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Subionospheric early VLF signal perturbations observed in one-to-one association with sprites

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[1] Observations on the night of 21 July 2003 of the ionospheric effects of a thunderstorm in central France are reported. From 0200 to 0315 UT, a camera system in the Pyrenees Mountains captured 28 sprites, triggered by +CG lightning as observed by the French METEORAGE lightning detection system. A narrowband VLF receiver located on Crete, at ∼2200 km southeast of the storm, observed subionospheric VLF signals from six ground-based transmitters. The amplitude of one of the VLF signals, originating at a transmitter located ∼150 km west of the storm and passing through the storm region, exhibited rapid onset perturbations occurring in a nearly one-to-one relationship with the optical sprites. These "early" VLF events are consistent with a process of narrow-angle forward scattering from a volume of enhanced ionization above the storm with lateral sizes larger than the VLF radio wavelength. The many +CG and −CG discharges that did not produce sprites were also found to not be associated with detectable VLF amplitude perturbations, even though some of these discharges reached relatively large peak currents. The rapid onsets of several of the sprite-related VLF perturbations were followed by relatively long onset durations, ranging from ∼0.5 to 2.5 s, indicating that these events were early but not "fast." These "early/slow" events may suggest a slow process of ionization build-up in the lower ionosphere, following intense lightning discharges that also lead to sprites. A limited number of early VLF perturbation events were also associated with whistler-induced electron precipitation events, or classic Trimpi perturbations, undoubtedly produced by the precipitation of electrons due to whistler-mode waves injected into the magnetosphere by the same lightning flash that led to the production of the sprite.

INDEX TERMS: 2435 Ionosphere: Ionospheric disturbances; 2427 Ionosphere: Ionosphere/atmosphere interactions (0335); 6934 Radio Science: Ionospheric propagation (2487); 0669 Electromagnetics: Scattering and diffraction; *KEYWORDS:* sprites and VLF perturbations, early/fast VLF events, early/slow VLF events, VLF sprites, lightning discharges

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1. Introduction

[2] Sprites are vertically elongated, luminous structures above active thunderstorms at altitudes from ∼40 to 90 km, typically lasting less than 100 ms. Sprites are generated by quasi-static electric fields which temporarily exist at high altitudes following positive, cloud-to-ground (+CG) lightning discharges, with charge moment changes in excess of ∼600 C-km [*Hu et al.*, 2002]. The study of sprites and related Transient Luminous Events (TLEs) of the middle and upper atmosphere, such as elves [*Inan et al.*, 1997] and blue jets [*Wescott et al.*, 1996], is a relatively young research field in which several fundamental questions/problems remain unresolved [*Rodger*, 1999; *Neubert*, 2003].

[3] The surging interest in sprites over the past few years has led to several multi-instrument campaigns worldwide, mostly in North America. In Europe, the experimental effort has been led by the Danish Space Research Institute (DSRI), which has organized campaigns since 2000, where the first sprites over Europe were documented [*Neubert et al.*, 2001]. During the summer of 2003, the sprite campaign EuroSprite2003 was launched with a number of complementary measurements being taken over southern Europe and at the magnetically conjugate region over southern Africa. This paper constitutes an initial report of the optical measurements from the Observatoire du Pic du Midi in the French Pyrenees and associated VLF perturbation events observed on VLF signals continuously monitored by a receiver on the island of Crete (35.31°N; 25.08°E).

[4] We present results from a unique set of observations made during the night of 21 July 2003 when 28 sprites were detected over an active mesoscale convective system in

