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Characteristics of long recovery early VLF events observed by the North African AWESOME Network

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[1] Lightning strokes are capable of initiating disturbances in the lower ionosphere, whose recoveries persist for many minutes. These events are remotely sensed via monitoring subionospherically propagating very low frequency (VLF) transmitter signals, which are perturbed as they pass through the region above the lightning stroke. In this paper we describe the properties and characteristics of the early VLF signal perturbations, which exhibit long recovery times using subionospheric VLF transmitter data from three identical receivers located at Algiers (Algeria), Tunis (Tunisia), and Sebha (Libya). The results indicate that the observation of long recovery events depends strongly on the modal structure of the signal electromagnetic field and the distance from the disturbed region and the receiver or transmitter locations. Comparison of simultaneously collected data at the three sites indicates that the role of the causative lightning stroke properties (e.g., peak current and polarity), or that of transient luminous events may be much less important. The dominant parameter which determines the duration of the recovery time and amplitude appears to be the modal structure of the subionospheric VLF probe signal at the ionospheric disturbance, where scattering occurs, and the subsequent modal structure that propagates to the receiver location.

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1. Introduction

[2] Early very low frequency (VLF) signal perturbations due to the transient luminous events (TLEs) have been widely studied [e.g., *Inan et al.*, 1993; *Pasko and Inan*, 1994; *Johnson and Inan*, 2000]. Recently, optical observations of TLEs made during EuroSprite campaigns were found to be associated with early signal perturbations when the Great Circle Paths (GCPs) of the VLF signals crossed the TLE's region [*Haldoupis et al.*, 2004] and that the perturbation characteristics were a function of the TLE-transmitter distance, TLE-receiver distance, and the scattering angle [*NaitAmor et al.*, 2010]. Recently, a new category of early VLF signal perturbations have been observed, exhibiting long recovery times (300s to as long as tens of minutes). The underlying cause of these events is still not clear [*Cotts and Inan*, 2007; *Salut et al.*, 2012; *Haldoupis et al.*, 2012]. *Cotts and Inan* [2007] presented observational characteristics of long recovery events and compared their occurrence rate over primarily land-based GCPs to that of sea-based GCPs. *Salut et al.* [2012] analyzed a larger database of long recovery events between Australia and Malaysia and found that of 403 early events, only 48 exhibited a long recovery time. However, *Salut et al.* [2012] did find a strong tendency (42 of 48) for long recovery events to occur over the ocean. In [*Cotts and Inan*, 2007; *Salut et al.*, 2012], no optical confirmation on the existence or absence of TLEs was available. Also, in their analysis, only a single VLF path was examined for each recorded event. In *Haldoupis et al.* [2012], the authors examined a small number of long recovery early events, approximately 10 events associated with five optically observed TLEs, and recorded by three different receivers. They attributed these events to the strong positive cloud to ground (+CG) lightning stroke which may produce an elve together with a high altitude sprite, and possibly a sprite halo as well. *Poulsen et al.* [1991] studied numerically the VLF signal propagation in presence of ionospheric disturbances due to lightning. In their model, they supposed that the mode coupling is negligible and, therefore, a single mode propagation is dominant. In their

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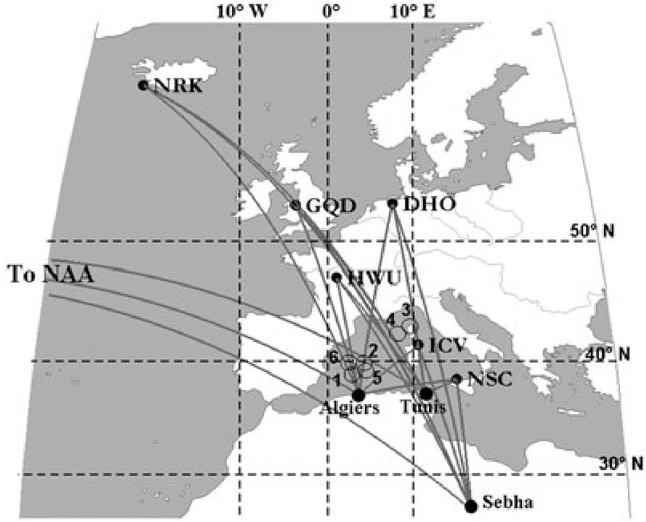

