, and type 3 exhibits indefinitely long recovery.

20 min, consistent with theoretical prediction of *Lehtinen and Inan* [2007]. The recovery signatures of 12 events exhibit a rapid initial partial recovery lasting for ∼0.5 to a few seconds, which is the behavior to be expected due to attachment of electrons generated by gigantic jet discharges as postulated by *Lehtinen and Inan* [2007]. The vast majority of the long recovery events are attributed to lightning discharges located over the water, similar to the occurrence of gigantic jets observed by *Su et al.* [2003] and *Chen et al.* [2008]. However, more experimental research needs to be conducted to certify the possible correlation between different types of long recovery events and gigantic jets.

[17] Analysis of the causative lightning of long recovery and early VLF events indicates that lightning associated specifically with long recovery events is more likely to be located at larger distances from the signal path. This suggests a larger and/or denser ionospheric modification which speculates a distinct physical nature involved in this subset of events. We also note that, as the recovery time gets longer, the tendency for the event to be over the sea increases, and early VLF events with unusually prolonged recoveries (≥1000 s) are exclusively observed in association with oceanic thunderstorm activity.

[18] **Acknowledgments.** The UKM part of this work was supported by the research grant UKM-LL-02-FRGS0033-20/2007 and UKM-OUP-NBT-30-153/2011. We are grateful to Stanford University VLF research group and Umran Inan in particular for their continuous encouragement and support. The AWESOME receiver in UKM was distributed under a NASA grant to Stanford University as part of the International Heliophysical Year. The authors wish to thank GLD360 and WWLLN for providing the lightning location data used in this paper.
[19] Robert Lysak thanks the reviewers for their assistance in evaluating this paper.

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Long-lasting *D*-region ionospheric modifications, caused by intense lightning in association with elve and sprite pairs

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Received 23 June 2012; revised 17 July 2012; accepted 17 July 2012; published 28 August 2012.

[1] Observations show that intense +CG lightning discharges which trigger both an elve and a sprite are associated with long-lasting conductivity modifications in the upper *D*-region ionosphere. They are observed as strong perturbations in VLF signals propagating through the disturbed region, manifested as *LO*ng *R*ecovery *E*arly VLF events (LORE), which can last up to 30 minutes. These same ionospheric modifications are also responsible for step-like changes, seen mostly in off-storm VLF transmissions, which offset signal levels even for longer times. The evidence suggests that when a very intense positive cloud to ground lightning stroke leads to an elve and a high altitude sprite, and possibly a sprite halo as well, there is production of long lasting elevations in electron density at VLF reflection heights that cause LOREs and severe effects on VLF propagation. The present results confirm past predictions and postulations that elves may be accompanied by long-lasting electron density perturbations in the lower ionosphere.
Citation: 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.

1. Introduction

[2] Tropospheric lightning may couple electrical energy, through quasi-electrostatic (QE) and/or electromagnetic (EM) fields, directly into the upper atmosphere and lower ionosphere. This energy coupling is best manifested by the occurrence of "transient luminous events" (TLEs), which are momentary luminous structures of various types, such as "sprites", "sprite halos", "elves", "blue jets", and "gigantic jets" [e.g., see *Cummer and Lyons*, 2005; *Barrington-Leigh et al.*, 2001; *Fukunishi et al.*, 1996; *Pasko et al.*, 2002]. Lightning discharges may also cause heating and ionization changes directly in the overlying *D*-region ionosphere, therefore leading to conductivity enhancements [*Taranenko et al.*, 1993]. These conductivity enhancements may affect propagation of very low frequency (VLF) transmissions that travel long distances in the Earth-ionosphere waveguide, causing abrupt perturbations in the VLF signal amplitude and/or phase. These VLF perturbations are known as "early" VLF events and have been studied extensively (see review by *Inan et al.* [2010]). Optical and VLF correlative studies established a close relation between sprites, sprite halos and occasionally elves, with early VLF perturbations [*Haldoupis et al.*, 2004; *Marshall et al.*, 2006; *Mika and Haldoupis*, 2008; *Haldoupis et al.*, 2010].

[3] An important and often overlooked property of the early events is their recovery time, ranging typically between 10 and 100 seconds [*Inan et al.*, 2010]. It is controlled by the electron density relaxation time at mesospheric altitudes mostly between 65 and 80 km [e.g., *Pasko et al.*, 1995; *Moore et al.*, 2003; *Haldoupis et al.*, 2009]. In addition to the common early events, *Cotts and Inan* [2007] reported a much less frequent class, characterized by much longer recoveries of up to 30 minutes. The same study also reported step-like early-events, in which the observed perturbations do not recover to pre-onset values for at least 30 minutes to an hour. *Cotts and Inan* [2007] relied on theoretical calculations by *Lehtinen and Inan* [2007] to postulate that the long recovery events result from lower-altitude (<50 km), long-lasting conductivity relaxation times associated with the mutual neutralization of long-lived heavy ions in the lower ionosphere. They went further to suggest an association with "Gigantic Jets" (GJs), which are huge upward discharges connecting the top of a thundercloud at ~10 km with the upper *D*-region ionosphere near 90 km [*Pasko et al.*, 2002].