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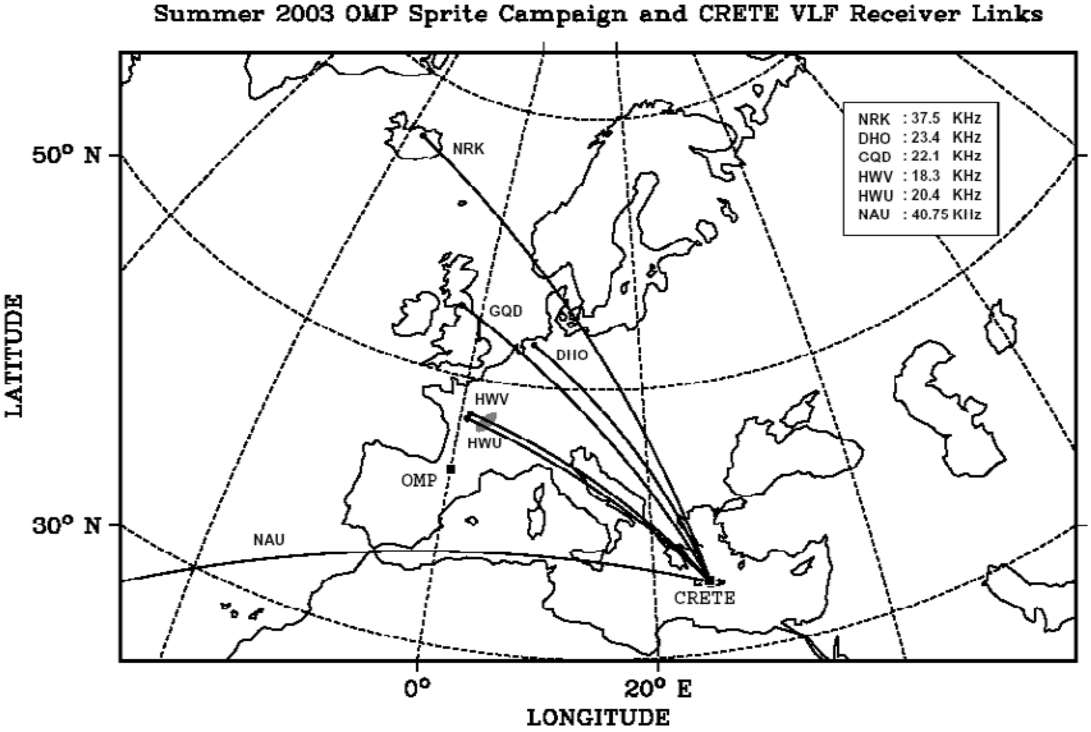


Figure 1. Configuration of the Crete VLF receiver. Also shown are the optical site (OMP) and the approximate extent of the 21 July 2003 thunderstorm in central France.

central France. The storm was ~100 to 200 km southeast of two French VLF transmitters, the signals from which were received on Crete, arriving over great circle paths (GCP) which cut through the core of the storm. Perturbations in the signal amplitudes, particularly in transmissions from one of the VLF transmitters, show clear sprite-associated signatures of modifications to the lower ionosphere occurring within less than 20 ms of the sprite onsets. While "early/fast" VLF perturbations, occurring within 20 ms of causative lightning discharges and having onset durations less than 20 ms, have been observed for some time [e.g., *Inan et al.*, 1988, 1993], the first association between early VLF (but not necessarily "fast") events and sprites was reported later [*Inan et al.*, 1995] and attributed to narrow-angle forward scattering from diffuse regions of ionization near the GCP between the VLF transmitter and the receiver. These VLF events, occurring in the midwestern United States, were found to be associated only with a small subset of sprites, with the association between sprites and VLF events not being one-to-one.

[5] Other measurements suggest subionospheric VLF perturbations may be induced only at short distances between the storm and transmitter, with signal perturbations detected in all directions around the sprite, even as backscatter [*Dowden et al.*, 1996]. These near-storm VLF events showed a one-to-one association with the occurring red sprites and were observed both as amplitude and phase perturbations. They were attributed to wide-angle (omnidirectional) scattering, from narrow ionization structures created by the sprites with lateral dimensions smaller than the VLF wavelength. The differences between the two sets of observations have stimulated a discussion, which reveals the complexity of the process, the instrumental limitations, and the need for more experiments [*Dowden*, 1996; *Inan et al.*, 1996].