Figure 1. VLF signals Great Circle Paths to the receivers and the geographic location of the ionospheric disturbance studied in different sections.

results, a positive phase shift and negative amplitude perturbation are produced by a disturbed region centered on or near the GCP, and that strongest magnitude of the scattered signal is produced by disturbance being closest to the GCP. In recent numerical simulation, *Marshall et al.* [2010] studied the electron density modification due to CG and in-cloud (IC) lightning. They demonstrated that CG or IC lightning may produce significant ionospheric density perturbations which may be observed as early VLF signal perturbations. *Marshall and Inan* [2010] modeled the VLF signal perturbations due to the ionospheric *D*-region electron density modification. In this study, they showed numerically that the received signal perturbation amplitude and polarity are strongly dependent on the modal structure of the VLF signal which is itself affected by path length, ionospheric and ground parameters, and transmitter frequency, all of which affect the received amplitude nonlinearly. The nonlinear influence of all of these factors can lead to small VLF perturbations (possibly too small to be measured) even for significant ionospheric disturbances. They further demonstrated that the electron density does not have as strong an effect on received amplitudes. This means that the absence of a measured perturbation to the VLF signal does not imply a lack of disturbance in the ionosphere. It is thus important to take into account the distance from transmitter to ionospheric to disturbance, and from ionospheric disturbance to receiver, requiring a large database of events, as was done by *Salut et al.* [2012]. However, even that paper only had data from one receiver available.

[3] In this paper, 1854 early VLF signal perturbations recorded at Algiers receiver in 2008 and 2009 between July and December. Some of these perturbations were due to the same ionospheric disturbance, but were detected on multiple transmitter paths to Algiers. Of the early VLF events identified, 130 are classified long recovery, which we define as exhibiting a recovery time more than 8 min. Many signal perturbations with recovery times greater than the ordinary early event time [*Sampath et al.*, 2000] (200 s) and less than 8 min were recorded and considered as intermediate recovery events. In this paper, we describe the characteristics (time and amplitude) of the long recovery events as function of the distance to Algiers receiver and lightning current amplitude. A comparative analysis using data from Tunis and Sebha receivers is also made.

2. Experimental Setup

[4] An AWESOME receiver [*Cohen et al.*, 2010] is installed at Algiers, Algeria (36.75°N, 03.47°E), Tunis, Tunisia (36.50°N, 10.08°E) and Sebha, Libya (27.03°N, 14.43°E), as seen in Figure 1, along with the locations of VLF transmitters and their great circle paths to the receiver. The AWESOME receiver consists of two magnetic loop antennas (oriented in North/South (or NS) and East/West (or EW) directions), a preamplifier, line receiver, a GPS antenna, and a computer with data acquisition card. It is capable of recording and storing narrow-band data (i.e., the amplitude and phase of specific VLF transmitter frequencies) and broadband data (i.e., 100-kHz sampling). Data is synchronized to GPS with inherent 100 ns accuracy. The receiver was installed as part of the International Heliophysical Year [*Scherrer et al.*, 2008]. The TLE images of the EuroSprite campaigns can be found on www.electricstorms.net. The lightning data are provided by the French lightning detection system: Météorage. The system measures the lightning discharge characteristics including peak current, multiplicity, polarity, and geographic location with a space-time precision of 1 km and 1 ms [*Pedeboy*, 2012]. More information on the Météorage detection system can be found on the official web page at www.meteorage.fr and references therein. The circles in the map of Figure 1 correspond to the geographic locations of a set of examples presented in different sections of the paper. The event times and coordinates are given in Table 1.

3. Importance of Geometry in Long Recoveries

[5] We now show case studies of long recovery events to reveal the variability of recovery time on transmitter-receiver geometry, and that long recovery events may occur in connection with weak lightning. During the night of 29 October 2008, a long recovery early event was recorded at Algiers due to thunderstorm activity in the Mediterranean Sea, as shown in the Figure 2, top. The recorded signal perturbation characteristics (duration times and amplitudes) differed among received transmitter signals. According to the Météorage lightning detection system, a relatively weak negative lightning stroke peak current amplitude (–14.1 kA) was associated with the events located 195 km north of the receiver. This is in contrast to the finding of *Haldoupis et al.* [2012] that long recovery events are often associated with powerful CG strokes. The event was close to the receiver and