[4] In this letter we present key observational evidence showing that early VLF events with long-lasting and step-like recoveries occur in association with simultaneous large elves and high altitude sprites, both triggered together by very intense positive cloud to ground (+CG) lightning discharges. We propose that LOREs (*LO*ng *R*ecovery *E*arly VLF events) are caused by large and long-lived electron density enhancements in the uppermost *D*-region ionosphere.

2. Experiments and Data

[5] The present observations include lightning, TLE video images, and VLF radio recordings during a localized thunderstorm that occurred over the sea about 100 km west of Corsica, around 42°N; 7.5°E. It lasted for ~6 hours during the night of 12–13 December 2009, from about 21–03 UT, and produced many TLE events. After 22:20 UT, when video observations started, there were a total of 50 TLEs recorded, mostly sprites; among them were 8 sprite-elve pairs and a few sprite halos. There was also a spectacular gigantic jet, the first observed in Europe, which was studied in detail by *van der Velde et al.* [2010].

[6] The TLE observations were taken from the Italian mainland by Ferruccio Zanotti, a member of the Italian

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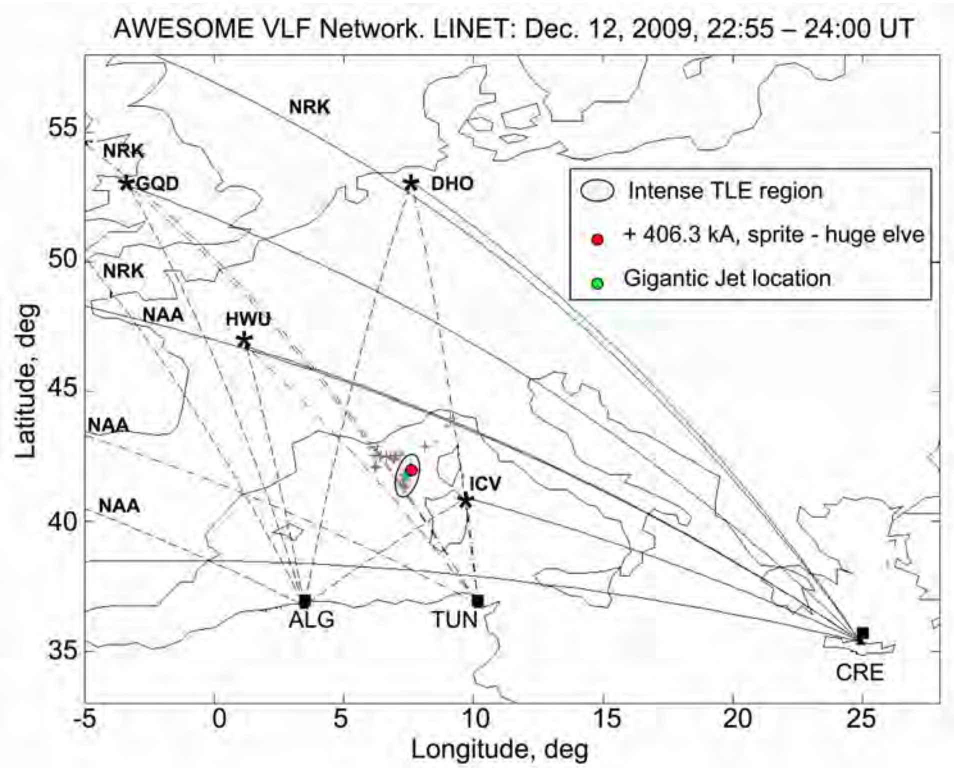

Figure 1. Geographic map showing transmitter (asterisk) and receiver (square) locations and great circle paths (GCPs) of the AWESOME VLF network in Europe and North Africa. The storm that produced the TLEs used in this study was located over the Mediterranean sea ~100 km west of Corsica. See text for details.

Meteor and TLE network (http:/www.imtn.it/), using a portable CCD color video camera located in Montignoso (44.01°N and 10.15°E), about 300 km northeast of the storm. The lightning data were provided by the European LIghtning detection NETwork (LINET). The VLF recordings were obtained with 3 narrowband receivers (Rx) located in Tunis, Crete and Algiers, all of which are part of the Stanford University AWESOME international VLF network [*Scherrer et al.*, 2008]. The AWESOME receivers [see *Cohen et al.*, 2010], are identical units using accurate GPS timing to sample at 20 ms the signals of various VLF transmitters (Tx) located around the globe.

[7] Figure 1 shows a map of VLF receiver locations (squares) and transmitters (asterisks), and great circle paths (GCPs) used in this study. We use four European transmitters (GQD-22.1 kHz, UK; DHO-23.4 kHz, Germany; HWU-20.9 kHz, France; ICV-20.27 kHz, Italy), along with NAA-24.0 kHz in Cutler ME, USA, and NRK- 37.5 kHz, in Keflavik, Island. Figure 1 also shows crosses identifying +CG lightning discharges measured by LINET from 22:55 to 24:00 UT. The shaded area depicts the region that produced powerful +CG discharges responsible for the strongest TLEs that occurred in relation with LOREs. Out of the 18 VLF links used in the present study, the NRK, GQD and HWU links to Tunis are the best suited for observing early VLF perturbations because their Tx-Rx GCPs pass through or near (<100 km) the storm, a condition that is necessary for narrow angle (forward) scattering and early VLF event detection [*Poulsen et al.*, 1993; *Johnson et al.*, 1999; *Haldoupis et al.*, 2010]. The rest of the Tx-Rx links, depicted also in Figure 1, have GCPs which are not optimal for early event detection because they pass relatively far from the storm, at distances larger than ~200 to 300 km.

