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VLF observations of ionospheric disturbances in association with TLEs from the EuroSprite-2007 campaign

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[1] Two Very Low Frequency (VLF) AWESOME remote sensing systems located at Algiers, Algeria (36.45°N, 3.28°E) and Sebha, Libya (27.02°N, 14.26°E) monitor VLF signal perturbations for evidence of ionospheric disturbances. During the EuroSprite-2007 campaign a number of Transient Luminous Events (TLEs) were captured over the Mediterranean Sea by cameras at Pic du Midi (42.94°N, 0.14°E) and at Centre de Recherches Atmosphériques (CRA) in southwestern France (43.13°N, 0.37°E). The cameras observations are compared to collected VLF AWESOME data. We consider early VLF perturbations observed on 12–13, 17–18 October and 17–18 December, 2007. The data from the two VLF receivers confirm the association between TLEs and early VLF signal perturbations with the perturbations amplitudes dependent on the observation configuration i.e. whether the TLE is near the receiver, near the transmitter, or far from both and the scattering process. The results also reveal that the early VLF perturbations can occur in the absence of a TLE.

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1. Introduction

[2] Very Low Frequency (VLF) remote sensing is a powerful tool to study the lower ionospheric disturbances. It has been used to study disturbances related to solar flares [*Bracewell and Straker*, 1949], meteor showers [*Chilton*, 1961], auroral enhancements [*Cummer et al.*, 1997], gamma rays of extraterrestrial origin [*Inan et al.*, 1999] and applied to detect ionospheric perturbation associated with a large seismic activity [*Hayakawa et al.*, 1996]. VLF signals originating from naval transmitters propagate efficiently in the Earth-ionosphere waveguide and are sensitive to the Transient Luminous Events (TLEs), which affect lower ionospheric conductivity. These disturbances are often manifested as sudden changes in the amplitude and/or phase of the VLF signal propagating on a nearby path, followed by a recovery to the ambient level on time scales of 10–100 seconds [*Pasko and Inan*, 1994].

[3] We consider a particular type of ionospheric disturbance, early VLF events, which are generated by lightning and can perturb the amplitude of a VLF transmitter signal by 0.2–6 dB. The term early refers to the fact that the perturbation occurs nearly in coincidence (within 20 ms) of the lightning stroke [*Inan and Rodriguez*, 1993], which distinguishes them from lightning-induced electron precipitation events (LEP) [*Peter and Inan*, 2007]. Within early VLF events, early/fast events are characterized by a rapid onset duration (<20 ms), whereas early/slow events are characterized with an onset duration of 100–1000 ms. Early VLF events are followed by a slow recovery (between 10 to 100 s or more) [*Inan et al.*, 1996]. Unlike Early VLF Events, LEP events are an indirect effect of lightning on the ionosphere. The lighting radiation propagates up to the Van Allen radiation belts as a whistler mode wave and interacts with trapped electrons through cyclotron resonance. The wave can thereby redirect the momentum of the electrons, reducing their pitch angle so that they precipitate onto the ionosphere causing a secondary ionization. It is this secondary ionization which is responsible of the VLF signal perturbation. In general the LEP disturbance region occurs poleward [*Lauben et al.*, 1999] from the causative lightning strike and is therefore in a different location than the sprites and/or Early VLF events. In this paper we discuss the early VLF signal perturbations and their relation to TLEs (sprites and elves) occurring above lightning activity.

[4] Sprites are luminous discharges occurring above thunderstorms and below the E-region (i.e., altitudes between

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40 and 85 km) generally in association with powerful positive cloud-to-ground (+CG) lightning strokes with long continuing currents [*Cummer and Inan*, 1997]. Sprites are typically considered to be the result of electric fields at high altitudes that exceed the breakdown threshold, as a result of quasielectrostatic fields built up from large +CG charge transfers (for a comprehensive review see *Neubert et al.* [2008]). It has been shown both theoretically [*Moore et al.*, 2003] and experimentally [*Johnson*, 2000] that the observed early/fast VLF signal perturbation may match well that which would be expected from a sprite halo.

[5] The first elves observation from the ground was made during the Sprites'95 campaign in US, using a multichannel light-sensitive cameras [*Fukunishi et al.*, 1996]. They occur at 75–105 km altitudes about 350 μs after intense (>60 kA) CG discharges. They consist of a horizontally expanding ring of luminosity (from 100 km to 300 km) and can attain 500 km and lasting for less than 1 ms [*Barrington-Leigh and Inan*, 1999].