Table 1. Events, Dates, Times, and Geographic Locations

Event Number	Date	Time	Coordinates
Event (1)	29 October 2008	23:28:02	2.81°E 38.44°N
Event (2)	4 November 2008	00:20:23	4.05°E 39.4°N
Event (3)	1 December 2008	02:53:35	8.93°E 42.53°N
Event (4)	12 December 2009	23:41:05	7.6°E 41.9°N
Event (5)	5 November 2009	21:46:20	4.22°E 38.77°N
Event (6)	12 November 2008	21:00:27	2.46°E 39.44°N

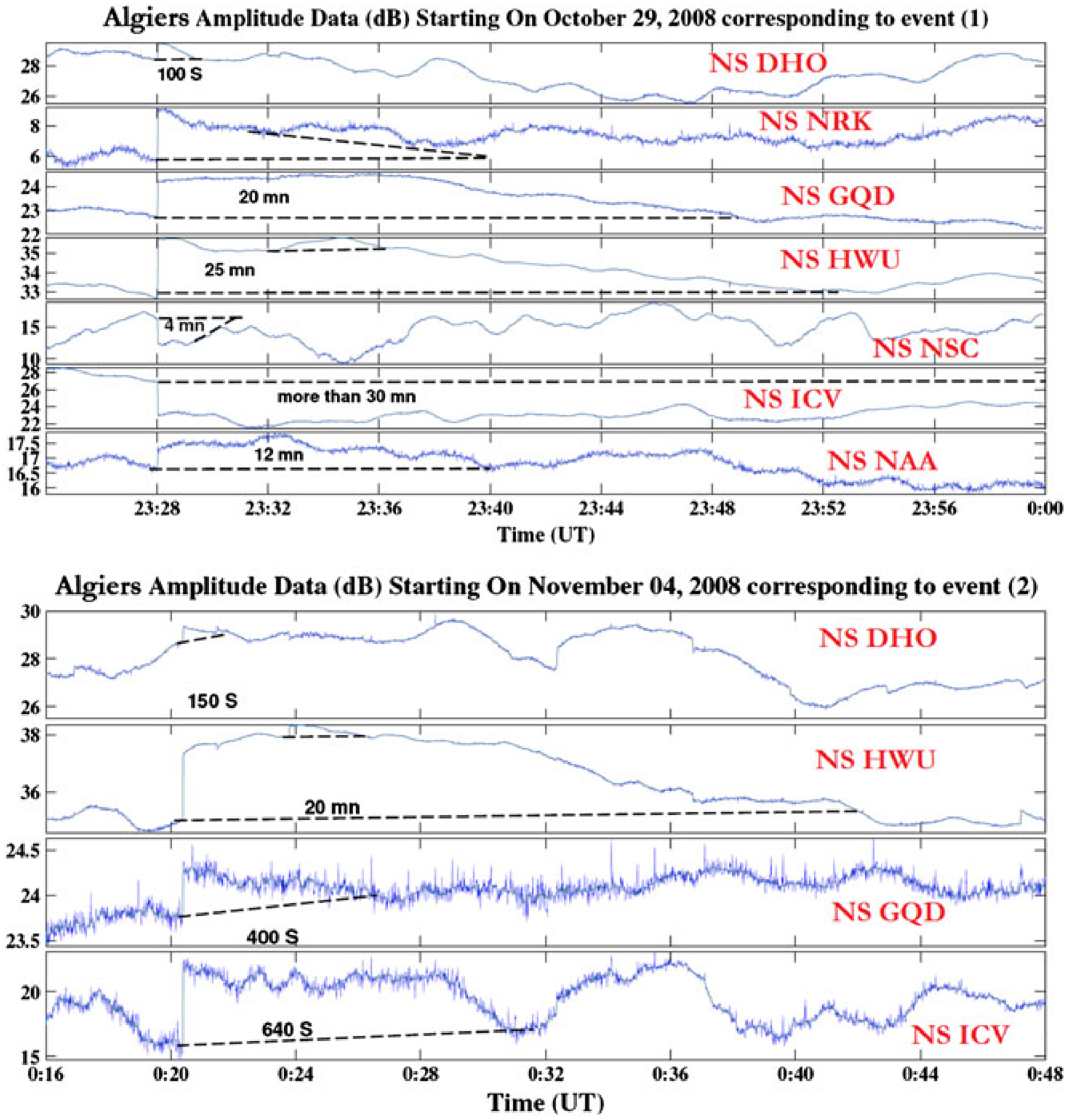

Figure 2. (top) Event (1) associated VLF signal perturbations recorded at Algiers on 29 October 2008. (bottom) Event (2) VLF signal perturbations recorded at Algiers on 4 November 2008.