[6] It has recently been suggested [*Barrington-Leigh et al.*, 2001] that early/fast VLF events may be associated with sprite halos, which are structureless regions of large (~100 km) transverse extent, lying above sprites at 70–85 km altitudes. Quantitative examination of this possibility [*Moore et al.*, 2003] indicates that the observed VLF scattering from electron density changes associated with sprite halos can account for the observed properties (both diffraction pattern and magnitude) of at least some early/fast VLF perturbation events.

[7] The present paper offers new observational evidence of sprite-related early VLF events and their characteristics. A better understanding of this phenomenon holds the promise of quantifying ionization in the upper atmosphere associated with lightning discharges and sprites (or sprite halos), a fundamental byproduct of the lightning-ionosphere interaction processes that is difficult to observe by other means.

2. Experiments and Data

[8] The optical measurements were taken from the Observatoire du Pic du Midi (42.9°N; 0.09°E) with a low-light CCD camera system mounted on a motorized pan-tilt unit, which allowed observation within 360° of azimuth and −35° to +35° of elevation. The camera was remotely controlled over the Internet and adopted an automatic event

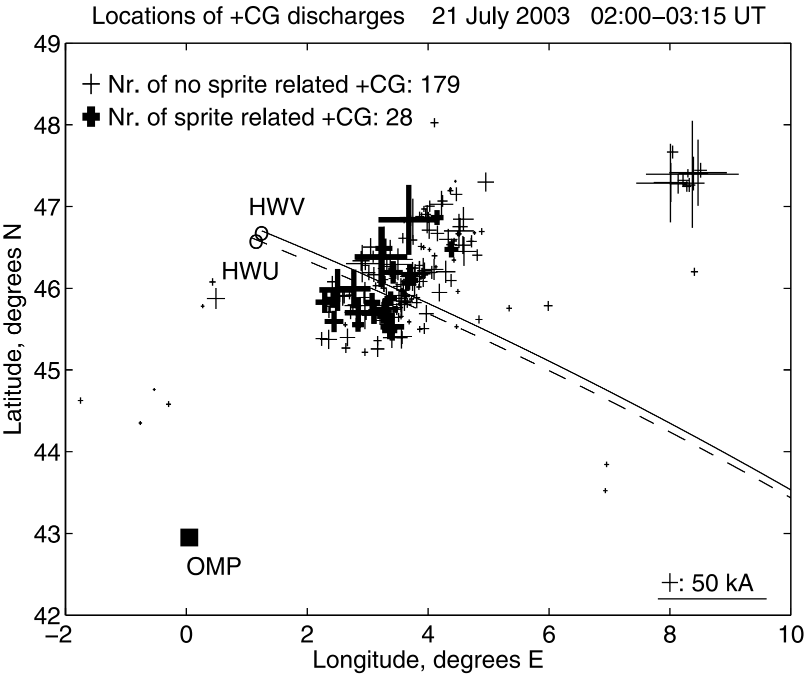


Figure 2. Map of the +CG discharge location for the storm of 21 July 2003. The thick crosses correspond to sprite-producing +CG lightning discharges. The size of each cross is scaled with the +CG peak current.

detection algorithm. Images were stored on a local computer that also controlled the operation of the system. The digitized video files were time-stamped using the PC system time which was synchronized to UT time through the Network Time Protocol (NTP). The exposure time used for the optical images was 20 ms and the timing accuracy ±20 ms.

[9] The Crete VLF station (35.31° N, 25.08° E) started its routine operation 18 July 2003. It consists of a receiver identical to those of the Holographic Array for Ionospheric Lightning (HAIL) system [*Johnson et al.*, 1999]. The wideband signal is detected with a 1.7×1.7 m^2 magnetic loop antenna and is sampled at 100 kHz with 16-bit resolution and with GPS-based timing. The sampled wideband waveform is then digitally filtered into six narrow bands centered around the selected frequencies of signals from ground transmitter stations, five of which are in Europe and one of which is in Puerto Rico. The message modulations imposed on the signals are digitally demodulated, extracting the amplitude and phase of the coherent signals as a function of time. The system thus provides continuous monitoring of the phase and amplitude variations of the signals from the six transmitters, which reflect changes of ionization properties in the lower ionosphere and upper atmosphere along the signal path. The transmitter call signs, their frequencies, and the corresponding GCPs to the Crete receiver are shown in Figure 1.