[6] The correlation, however, between TLEs and early VLF events remains unclear. *Haldoupis et al.* [2004] found a one-to-one association between sprites and early VLF events using a VLF receiver in Crete during the EuroSprite-2003 campaign. They concluded that sprites produced by +CG lightning discharges were associated with early VLF perturbations in the HWU transmitter signal (in France) in one-to-one correspondence. Note that in the study made by *Haldoupis et al.* [2004], the lightning/TLE activity was located very near (<200 km) to the VLF transmitter (HWU, in France). *Mika et al.* [2005] analyzed VLF signal perturbations during EuroSprite-2003 in connection with many sprites observed in central France. Their results supported the findings reported by *Haldoupis et al.* [2004] on the one-to-one association between sprites and early VLF signal perturbations. On the other hand, *Marshall and Inan* [2007] examined data recorded in the midwestern United States during different dates of high sprite activity between 1995 and 2000, and found that only 48% of sprites were accompanied by VLF signal perturbations, attributing the difference to the relative location of the causative lightning along the VLF signal path (i.e., near transmitter or near receiver), meaning that some disturbances may be undetectable at long distances from the disturbed region. *Rodger et al.* [2001] stated that successive lightning strokes can enhance significant change in the electron density at the lower ionosphere. [*Marshall et al.*, 2008] modeled numerically the possibility that early VLF signal perturbations are caused by lightning electromagnetic pulses driven dissociative attachment. They proposed a new mechanism involving electron density changes due to EMP pulses from successive in-cloud lightning discharges associated with CGs discharges, which are likely the source of continuing currents and much of the charge moment change in CGs. They showed that a sequence of pulses can produce appreciable density changes in the lower ionosphere and that these density changes can result in appreciable perturbations in the amplitude and/or phase of observed VLF signal.

[7] In this paper, we will utilize observations in three different configurations: where the TLEs are near the receiver, where the TLEs are near the transmitter, and where the TLEs are far from both. During the EuroSprite-2007 campaign many sprites and elves were captured by cameras near the Mediterranean Sea, while VLF data were simultaneously recorded in Algiers and Sebha VLF receivers. Two cameras were placed at Pic du Midi (42.94°N, 0.14°E), and at Centre de Recherches Atmosphériques (CRA) in southwest France (43.13°N, 0.37°E). Presented in this paper are the results of VLF signal perturbations measured by the Algeria VLF Atmospheric Weather Electromagnetic System for Observation, Modeling, and Education (AWESOME) system (from Oct. to Dec. 2007), with comparisons from the Libya AWESOME system during the same period. The focus of the study is to determine the importance of relative location on the association between early VLF perturbations and TLEs observed during EuroSprite-2007 campaign.

2. Experiment Setup

[8] Both the Algeria and Libya VLF systems were provided on a long-term basis by Stanford University under the International Heliophysical Year (IHY) program, and installed at Algiers (36.45°N, 03.28°E) in August 2006, and Sebha (27.02°N, 14°E) in June 2007. The AWESOME system is composed of two magnetic loop antennas (oriented in North/South and East/West directions), a preamplifier, line receiver and a GPS antenna. It is capable of recording and storing narrowband 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 [*Cohen et al.*, 2010]. During the EuroSprite-2007 campaign (from June to December) the TLEs were captured by a light-sensitive, TV frame rate, camera at Pic du Midi (42.94°N, 0.14°E) and a Watec 902H camera at Centre de Recherches Atmosphériques (CRA) in southwestern France (43.13°N, 0.37°E), The EuroSprite experimental setup is described in [*Neubert et al.*, 2005] and [*Chanrion et al.*, 2007]. The optical video camera systems include trigger software for automated optical event detection are designed to be remotely controlled via the Internet. The TLEs and lightning properties from June to December 2007 are found on www.electricstorms.net.

3. October Events

[9] On 12–13 October 16 sprites and one elve were captured by a camera at Pic du Midi off the north-eastern coast of Algiers (~200 km in the north-east). Only the VLF signals of NSC (38°N, 13.50°E, 45.9 kHz) and DHO (53.10°N, 7.60°E, 23.4 kHz) showed clear and significant perturbations. At the time of the EuroSprite-2007 campaign, the Algiers receiver did not record signals from the ICV (40.88°N, 9.68°E, 20.27 kHz), HWV (40.7°N, 1.25°E, 21.75 kHz) and HWU (46.42°N, 1.14°E, 20.09 kHz) transmitters. Based on the signal-to-noise ratios of the transmitter signal, a value of 0.2 dB was chosen as a minimum detectable perturbation amplitude. All early perturbations considered in this study have signal amplitudes greater than this threshold. Figure 1 shows the VLF signals of NSC and DHO in high-resolution (50 Hz) associated with two TLEs: one above the receiver location and the second centered ~200 km to the east. The location of the sprite was approximately given by the position of the parent positive cloud to ground stroke given by the Meteorage lightning detection network. The parent stroke was chosen to be the first one that occurred within 200 ms