thus affected several VLF transmitter paths to Algiers. We divide the transmitter paths into two categories: short paths (ICV and NSC) and long paths (NRK, NAA, GQD, DHO, and HWU). With one exception (DHO), all long paths exhibited a long recovery, but only one short path demonstrated a long recovery. Even weak amplitude perturbations may have long recovery times (such as NAA). Another example of a long recovery event recorded on 4 November 2008 at 00:20:23 is shown in Figure 2, bottom. The causative lightning was 311 km from the receiver and was again weak (–11.1 kA peak current), long recovery signal perturbations were recorded on ICV and HWU paths only. Moreover, the DHO path crossed even closer to the event compared to ICV and HWU, yet did not exhibit a long recovery event whereas the other two did. Furthermore, the GCPs of NRK, GQD, and HWU to Algiers are nearly overlapping and thus crossing the disturbed region along nearly the same line. Despite this fact, the recovery times for these three paths were significantly different. It is therefore clear that the recovery perturbation times are closely related to the geometry and thereby the modal structure of the signal at the ionospheric disturbance. Figure 3 shows a geographic map of all identified long recovery events where a majority of these events occurred in the Mediterranean Sea consistent with previous statistical analyses of these events [*Cotts and Inan*, 2007; *Salut et al.*, 2012]. It has recently been found that lightning return strokes are more powerful over the Sea than the ground [*Said et al.*, 2013].

4. Observation at Multiple Receivers

[6] We now compare the signal perturbations recorded at different receivers. The first example concerns early events recorded on 1 December 2008 at 02:53:35 in association with a lightning stroke current amplitude of –59.6 kA, as shown in Figure 4. Only the ICV-Algiers and NRK-Sebha exhibited long recovery signal perturbations, but for the other signals the perturbations recovered more typically (a few minutes). Even though the GQD-Sebha nd the HWU-Sebha GCPs were closer to the disturbed region than the

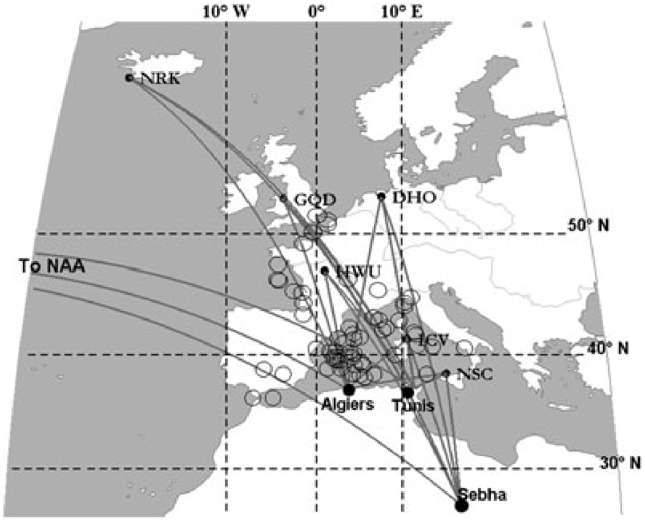

Figure 3. Geographic locations of the disturbed regions.