[10] Lightning data are provided by METEORAGE, the National French network for lighting detection. The system measures characteristics of the CG discharges including polarity, the peak current, multiplicity, geographic location with a precision of 1 km, and a time accuracy of 1 ms.

[11] The observational data were taken during a mesoscale thunderstorm in the postmidnight of 21 July 2003 over central France. The approximate storm location and extent is indicated in Figure 1 by the small shaded area at ~46°N, 3°E. The storm was only 150 to 200 km southeast of the HWV (Le Blanc, 46.7°N, 1.26°E) and HWU (Rosnay, 46.6°N, 1.1°E) VLF transmitter sites, and ~2200 km from Crete. The HWV and HWU transmitters are particularly interesting as their paths pass through the storm region.

3. Observations

[12] The camera captured 28 sprites during a 75-min period from ~0200 to 0315 UT, all associated with +CG discharges. The METEORAGE system reported that during the same time, 1274 −CG and 207 +CG discharges occurred in all. As usual, the +CG flashes were typically more energetic with peak currents ranging from 20 to 250 kA.

[13] Figure 2 shows the spatial distribution of all +CG flashes. The +CG flashes are identified by crosses scaled linearly with the peak current, and those associated with sprites are indicated with thick-line crosses. As seen, both GCPs cut through the core of the activity and therefore are suited for detecting lightning-induced VLF perturbations in the lower ionosphere above the storm. The perpendicular distances from the sprite-causative +CGs to the GCPs range from a few kilometers to ~100 km, with a mean near 55 km, whereas their peak currents range from ~20 to 180 kA, with a mean near 60 kA. Of course, one has to be aware that the sprite locations do not necessarily coincide with the causative +CG discharge locations and that at times they can be significantly displaced by as much as 60 km [e.g., see *Wescott et al.*, 1998].

[14] Inspection of the sprite occurrence sequence and the VLF amplitude times series revealed a striking coincidence between the sprites detected and the onset of abrupt pertur-