3. Observations

[8] The present letter discusses LOREs and their association to TLEs. There were at least 10 LOREs which occurred during the storm, with recoveries ranging from 5–30 min. Analysis of all available data reveals that the stronger events are characterized by unusually large amplitude (5–10 dB) and phase perturbations (20°–80°) which occurred mostly in association with intense +CG lightning discharges (mostly from 150–400 kA peak currents) that produced both sprites and elves in the upper *D*-region ionosphere.

[9] The most prominent event was triggered by a powerful +CG 406.3 kA lightning stroke at 23:41:07.2613 UT, which was the strongest measured by LINET during the entire storm [*van der Velde et al.*, 2010]. This huge lightning discharge produced a spectacular elve at higher *D*-region altitudes as well as a cluster of sprite carrots and likely a sprite halo as well. The elve emissions expanded out radially over large distances, forming a momentary ring of light with an outer diameter estimated at ~500 km. This exceptional situation was accompanied by the onset of a long lasting modification of the upper *D*-region ionosphere, evidenced by a pronounced LORE in both VLF amplitude and phase. The onset amplitude perturbations of the “near-storm” HWU and NRK links to Tunis reached 8 and 5 dB, respectively, while it took them both more than 25 minutes to return back to pre-event levels. In addition this event also caused step

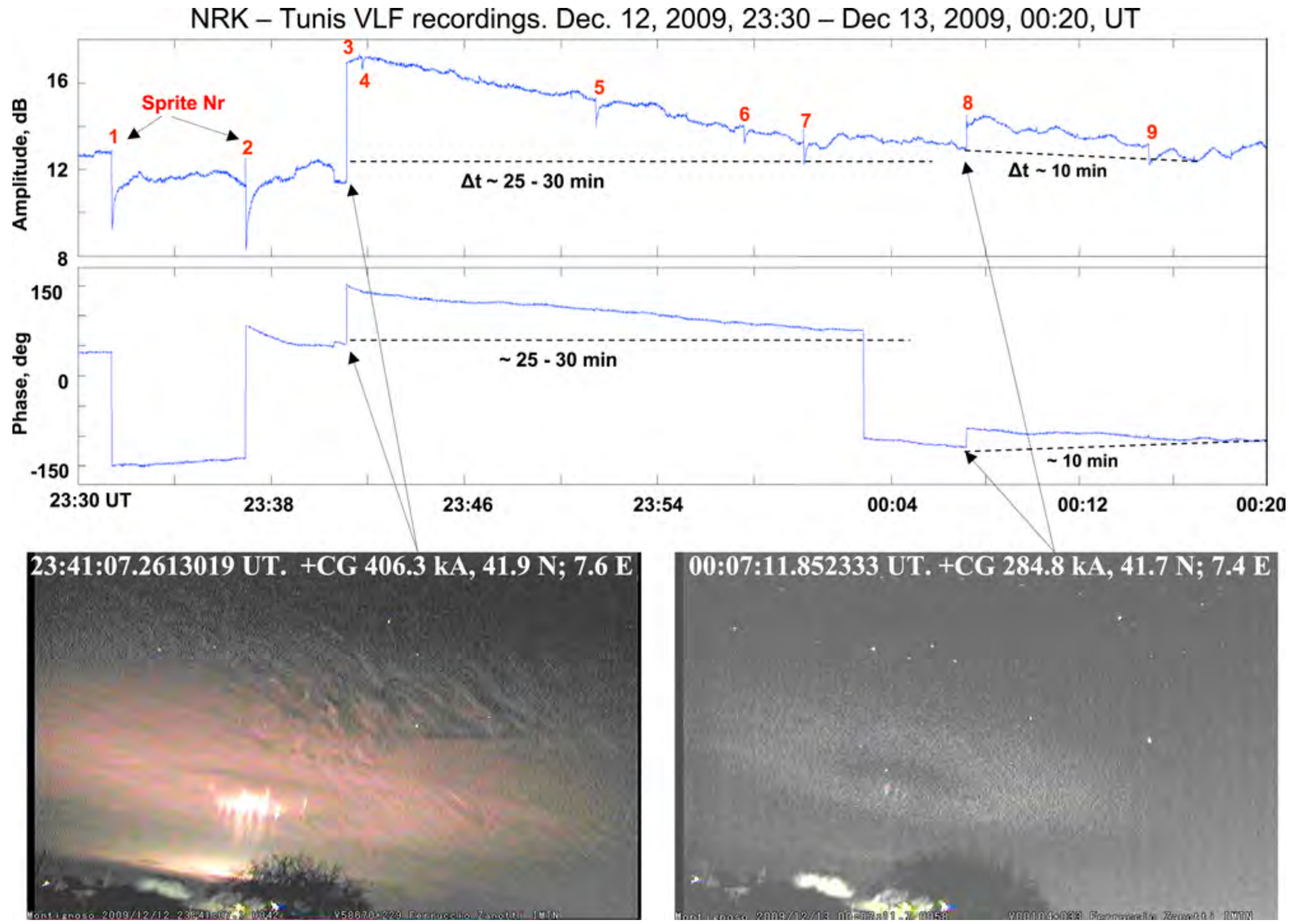

Figure 2. Large amplitude and phase perturbations of long recovery early VLF events caused by very intense +CG discharges, which trigger large elves and sprites in the upper *D*-region and apparently also long-lasting electron density perturbations.

like early perturbations in several VLF transmissions received in Algiers and Crete, for which their GCPs were "far-storm", passing at relatively large distances from the causative lightning flash. Surprisingly, the event caused no perturbation in the GQD-Tunis link despite that its GCP cut through the storm area (Figure 1).