NRK-Sebha GCP, the perturbation recovered rapidly. For the paths of HWU-Algiers GQD-Algiers and ICV-Algiers, the perturbations were due to the wide-angle scattering. The example shown in Figure 5 presents signal perturbations recorded on 12 December 2009. These events were reported in *Haldoupis et al.* [2012] where only signal perturbations exhibiting a long recovery times were presented. Simultaneous data from three additional receivers are presented in Figure 5. In the Algiers receiver data, early signal perturbations were recorded on the NRK, NSC, ICV, GQD, and DHO, but only the ICV path showed a long recovery time. Moreover, none of the transmitter paths to Algiers crossed the disturbed region. In Tunis data, the disturbed region was well-situated for multipaths analysis. The NRK, DHO, and HWU paths crossed the disturbed region and showed a long recovery perturbation. The ICV transmitter was only 210 km from the causative lightning, and thus the TLEs captured during the perturbation times may have created an ionospheric disturbance over the transmitter region, similar to the geometric configuration of *Haldoupis et al.* [2012]. The signal perturbations recorded in Tunis showed that the recovery times were more than 8 min in the case of NRK, DHO, and HWU. In the case of the ICV and NAA, the perturbation durations were much shorter (between 100 and 180 s). In the same night, early signal perturbations were recorded at 23:36:56 due to gigantic jet (GJ) as reported in *van der Velde et al.* [2010], and thus the perturbation recorded at 23:41:05 in GQD-Tunis path was a continuation of the GJ signal perturbation, which ended at 23:52:00. For the case of the Sebha receiver, a long recovery event was recorded on the NRK path only. The data showed that paths which exhibited long recovery times in Tunis had intermediate recovery time in Algiers and Sebha, while those events which exhibited an intermediate recovery time in Tunis had a long recovery time in Algiers and Sebha. Observing the DHO signal, the perturbation was positive in Tunis data and negative in Algiers. On the GQD path, the perturbations were positive in Algiers and Sebha and negative in Tunis. For the NRK signal, the

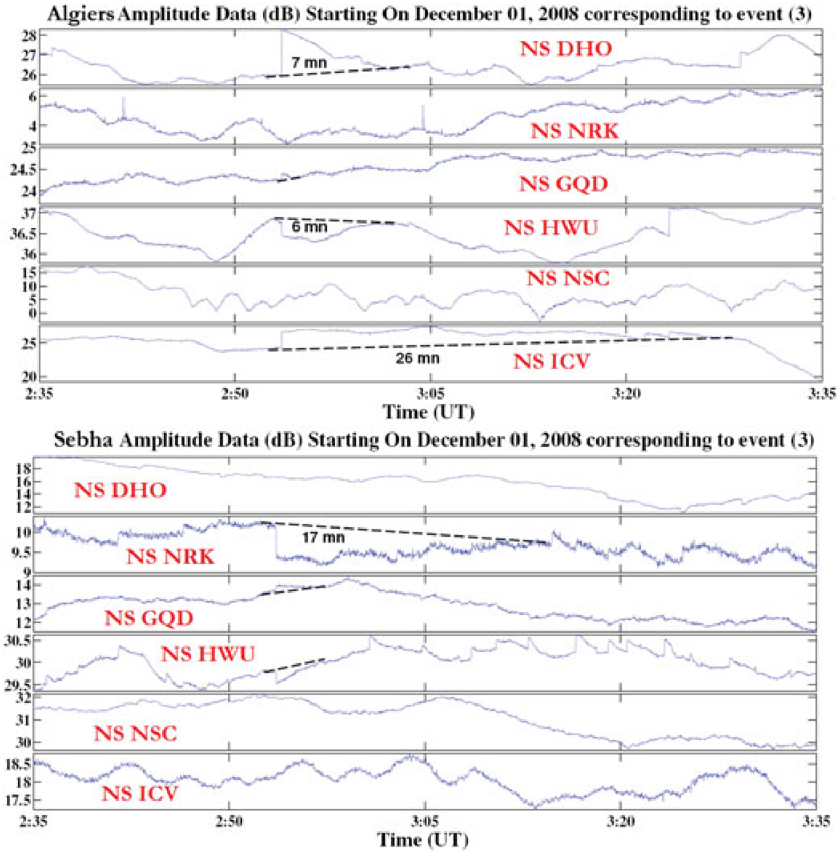

Figure 4. Event (3) VLF signal perturbations recorded at (top) Algiers and (bottom) Sebha on 1 December 2008.