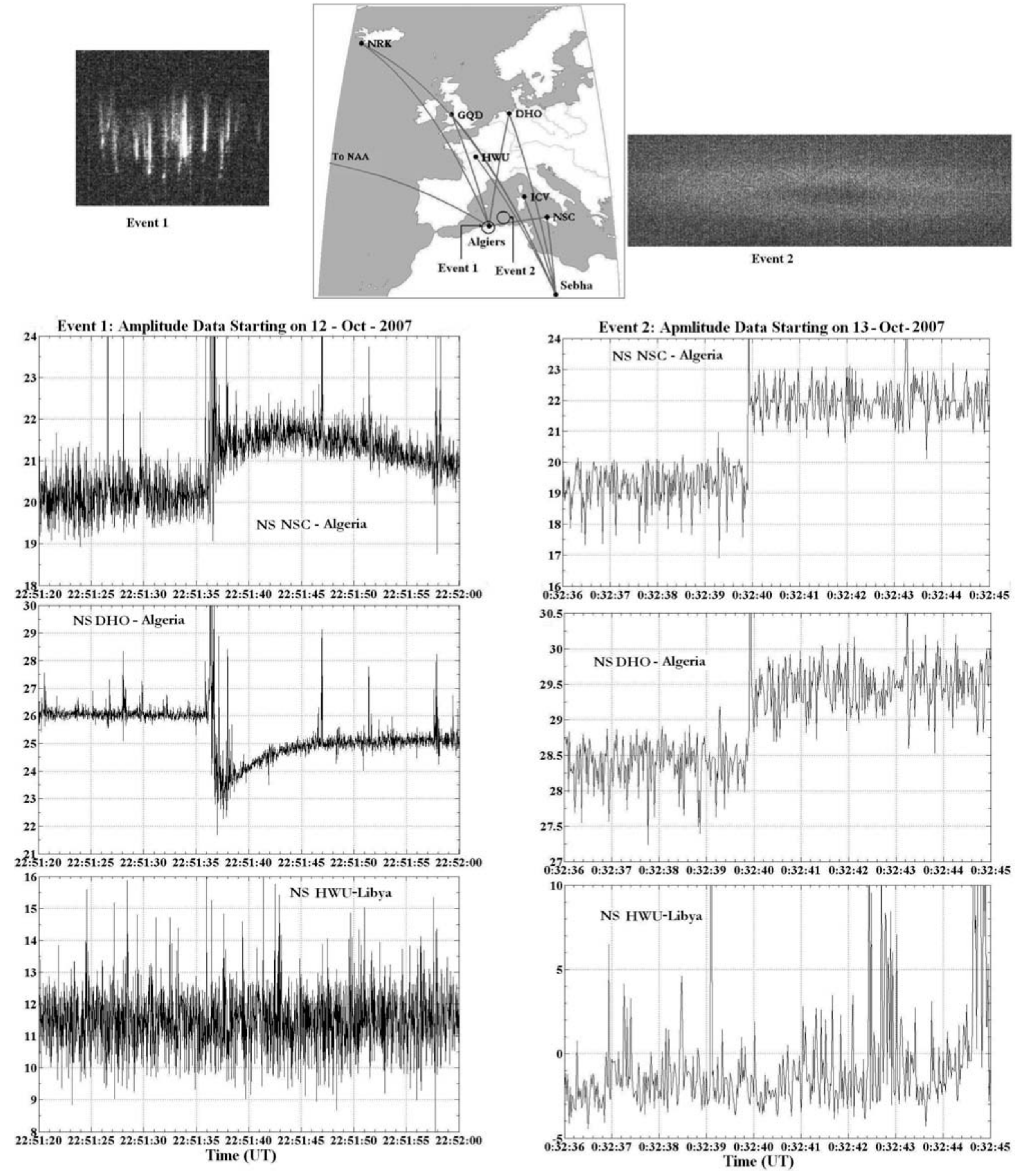

Figure 1. (top) The October 12–13 events geographic locations, TLEs images labeled Event(1) and Event(2). (bottom) VLF signals perturbations associated with the TLEs events and recorded by the two receivers.

before the TLE and within twice the field of view of the camera [*São Sabbas et al.*, 2003]. The VLF perturbations times and sprites occurrence sequences revealed that onset duration of all the abrupt perturbations in amplitude (identified as early) of both DHO and NSC signals coincide well (within 100 ms) of sprites times.