[10] Figure 2 documents the main characteristics of the event. Shown in the upper part are time series of signal amplitude and phase for the NRK-Tunis link, recorded during the storm interval 22:30 to 00:20 UT of Dec. 12–13, 2009. During this time, there were 9 sprites observed (marked in Figure 2 by a count number) which occurred in full correspondence with onsets of early VLF events, in line with what has been reported by *Haldoupis et al.* [2004, 2010]. As seen in the lower left panel image, the exceptional +CG discharge triggered both an upper altitude sprite and an elve. The latter was immense, extending over most of the camera's 56° field of view and momentarily illuminating a large area of the lower thermosphere. Actually, the elve acted as a snapshot, revealing wave-like formations in neutral density that display quasi-parallel tilted striations, most likely caused by the downward phase-propagation of atmospheric gravity waves.

[11] The amplitude and phase recoveries of the LORE in Figure 2 persist for ~25 min until a subsequent +CG 284.8 kA lightning flash at 00:07:11.8523 UT triggered a smaller signal perturbation. As shown in the lower-right image of Figure 2, this same lightning flash also produced a few very faint sprite columns and a large elve ring. The signal perturbation here is also a LORE, with an amplitude and phase recovery lasting for ~10 min. The rest of the early events in Figure 2 were typical, having recoveries <100 seconds. To the time resolution of the CCD camera these were associated only with usual mesospheric sprites, in line with what is well known from previous studies [e.g., see *Haldoupis et al.*, 2010].

[12] In addition to the significantly longer than typical recovery times of LOREs, the LORE recovery signatures are also different from those of typical events. Given the logarithmic amplitude scale in Figure 2, typical early events are seen to exhibit a recovery time which is initially rapid, slowing down towards the end of the event. The LOREs, on the other hand have a nearly exponential recovery time, which differentiates them from typical early events and indicates that a different set of chemical reactions are responsible for the two recovery signatures. Such a long-lasting relaxation process could be attributed to the electron density loss rate, which at upper *D*-region heights is affected mainly by electron attachment and dissociative recombination, and less by electron detachment processes which are much slower, that is, lasting several tens of minutes [e.g.,