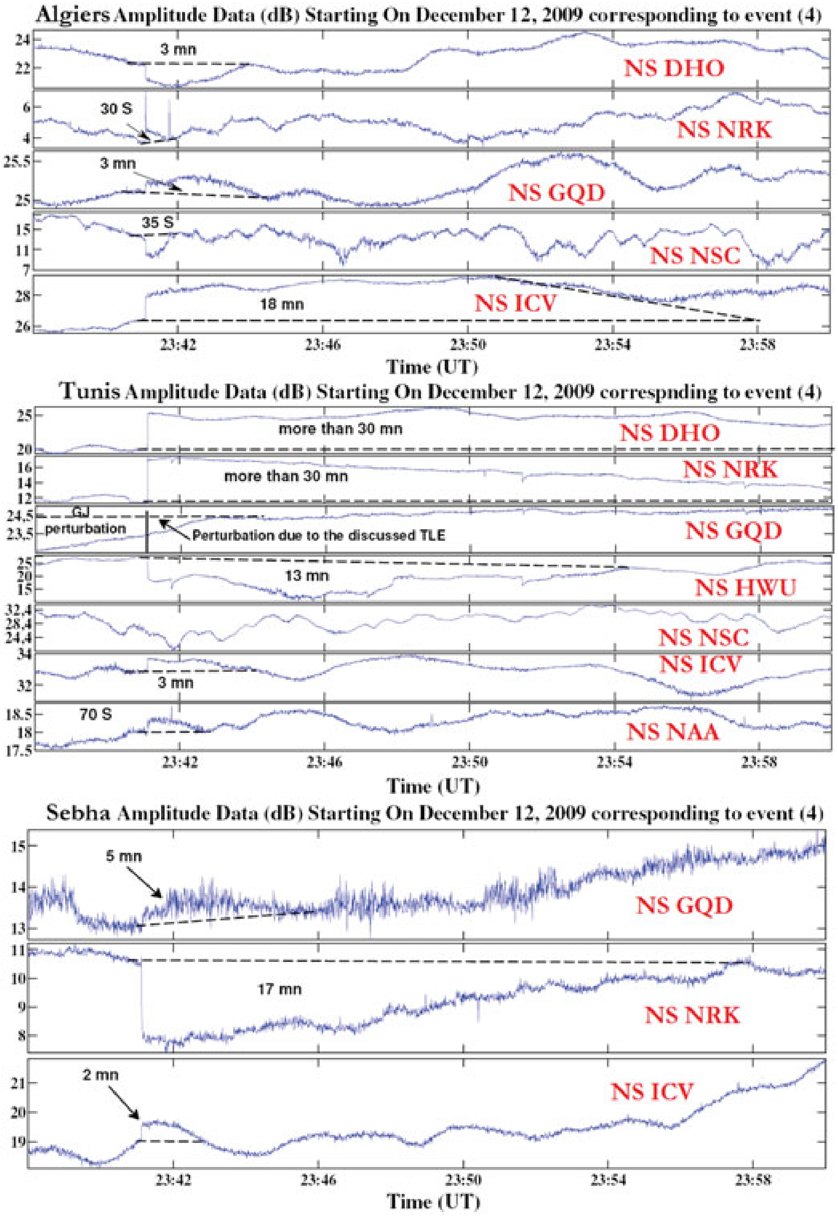

Figure 5. Event (4) VLF signal perturbations recorded on 12 December 2009.

perturbation polarity was positive in Algiers and Tunis but negative in Sebha. This suggests that TLE dimension and lightning stroke current amplitude and polarity may play only a secondary role on the observation of a long recovery events, as opposed to the relative distance between the disturbed region and both the transmitter and the receivers, the scattering angle, the ionospheric composition and the frequency of the transmitting signal among others as reported by *Marshall and Inan* [2010].

5. Lightning Current Amplitudes and Long Recovery Early Events

[7] After giving examples on the characteristics of the long recovery events recorded at Algiers on different paths, we now discuss the association between the lightning stroke peak current and the observation of the early events (long recovery and typical). This comparison was made by *Haldoupis et al.* [2012] where they concluded that these events were generated in association with strong lightning strokes responsible for TLE formation. The data presented in this section may disagree with this association, suggesting that the existence of long recovery early events is only partially dependent of the lightning current amplitudes and polarity. On 5 November 2009 at 21:46:20, some early events were recorded on different paths to Algiers as represented in Figure 6, top, the causative lightning stroke peak current associated with these events had a large peak current of +197.7 kA and was located at 346 km from Algiers receiver. The perturbation recovery times were more modest; 600 s for the DHO-Algiers path, 200 s for the GQD-Algiers, and 40 s for NSC-Algiers and ICV-Algiers paths.