[10] The event labeled (1) was a sprite occurring above the receiver location and perturbed NSC and DHO signals paths only. As shown in the Figure 1, an early VLF perturbation was recorded in the NSC signal with onset duration of ~200 ms, the time that the perturbation needs to reach its maximum, and an LEP event recorded in the DHO signal with

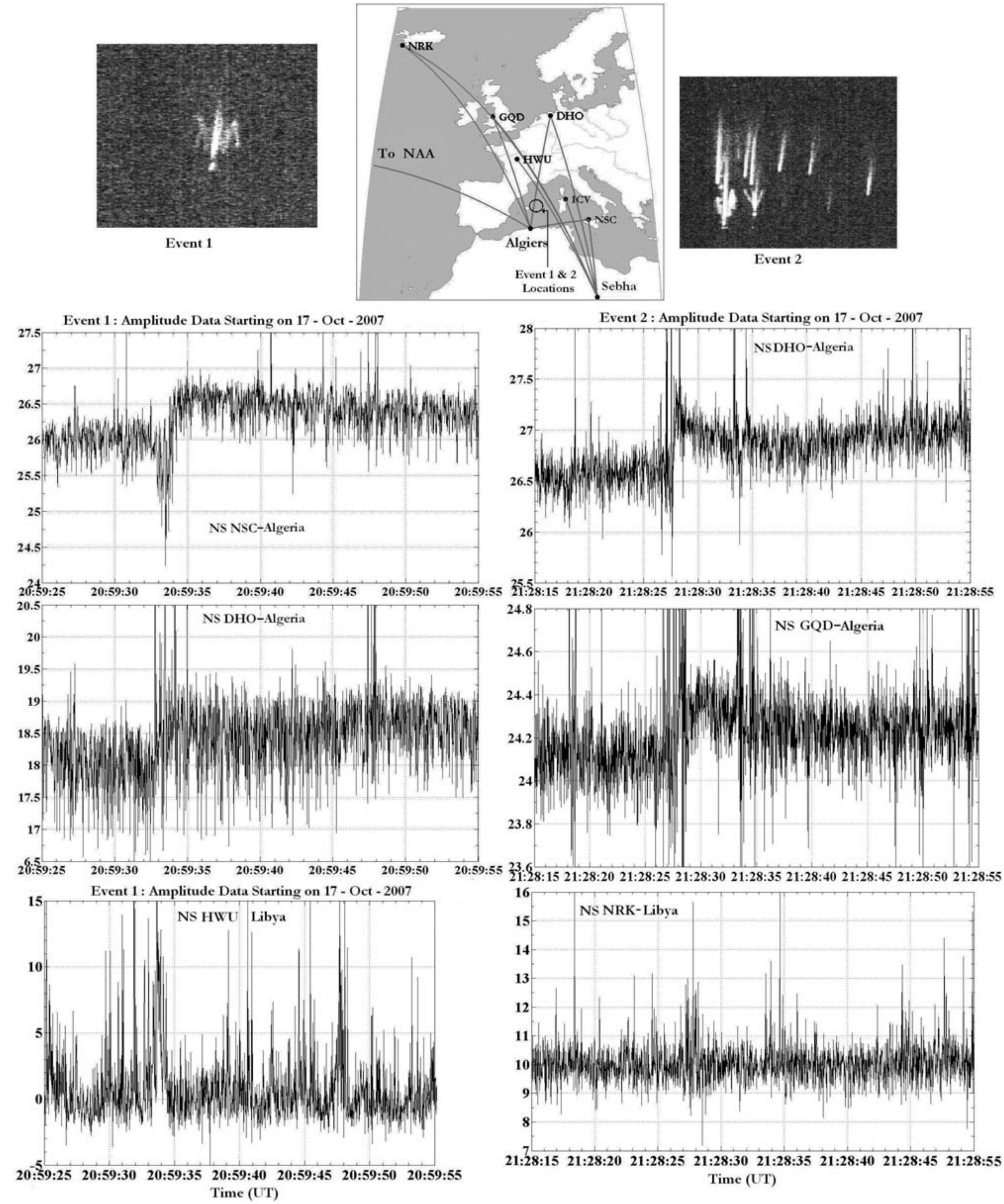

Figure 2. (top) The October 17–18 events geographic locations, TLEs images labeled Event(1) and Event(2). (bottom) VLF signals perturbations associated with the TLEs events and recorded by the two receivers.

amplitude near 3 dB. For GQD (52.91°N, −3.28°E,19.6 kHz), NRK (63.85°N, −22.45°E, 37.5 kHz) and NAA (44.64°N, −67.28°E, 24 kHz) only sferics were recorded and no associated VLF perturbation is discernable, this maybe due to the multiplicity of propagating modes which are different from signal to other so certain modes weren't perturbed by the disturbance region. The event (1) location was far from the HWU-Sebha signal path so only the sferic signature was