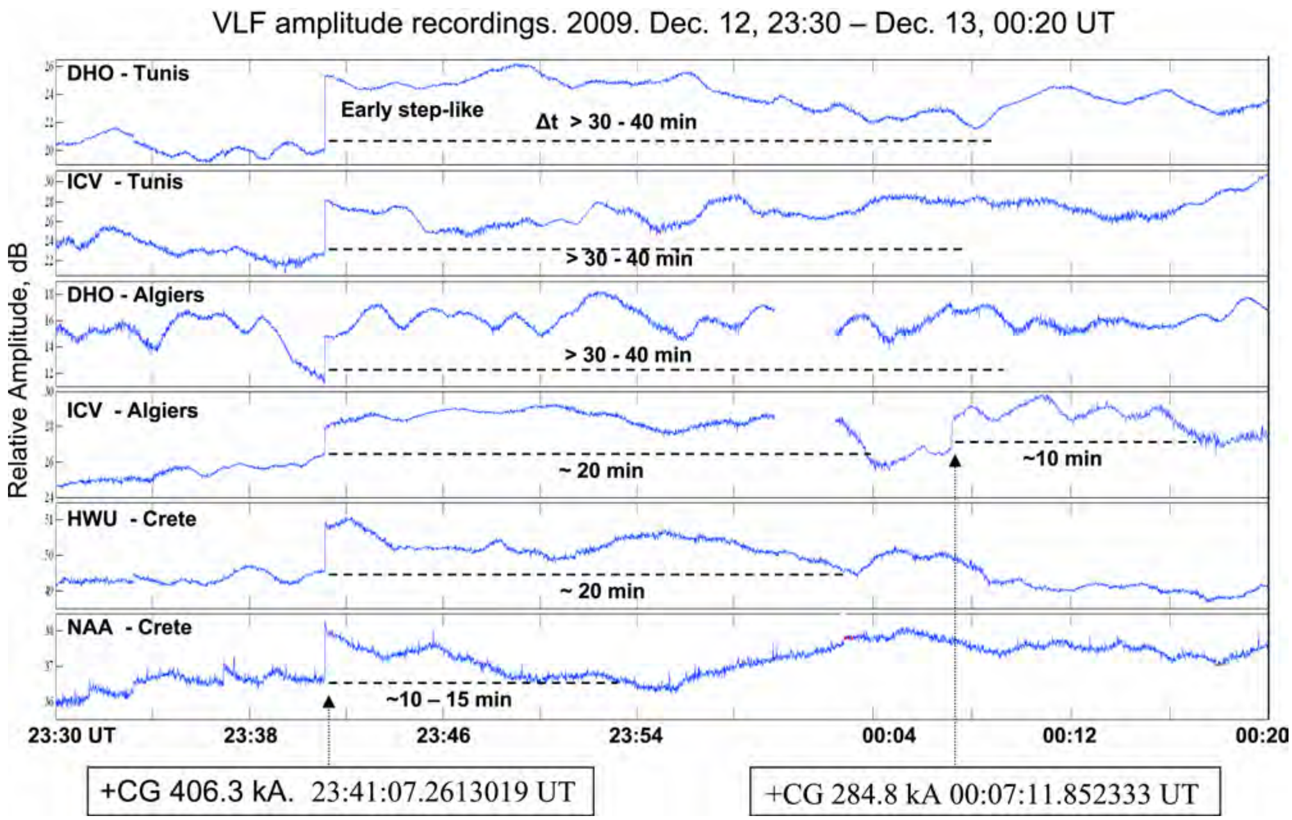

Figure 3. Step-like early VLF events corresponding to the elves shown in Figure 2, both triggered by very intense +CG lightning strokes. They are observed at by transmitter-receiver GCPs passing at relatively large distances from the causative lightning flashes. These type of early perturbations offset the transmission signal levels for long times. See text for more details.

Glukhov et al., 1992; *Rodger et al.*, 1998; *Haldoupis et al.*, 2009].

[13] The large LORE discussed in Figure 2 was also accompanied by considerable perturbations in VLF signals received in both Algiers and Crete, despite the fact that their GCPs passed more than 250 km away from the storm center. Interestingly, most of these relatively "far-storm" early signal perturbations were "step-like", a type identified and reported also by *Cotts and Inan* [2007]. Figure 3 illustrates several such step-like signatures observed at far-storm VLF signal transmissions in Tunis, Algiers and Crete, all of which are coincident with the +CG 406.3 kA lightning discharge that caused the massive elve and sprite shown in Figure 2. As seen, step-like perturbations are large (up to ~5 dB) and offset the signal level in some cases more than 40 min. In Figure 3, the latter is particularly true for the DHO-Tunis, DHO-Algiers and ICV-Algiers VLF links.

[14] The step-like perturbations described above have not been observed with typical, QE-related early VLF events, apparently because they are signatures associated with a large and spatially extended region of ionization in relation with an elve, which affects not only the lower *E*-region but also the upper *D*-region, down to VLF reflection heights. For example, one could interpret the TLE in Figure 3 that is caused by the +CG 284.8 kA stroke at 00:07:11.8 UT to be elve-dominated. Given the geometries in Figure 1, a possibility exists that the step-like events are due to strong VLF reflections off the boundaries of long-lasting, large horizontally-extended volumes of electron density enhancements in the upper *D*-region, caused by impacting ionization effects of a lightning-induced EMP field that also excites an elve.

[15] The contribution of a sprite and elve produced by the same +CG discharge is possibly twofold. First, the sprite process and its associated QE fields can enhance the ionization at VLF reflection altitudes through secondary impact ionization of electrons produced there earlier by the same EMP that also excites the elve. Second, a sprite can contribute to ionization enhancement through a process that involves the effects of sprite halos. Although possibly subvisible, halos could be present in the cases reported in this study. Halos, which appear near the VLF reflection heights to lower altitudes (say, between 90 and 75 km), could have a significant effect on ambient electron conductivity because they are caused by more impulsive charge moment changes as compared to typical sprites not accompanied by halos [*Qin et al.*, 2011].

[16] To reinforce these findings, Figure 4 presents VLF and TLE observations for 3 additional cases of LOREs. The figure includes three TLE images which show sprite and elve pairs associated with LORE onsets in different Tx-Rx VLF links, both for near-storm (Tunis) and far-storm (Crete and Algiers) links. These events are less pronounced than the strong case discussed in Figure 2, but they show similar characteristics. Although the causative +CG lightning discharge went unrecorded by LINET for the middle sprite-elve pair image, there is little doubt it has occurred because high resolution VLF records revealed a powerful sferic to be present at onset in the signals of the links shown in Figure 1.