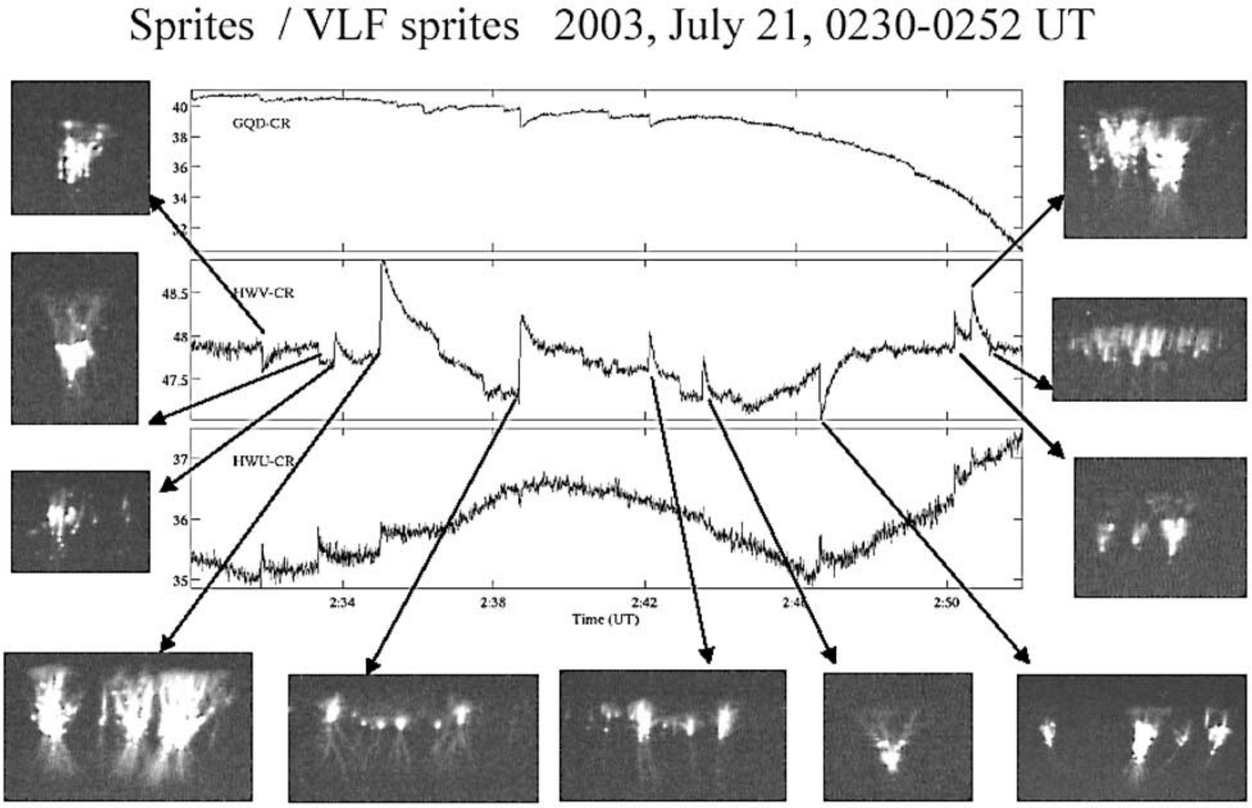


Figure 3. VLF amplitude time series measured from Crete and 11 optical sprites measured from OMP during a 22-min storm interval. Nearly all optical sprites coincide with the onset of VLF perturbations identified as early VLF events.

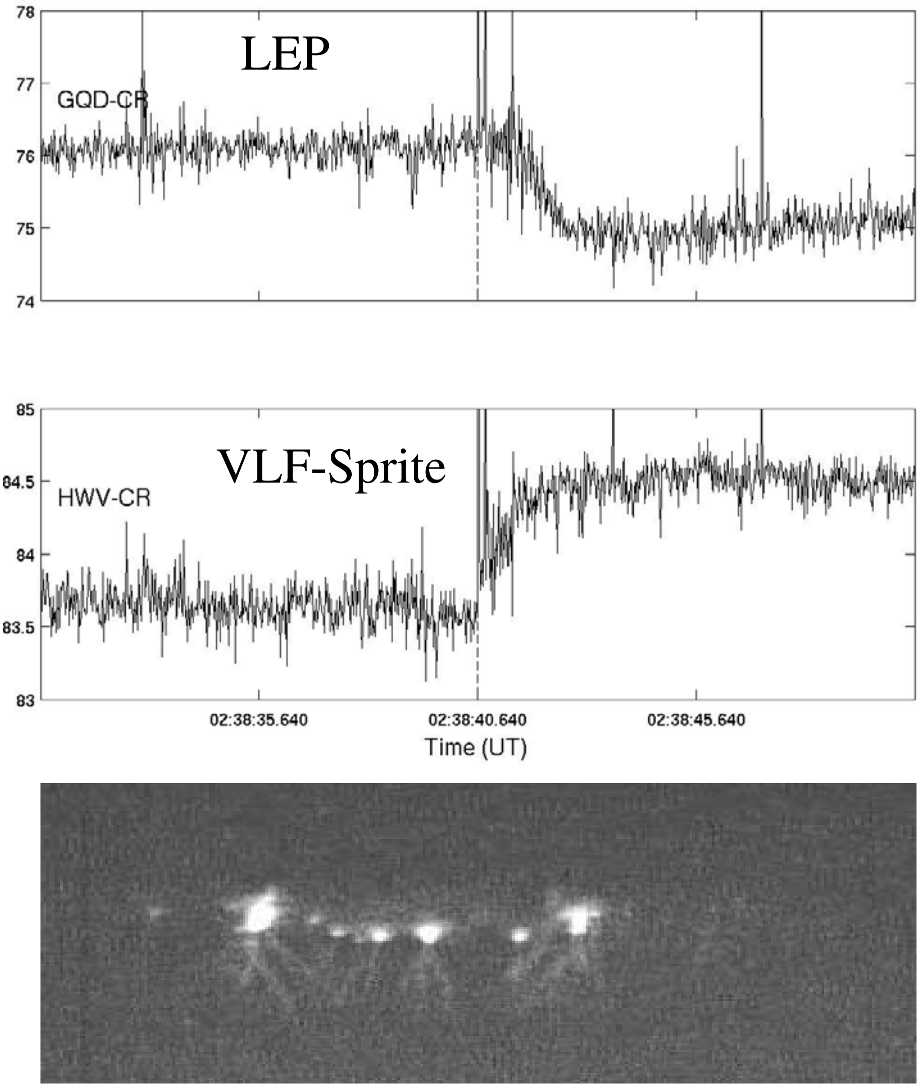
bations in amplitude, which were identified as "early" VLF events. This association is illustrated in Figure 3, which corresponds to the time interval from 0230 to 0252 UT when 11 out of the 28 sprites were observed. The VLF time series display the signal amplitude-to-noise ratio in dB for the HWU-CR (HWU-Crete) and HWV-CR links traversing the storm region and the GQD-CR link north of the storm.