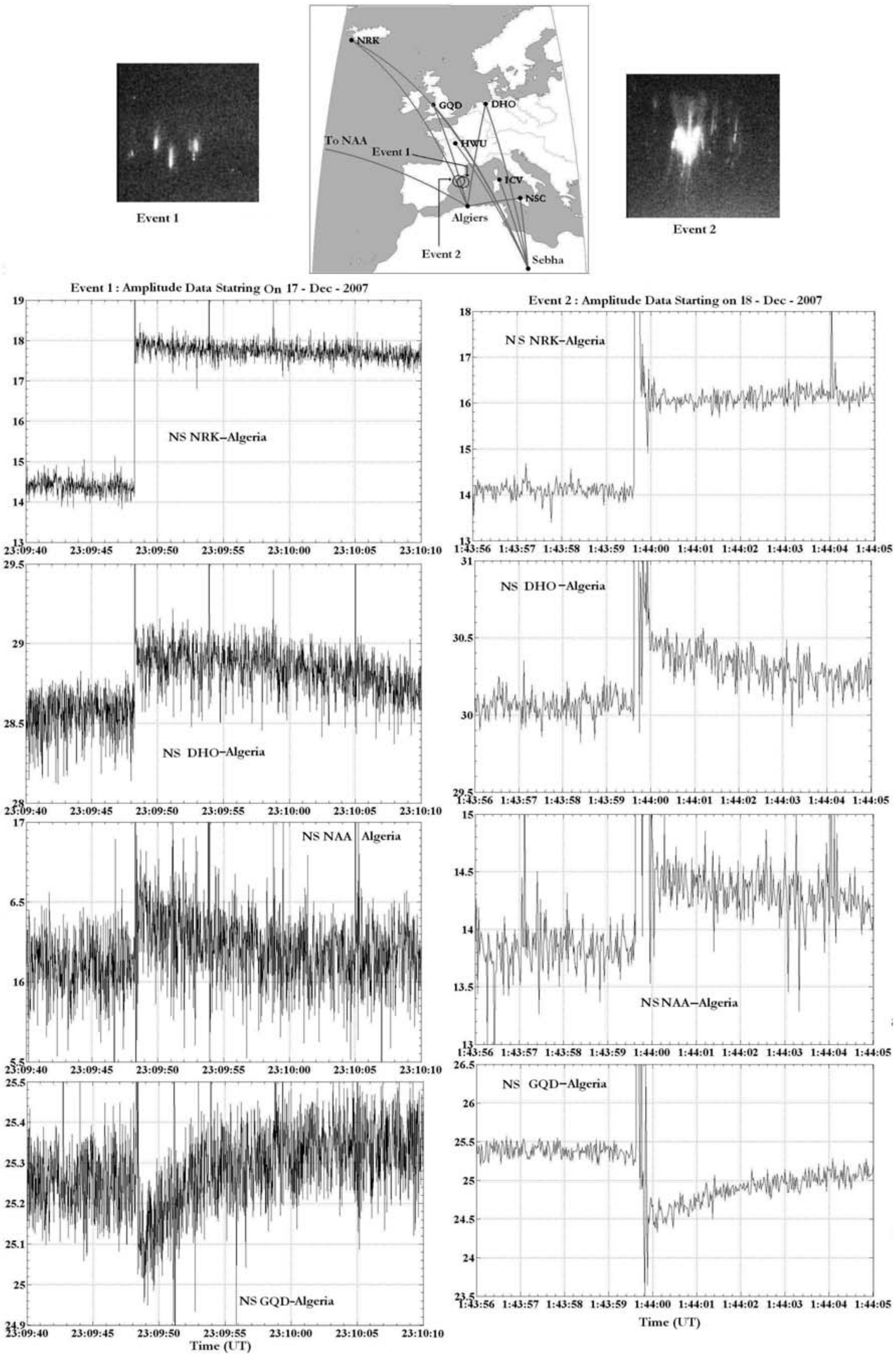

Figure 3. (top) The December 17–18 events geographic locations, TLE images labeled Event(1) and Event(2). (bottom) VLF signals perturbations associated with the sprites events.