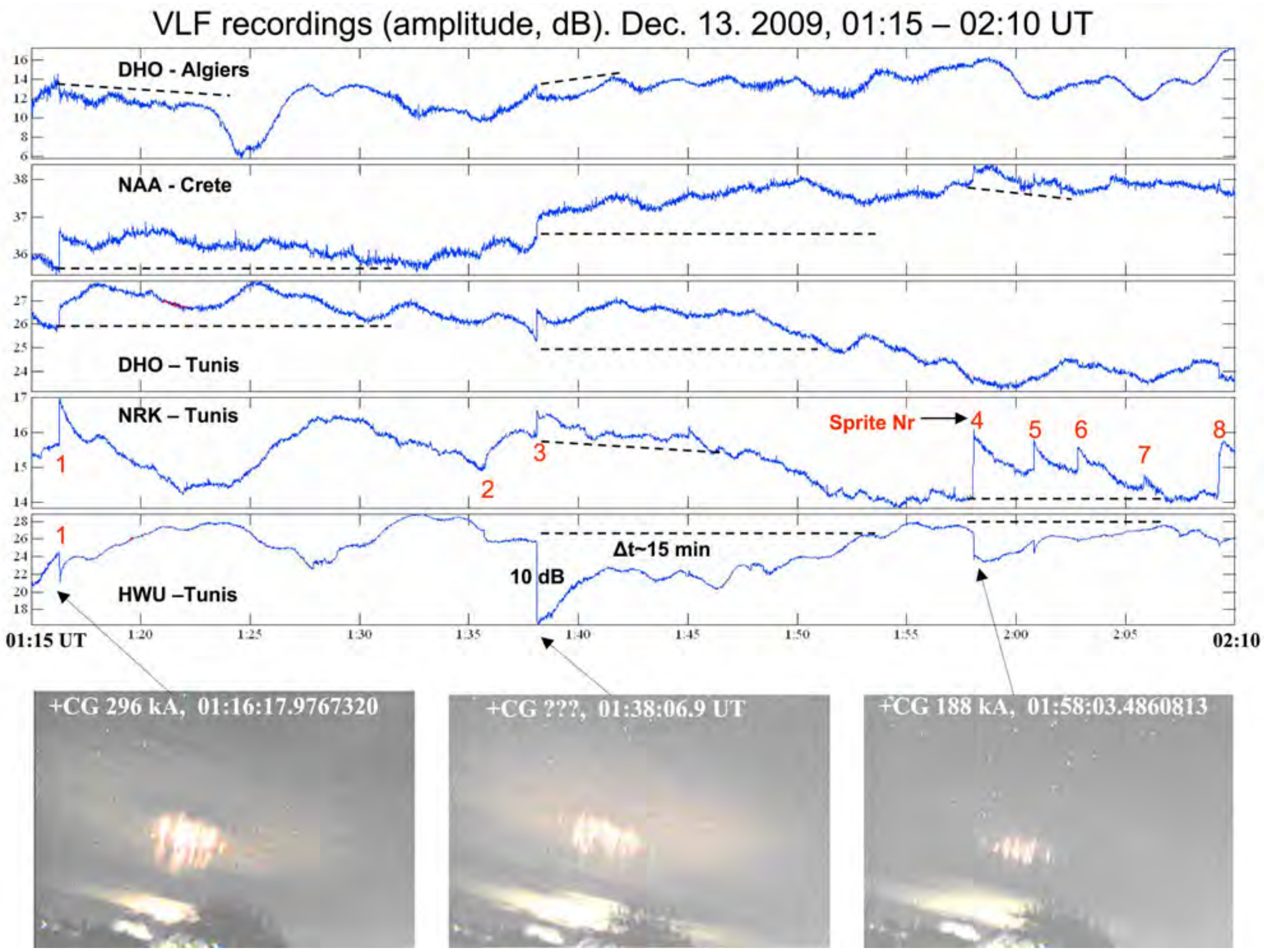

Figure 4. Examples of more LOREs caused by intense +CG discharges and in association with the generation of both, sprites and elves in the upper *D*-region ionosphere.

The right hand-side image that is caused by a +CG 188 kA stroke, also included a sprite-elve pair, but the elve was very faint in this case. Of the 10 LOREs identified in the current analysis 8 were associated with sprite-elve pairs while 2 were associated with +CG lightning flashes causing sprites only. For the 2 cases where an elve was not observed, it is possible that it may simply have been missed by the relatively slow frame rate of the CCD camera, combined with the very short duration ($\sim$1 μs) of the elves themselves.

4. Discussion

[17] The findings indicate that LOREs, reported first by *Cotts and Inan* [2007], may occur in relation with lightning-induced electronic conductivity modifications in the upper *D*-region ionosphere rather than heavy ion conductivity changes in the lower atmosphere below $\sim$50 km. Our interpretation of observations suggests that LOREs are likely due to horizontally extended and long-lasting electron density perturbations, at 85 km or higher, generated by intense +CG lightning discharges that cause large elves followed also by high altitude column sprites. In addition, we suggest that the long enduring step-like early VLF events, also reported first by *Cotts and Inan* [2007], are due to oblique VLF reflections off the lateral boundaries of large regions of long-lasting elevations in electron density. This is a postulation and, based on this data alone, one may not exclude the case of narrow-angle forward scattering. This can be because the elve-associated ionization regions are widely extended horizontally outwards and thus are able to perturb GCPs which are at distances larger than those observed with smaller disturbances that produce typical early events (<100 km [e.g., see *Johnson et al.*, 1999]).