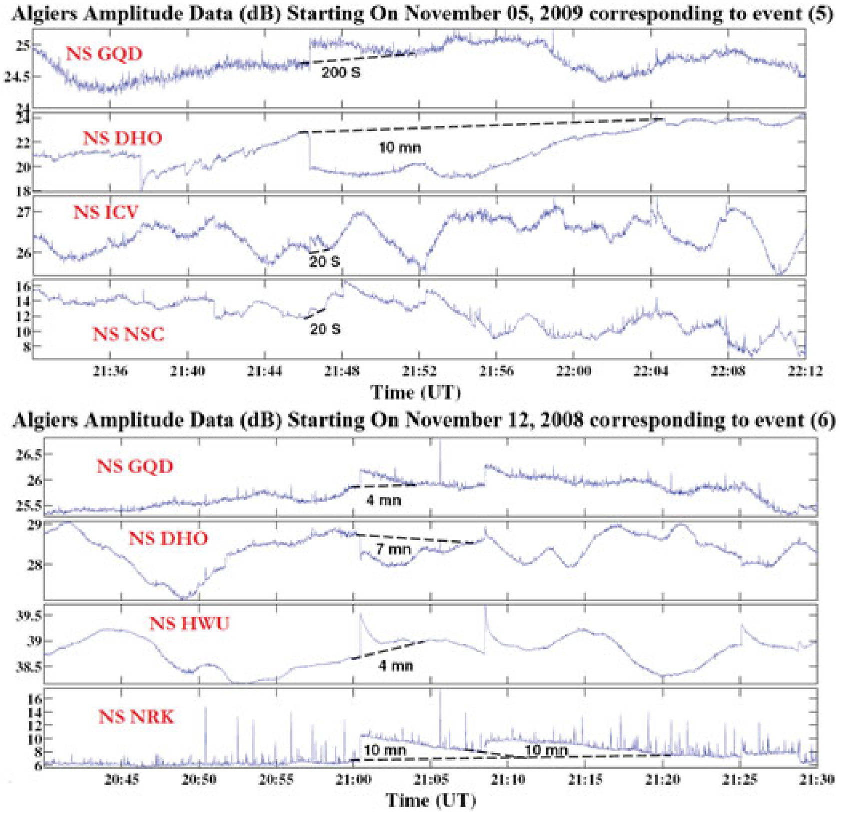

Figure 6. (top) Event (5) VLF signal perturbations recorded at Algiers on 5 November 2009. (bottom) Event (6) VLF signal perturbations recorded at Algiers on 12 November 2008.

Even though the DHO transmitter passes further from the lightning location than the NSC and ICV, the perturbation properties were larger on the NSC and ICV paths. Furthermore, the map plotted in Figure 1 shows that the DHO path crossed the disturbed region and thus was forward scattered, whereas the scattering on other paths was wide angle.

[8] A second example of early events associated with a large peak current lightning stroke is shown in Figure 6, bottom. The events were recorded on 12 November 2008 at 21:00:27 with a causative lightning stroke recorded at 320 km from the Algiers receiver; the lightning peak current was +118.3 kA. Another event, not considered in this discussion, recorded at 21:08:32, where only NRK path exhibited a long recovery time. Note that, even though the NRK-Algiers, GQD-Algiers, and HWU-Algiers GCPs crossed the disturbed region along nearly the same path, the long recovery perturbation was recorded only on the NRK-Algiers signal, while the recovery time on the other signals fell into the intermediate recovery time of 3–7 min. Unlike Figure 3, the lightning in these cases were very powerful +CG strokes with peak currents of +118.3 kA and +197 kA, which are not associated with long recovery events on all GCP paths. To quantify the dependence of recovery time on causative lightning stroke peak current statistically, we plot the number of early events (long and typical) and the lightning stroke as function of the lightning peak current amplitude as shown in Figure 7. It is clear from the plot that a high number of long recovery early events were associated with a relatively low lightning peak current amplitude –50 kA $\le I \le$ 50 kA. The results given in this section clearly show that