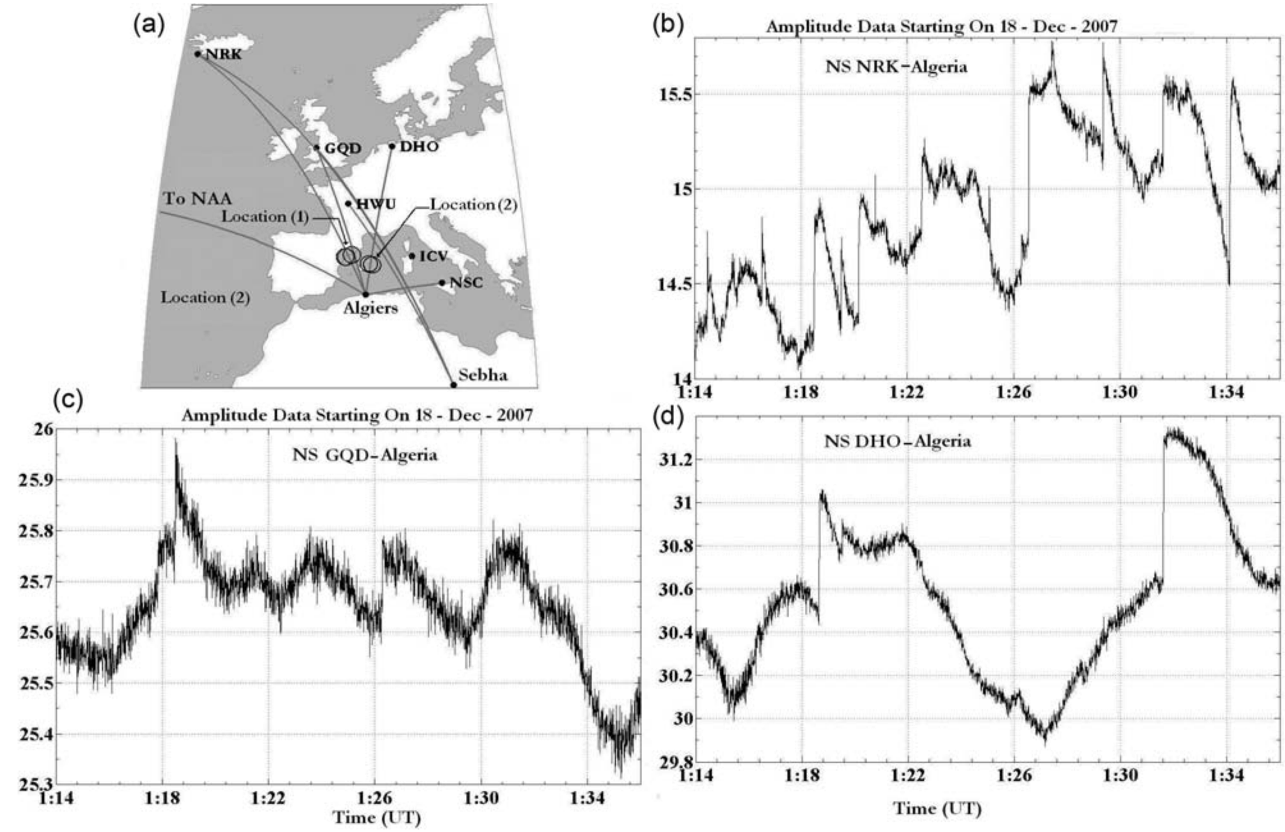

Figure 4. (a) Geographic locations of the December 18 lightnings associated with the events occurred between 01:14 and 01:36. The geographic locations of the events observed in NRK signal. (b) The NRK signal perturbations. (c) GQD and (d) DHO signals amplitudes.

recorded. The event (2) corresponds to an elve captured at 00:32:39 UT and occurring close to NSC-Algiers, HWU-Sebha, GQD-Sebha and NRK-Sebha GCPs rather than DHO-Algiers path. It was associated with early VLF perturbations recorded at Algiers only with onset durations of 120 ms in the NSC signal and 180 ms in the DHO signal, and corresponding amplitudes of 3 dB and 1 dB, respectively. For the distant receiver data, only sferic signatures were recorded during the elve time. The existence of the perturbation in the DHO-Algiers signal can be attributed to scattering from the elve body, which is probably large enough to be overhead at Algiers. And the absence of early VLF signal perturbations associated with the elve on the HWU, NRK and GQD signals recorded at Sebha is likely a result of the disturbance being further from the receiver.

[11] During 17–18 October 2007 the activity was ~400 km north of Algiers. Shown in Figure 2 are signals perturbations due to the sprites (Events 1 and 2) observed by the Pic du Midi camera, and occurring in the same region: Event (1) at 20:59:32 UT, and Event(2) at 21:28:27 UT, the associated VLF signals perturbations were early/slow with onset durations of 320 ms in DHO and 600 ms in NSC, 300 ms in DHO and 600 ms in GQD. Moreover, the sprites occur exactly in the DHO-Algiers path and the perturbations were a direct scattering process. For the NSC and GQD the signals perturbations were due to a wide scattering angle process as the locations of the TLEs were far from their paths to the receiver. The distant receiver data (Sebha) did not show any signal perturbations associated with the two events.