[18] The observation showing elves to be nearly always present at the onset of LORE and step-like event occurrences, suggests that the EMP emitted by a strong +CG lightning discharge plays a primary role in triggering the LORE process. This is likely to be reinforced by the QE effects that follow in time to produce the accompanying high-altitude sprite and possibly sub-visual halos. The present observations indicate, but cannot prove, that the elve-sprite combination is of key importance in the LORE generation mechanism. This is not unlikely, given that typical early events with short recoveries (i.e., <100 s) are occurring mostly in relation only with sprites, sprite halos and rarely with elves, because in most cases elves occur at higher altitudes where ionospheric recovery times are intrinsically longer (several minutes to a few tens of minutes [e.g., see *Rodger et al.*, 1998]), but these altitudes are usually above the VLF reflection height. There may thus be a possibility of a coupling mechanism between the sprite and elve that allows the electron density left behind by the elve,

which is ordinarily too high in altitude in order to affect VLF propagation, to scatter VLF waves when a sprite initiates just below it. On the other hand, one may not exclude that LOREs could occasionally be seen to occur in association only with elves (for example, those produced by very intense −CG discharges), or only with high altitude sprites, and/or sprite halos, which can relate with regions of long lasting electron density enhancements there. In the present data set, this scenario occurred in two cases when LOREs of smaller duration (∼5 to 8 min) were caused by +CG lightning of ∼180 kA and ∼200 kA peak intensities that also caused sprites, but not elves.

[19] The present observations confirm previous results about the effects in the upper *D*-region ambient plasma triggered by strong lightning strokes which are causative of both elves and sprites. *Fukunishi et al.* [1996], in the first paper on elves, referred to unpublished results mentioning that: "elves were always accompanied by large amplitude VLF perturbations". This motivated them to introduce "elves" for *E*missions of *L*ight and *V*LF perturbations due to *E*MP *S*ources, an acronym which was later abandoned, though the term elves persists. In addition, the same authors reported that: "strong elves appear to occur in response to some especially energetic +CG flashes which were accompanied nearly always with sprites". Although it was mentioned, examples of such large and long lasting early VLF perturbations were never reported openly before to occur in relation with elves and sprite pairs. Furthermore, *Fukunishi et al.* [1996] stated that, "the large horizontal extent and high luminosity of these events suggested a significant effect on the lower ionosphere and on radio wave propagation", which was in line also with theoretical predictions by *Taranenko et al.* [1993] that appeared prior the elves' discovery. The present observations confirm these earlier predictions and postulations.

[20] In discussing the topic of VLF perturbations associated with elves in his review paper, *Rodger* [2003] pointed out that "an intense lightning EMP that causes an elve also leads to changes in ionization which at elve-altitudes will be relatively long lasting". He 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 VLF events would likely appear as sudden step-like changes in received signal amplitude and phase without a clear relaxation signature". These predictions, which are made several years ago by *Rodger* [2003], are now confirmed for first time by the present LORE and step-like early VLF observations, although they do not seem to match the predicted narrow scattering pattern.

5. Conclusions

[21] Out of the 10 LOREs identified in this study 8 were associated with sprite-elve pairs. The results constitute evidence that strong +CG lightning can cause largely-extended and long-lasting severe modifications of the ionosphere at upper *D*-/lower *E*- region, which could have significant effects on radio signal propagation. An improved understanding of this phenomenon, however, requires more research and additional data in order to be better quantified. Such work includes theoretical development of an appropriate ionospheric disturbance model as well as theoretical modeling of VLF scattering from such disturbance regions. In addition, application of an upper *D*-region chemical model may also be needed to simulate the long recoveries of the observed perturbations in plasma density. The application of a simplified model by *Rodger et al.* [1998] for the upper *D*-region, in which the electron continuity equation includes only dissociative recombination and electron attachment as loss terms, showed that the observed LORE durations are easily accountable. For example, if the nighttime ambient electron density was elevated by 5 to 20 times at 85 km, then it relaxes back to its pre-event levels in about 20 to 25 min, which compares well with the observations. More detailed modeling studies of the present observations will be undertaken in a future study.

[22] Finally we touch upon on a couple of points in brief. One, which was not commented here but could be of importance and needs to be considered more experimentally, is that these exceptional observations associate with a localized maritime thunderstorm, as it was also the case for the large elves observed *by Fukunishi et al.* [1996] and the great majority of the LORE events reported by *Cotts and Inan* [2007]. Another point, which was introduced above but certainly needs more consideration and attention, as it may involve important physics behind it, is that LOREs seem to occur overwhelmingly in correspondence to an "elve and sprite" pair, rather than an elve or sprite alone. This is an important indication that would imply the presence of a coupling process between the two phenomena which are driven by different physical processes, that is, EMP and QE fields, acting upon the medium in time sequence. We cannot offer here details of how the mechanism of sprite-elve coupling might work, but do note that existing theories of both sprite and elve production, treated separately, are unable to produce LOREs, the former because the ionization is too low in altitude, and the latter because the ionization usually is too high for VLF scattering to occur. Given our suggestion that LOREs are mostly associated with sprite-elve pairs, which also agrees with the first elves observations of *Fukunishi et al.* [1996], it is possible that LORE production requires both to be present.

[23] **Acknowledgments.** We are grateful to colleagues and students at Stanford who keep the international AWESOME VLF network project going strong. Many thanks go to Nino Amvrosiadi and Yannis Tsabos in Crete, as well as to our colleagues Hassen Ghallila in Tunis and Samir Nait Amor in Algiers hosting and maintaining the VLF receiver stations. The lightning data were kindly provided by Stefano Dietrich of the Italian LINET team. Our very special thanks go to Ferruccio Zanotti, an amateur photographer who did a great job in capturing the revealing TLE events used in this study. Partial support for this work was provided by ELKE, University of Crete. Partial support for this paper was provided by ELKE, University of Crete, and the DARPA grant HR0011-10-1-0058-P00001 to Stanford University.