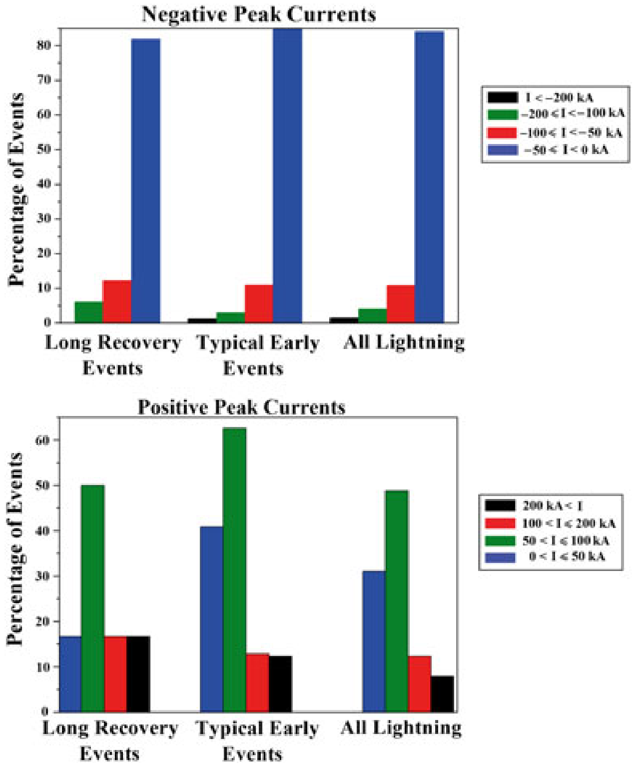

Figure 7. Normalized number of long recovery events, typical early events and all lightning, as a function of the lightning stroke peak current.

the long recovery events (and early events in general) are most often associated with low-peak current –CG lightning (not always associated with TLEs) and is in stark contrast with previous emphasis on large +CG lightning-associated long recovery events. However, it is important to note that this analysis does not account for the relative difference in occurrence *rate* of low-peak-current lightning strokes compared to that of high-peak-current lightning strokes, and that the likelihood of a long recovery observation compared to peak current may show a different trend than the absolute number count presented here. Note also that the data shown in Figure 7 comprise only those early events for which lightning strokes were identified in the Météorage lightning data.

6. Discussion

[9] The results here clarify the relationship between long recovery early signal perturbations, transmitter-disturbance-receiver geometry, and lightning peak current. The single receiver data from Algiers showed that the early signal perturbations may appear as a long recovery event on some paths and have intermediate or typical event recovery times on other paths. Also, the probability that the event exhibits a long recovery time is dependent on the location of the disturbed region relative to the transmitter or the receiver, though in this data set, the variable of land-based compared to sea-based paths cannot be separated from the distance to the disturbed region. The lightning stroke peak current amplitude was found to be a secondary determining factor in the recovery time of such events. Indeed, in the set of examples presented here, some of the long recovery events (recorded at different paths) were associated with low lightning peak current and some were associated with large peak current. This means that the existence of these perturbations may be independent of the type of TLE, although large peak current lightning strokes associated with the production of sprites and elves together may also produce long recovery events somewhat more often. Low peak current negative lightning strokes, however, are clearly capable of generating long recovery events. The multi-receiver data comparison provides clear evidence on the role of the signal modal structure and the scattering process on the observation of the early events.

[10] It is well known that the ionospheric *D*-region disturbances often occur during thunderstorm activity, due to significant electron density changes. The VLF signal perturbations are then a consequence of the electron density changes in the atmosphere. Thus, when a signal path crossed the disturbed region, the perturbations in amplitude and phase are recorded. It is also known that the VLF electromagnetic waves are a superposition of several modes [e.g., *Poulsen et al.*, 1991] each of which are scattered differently as they interact with the ionospheric disturbance. The received signal is then a superposition of all propagating modes. From this point of view, the perturbation properties (amplitude and recovery time) are then highly affected by the wave modal structure and interferences at the disturbed region and then the propagation of the disturbed modes to the receiver. The differences in modal structure of various GCPs at the location of the ionospheric disturbance explain the observed differences in the perturbation properties at different paths to different receivers.

7. Conclusion

[11] The results given in this paper clearly show that the observation of long recovery early events is due to the modal structure of the VLF signal, the relative distance of the disturbed region to both the transmitter and the receiver, and the scattering process. The lightning current peak amplitudes and presence or not of TLEs were found to play a secondary role in the observation of these events. Therefore, theoretical and numerical models should consider the concept of modal composition especially when the distance between the transmitter and the receiver is short. For the long path, only the fundamental mode is important and thus the situation is less complex.

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