4. December Events

[12] A total of 57 TLEs (sprites and elves) were captured on 16–18 December 2007, during EuroSprite-2007 campaign. Due to a local power failure only events on 17–18 December were recorded by the Algiers VLF receiver. On these days 18 sprites and 10 elves were observed by the CRA camera in a storm located ~500 km northwest of the receiver, near Spain. Here, the TLEs were well situated for multi-signal paths observations. Figure 3 shows a plot of the amplitude of NRK, DHO, NAA and GQD VLF transmitter signals, which clearly exhibit early VLF perturbations associated with the sprite occurring on 17 December at 23:09:43 UT. The onset durations were 40 ms, 60 ms and 220 ms for NRK, DHO and NAA respectively. In the GQD signal the time difference between the lightning stroke and the beginning of the perturbation is near 100 ms, and the time that the perturbation took to reach its maximum is ~150 ms. Figure 3 shows another interesting sprite occurring on 18 December at 01:43:59 UT and also associated with an early VLF perturbation recorded in different transmitter signals. The onset durations were 120 ms, 200 ms and 320 ms for NRK, DHO and NAA, respectively. As in the October events, the two sprites locations were far from the DHO and NAA paths to the Algiers receiver but their

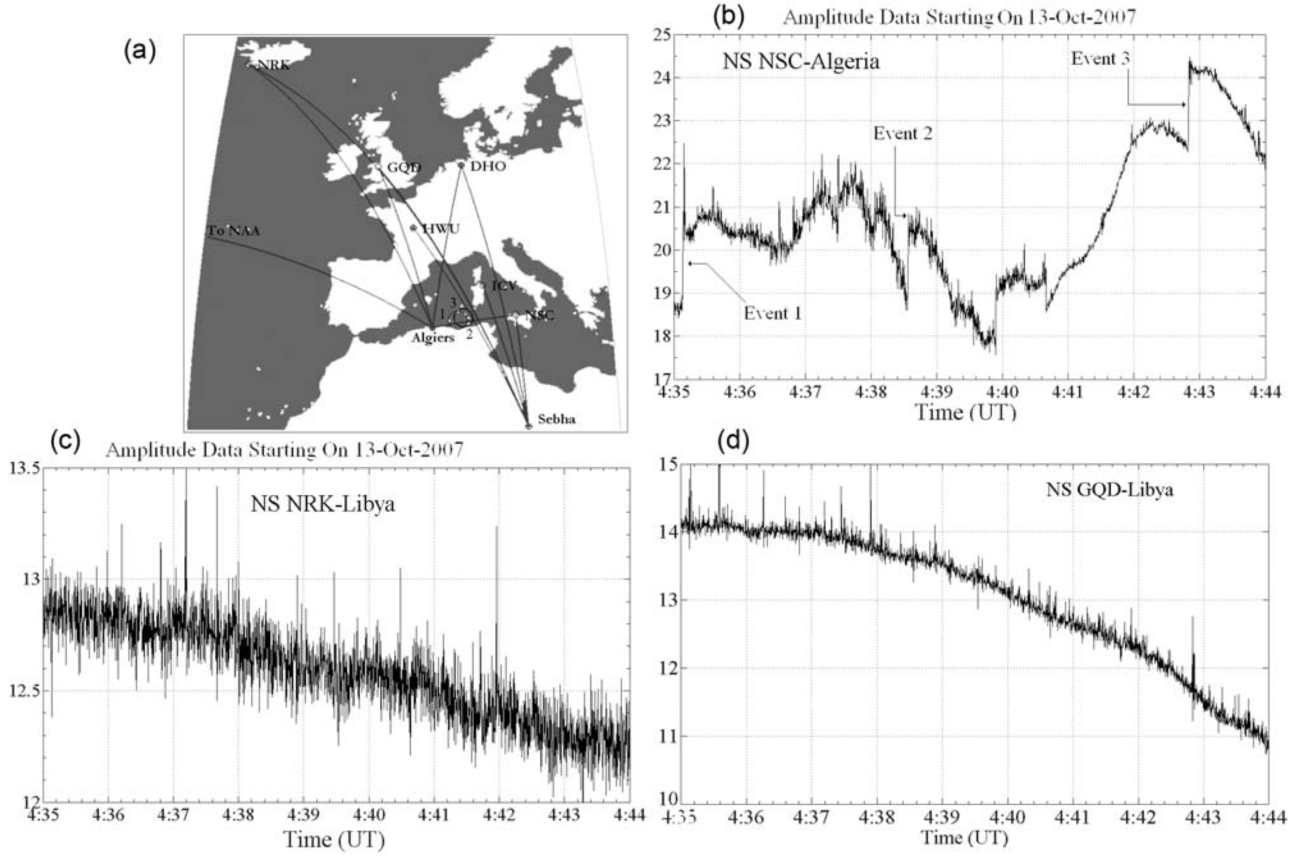

Figure 5. (a) The October 13 event geographic locations. (b) VLF signal perturbations associated with the lightning events (no TLE) recorded by Algiers receiver. (c) NRK and (d) GQD signals recorded at Sebha.

associated signals perturbations were clearly recorded with amplitudes greater than the threshold value. For the distant receiver data (Sebha) only sferic signatures of the lightning strokes were recorded. This confirms the possibility of a wide scattering angle process, and proves that observation of early signal perturbation is possible even if the TLE location is not near the transmitter-receiver path, on the condition that the distance between the disturbed region and the receiver is not too large.