[24] The Editor thanks Robert Moore and an anonymous reviewer for assisting in the evaluation of this paper.

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SARA’s Contributions to Space Weather

Whitham D. Reeve, Director at Large, SARA

The Society:

The Society of Amateur Radio Astronomers (SARA) was founded in 1981 and has about 350 members worldwide. SARA is governed by an elected board of directors and officers. One of its missions is to educate people interested in pursuing amateur radio astronomy, and it has a number of educational outreach activities related to this mission. In addition, SARA members are involved in many projects related to space weather, both through their society and on their own initiative: http://radio-astronomy.org/.

Space weather:

SARA members contribute to knowledge of space weather by direct observations and by encouraging inquiry and sparking interest among people of all ages. SARA and its members actively participate in a number of programs, described below, directly related to solar radio observations and space weather. As an international organization SARA helps bridge gaps between the public and government agencies.

Mentors, technical help and conferences:

SARA provides mentors for members new to radio astronomy, and it provides technical assistance through its email list and forum (https://groups.google.com/forum/?fromgroups#!forum/sara-list) and website. It is quite possible that an experienced SARA member is nearby who can personally answer questions about projects that challenge the average high school, middle school or University educator. SARA holds conferences each year, in which members and professional researchers discuss their projects and tour professional radio astronomy facilities.

Some SARA programs and projects related to space weather are:

SuperSID: SARA is a partner with the Stanford Solar Center at Stanford University in California on the SuperSID program. This is an education project to build and distribute inexpensive ionospheric monitors around the world to encourage the study of space weather. SuperSID itself is an inexpensive VLF monitor and loop antenna that is used to detect sudden ionospheric disturbances (SID) resulting from solar flares. Many SARA members upload data to Stanford's SuperSID database where it can be freely accessed. Stanford and SARA have shipped almost 600 SID/SuperSID units worldwide with units on every continent (even Antarctica). SARA provides SuperSIDs through grants to teachers and students. The SuperSID also may purchased from SARA ready-built: http://solar-center.stanford.edu/SID/. Photo courtesy of SARA

e-CALLISTO: e-CALLISTO is one of the fifteen worldwide instrument projects that are part of ISWI. The e-CALLISTO is a frequency agile solar radio spectrometer that operates in the VHF and UHF frequency bands with frequency expansion easily accomplished through up- and down-converters. Several SARA members around the world participate in the e-CALLISTO network and upload radio flare data to ETH-Zurich for dissemination to anyone interested. The e-CALLISTO Receiver may be purchased as a kit or ready-built: http://www.e-callisto.org/. Photo courtesy of W. Reeve

NASA Radio Jove: Many SARA members participate in the Radio Jove Project in which students and amateur radio scientists observe and analyze natural radio emissions from Jupiter, the Sun, and our galaxy. Observations are made primarily in the HF band around 20 MHz using a receiver (top) and simple dipole antennas (dual-dipole shown bottom). Radio Jove observers upload their observations and data to a NASA sponsored database where it can be freely accessed. SARA grants Radio Jove receivers and antennas to students and teachers around the world. The Radio Jove receiver and antenna also can be purchased as a kit or ready-built: http://radiojove.gsfc.nasa.gov/. Photos courtesy of Jim Thieman, NASA/Goddard

SAM-III: The SAM-III, or Simple Aurora Monitor, is a 3-axis magnetometer used throughout the world by amateur radio astronomers to measure geomagnetic disturbances from coronal mass ejections and changes in the solar wind. The SAM-III includes a signal processor and up to three sensors located at a magnetically quiet location. Users can participate in the SAM Magnetometer Project, which is a worldwide network of instruments and has a goal of placing a SAM on every continent. The SAM-III may be purchased as a kit or ready-built: http://www.sam-magnetometer.net/. Photo courtesy of W. Reeve

The INSPIRE Project: SARA members participate in the NASA INSPIRE Project (Interactive NASA Space Physics Ionosphere Radio Experiments). INSPIRE uses a VLF-3 receiver and a whip or loop antenna for reception of natural radio phenomena in the ELF and VLF frequency bands below 10 kHz. These include lightning-produced whistlers, sferics and tweeks, which are influenced by Earth's magnetosphere and the solar wind. The VLF-3 receiver may be purchased as a kit: http://theinspireproject.org/. Photo courtesy of The Inspire Project

AAVSO: Several members contribute data on solar flares to the AAVSO (American Association of Variable Star Observers) and a SARA member is one of the two solar coordinators for this group: http://www.aavso.org/

Publications:
The SARA journal, *Radio Astronomy*, is published and electronically distributed to members six times per year. A sample journal may be downloaded here: http://www.radio-astronomy.org/pdf/2012_may_hi_res.pdf. Also, SARA members write articles in various other journals and magazines including QEX, the Classroom Astronomer, and Astronomical Society of the Pacific.

Membership:
Membership in SARA costs only US$20/year (students US$5): http://radio-astronomy.org/membership

Published by SERC of Kyushu University
ISWI Newsletter
under the auspices of the United Nations

This pdf circulated in Volume 4, Number 107, on 24 October 2012.