5. VLF Signals Perturbations Recorded in Absence of TLEs

[13] To address the role of distance between ionospheric disturbance and the receiver, it is helpful to utilize data from multiple receivers at different distances from the storm. Data comparison between the two similar receivers of Algiers and Sebha shows that one-to-one association between early VLF perturbations and TLEs are not generally exact. More importantly, the degree of association may also be a function of the disturbance distance from the receiver and transmitter. In order to discuss this possibility, some early signal perturbations recorded in October 13 and December 18 by Algiers receiver where no TLEs were captured by the cameras are compared to those from the Sebha receiver. In Figure 4 are plotted the NRK, GQD and DHO signals amplitudes recorded at Algiers on December 18 between 01:14:00 and 01:36:00. From Figure 4, 10 early events were recorded in the NRK signal with amplitudes above the threshold value, while only two early events were recorded in both GQD and DHO signals. The camera at CRA was operated continuously during the period displayed in Figure 4 (i.e. from 1:14 to 1:36) but no observation was made, although the conditions were the same as the previous and the following TLEs detections, 1:06:03 and 1:43:59, respectively. We consider case by case the signal perturbations recorded and displayed in Figure 4 and we analyze the lightning flashes which could be associated. It is possible that some perturbations could be due to undetected elves. As in the previous case there are two main reasons which could explain why the camera did not detect these elves: (i) the camera was pointed in the correct direction but the peak current of the lightning flash recorded at the time of the VLF perturbation was not large and therefore an elve (if it was produced) would not be very bright. The cases corresponding to this configuration were at 1:34:07, 1:29:21, 1:26:33 and 1:20:10. All these CG flashes were located around 41° latitude and 1° longitude (location 1 in Figure 4); (ii) the peak current of the CG flash associated with the perturbation was large but the camera did not point exactly in the direction of the flash. This scenario applies to the case at 1:31:37 with a perturbation visible on both Algeria graphs (NS NRK and NS DHO) and a CG flash at 01:31:37,3988 and a peak current of −305 kA. Such a value of peak current could have produced an elve but this elve might be centered around

40° of latitude and 4° of longitude (location 2 in Figure 4). So, the DHO perturbation was larger than the NRK perturbation because the DHO signal crossed exactly the zone of the ionosphere concerned by the TLE perturbation. However, it is difficult to conclude definitively in this case because the GQD signal did not indicate any perturbation although it was close to the NRK path in the region of this lightning flash. For other perturbations of the NRK signal (1:22:10, 1:19:00, 1:1:30) no CG flash was detected and no TLE was observed. In these cases it is difficult to understand the origin of the perturbations, because both CG flash and TLE could be missed by their respective detection systems. The second example of early events, where no TLEs were captured by the cameras, recorded in October 13 between 04:35:00 and 04:44:00 (see Figure 5). Figure 5 shows the CG discharges locations of events (1, 2 and 3), the NSC-Algiers signal amplitude and (GQD and NRK)-Sebha signals amplitudes. The events locations were close to all transmitters-receivers paths, but the early VLF events were detected at Algiers only, which may be due to the distance from the disturbance to the receiver.

6. Conclusion

[14] The paper provides an additional information into the association of TLEs and the lower ionospheric disturbances with the VLF signal perturbations as recorded by two AWESOME systems located at different sites (Algiers and Sebha). It shows that early VLF perturbations in the signal amplitude can occur in association with TLEs and due to the lightning flashes as reported by *Rodger et al.* [2001] and *Marshall et al.* [2008], and that the presence or absence of these perturbations is a function of the modal structure of the propagating VLF wave at the location of the disturbance, the type and size of the disturbance, the distance to the receiver from the perturbation and the scattering angle. In particular, none of the perturbations recorded by Algiers VLF receiver were detected by the more distant VLF receiver, due to long distance between the disturbed region and VLF receiver, despite the fact that the transmitter-receiver path to the more distance receiver passed closer to the ionospheric disturbance. The analysis showed also that different scattering angles can occur and play an important role in determining the perturbation signal amplitude, onset duration and the recovery time.

[15] While we have provided some key insight into the degree of correlation between TLEs and Early VLF events, further data and analysis is necessary.

[16] **Acknowledgments.** We acknowledge support from CRAAG (Algeria), Stanford University (USA) and Sebha University (Libya) for the installation of the two VLF AWESOME systems in Algeria and Libya. The authors would like to thank Umran Inan and Sheila Bijoor for helpful remarks and recommendations. We thank the Météorage company for providing lightning data.

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