[15] Figure 3 shows that the VLF events are clearly identifiable, especially on the HWV-CR (Le Blanc, 18.3 kHz) signal. As shown, each of the observed sprites correlates with an abrupt jump in VLF amplitude of either positive or negative polarity (except possibly for the last sprite at 0251:08.320 UT). High time resolution plots show that the perturbation onsets occur within ~20 ms (time resolution of the data) relative to the sprite times. This early VLF signature signifies a sudden change in ionospheric conductivity produced possibly by the energy released in the sprite-causative +CG flash and/or the cloud-ionosphere discharge (CID) associated with the sprite itself. In contrast, the phase perturbations of the VLF sprites were either nonexistent or were very weak and thus buried in the noise.

[16] The sprite-related VLF perturbations are not as clearly visible on HWU-CR (Rosnay, 20.4 kHz) signal, despite the fact that the GCPs of these two companion links were practically identical. We have no quantitative explanation for this difference, although the sensitive dependence of the mode structure and amplitude variations (as a function of distance along a GCP) on the VLF frequency is well known [e.g., see *Wait*, 1996]. Another possible reason could be the higher noise levels in the HWU link, possibly because of lower transmitted power, as evidenced from the time series themselves.

[17] We include the GQD-CR signal in Figure 3 because, although the GCP is 500–550 km north of the storm, this signal is the only one that exhibits perturbations in association with lightning discharges occurring in the same thunderstorm system. The data show the occurrence on the GQD-CR signal of negative VLF perturbations seen only in amplitude. The distinct onset delays (e.g., see Figure 4) of these perturbations identify them as due to lightning-induced electron precipitation (LEP) caused by energetic radiation belt electrons scattered into the loss cone by whistler waves from a lightning discharge [*Inan et al.*, 1993]. LEP events occurring on subionospheric VLF paths displaced poleward of a thunderstorm are known to occur and are expected as a result of precipitation induced by nonducted whistler waves [*Lauben et al.*, 2001]. It is interesting that at least four of the observed early VLF perturbations on the HWV-CR signal associate directly with LEPs on the GQD-CR signal. In these cases, the causative +CG discharges were the most energetic ones as compared with the rest of the sprite-related +CG flashes.

[18] Figure 4 shows an example of an early VLF event (HWV-CR, middle panel) accompanied by a LEP event to



Sprite at 02:38:40.640 UT

Figure 4. An example of an early/slow VLF event occurring above the storm and a LEP event seen ∼500 km north of the storm, both related to the optical sprite shown in the lower panel. The signal amplitude scale is expressed as logarithmic amplitude and not as signal to noise ratio in dB (as in Figure 3). The clipped amplitude excursions correspond to lighting-induced atmospherics. As shown, the onset duration, or built-up time, of the sprite-related early VLF perturbation is fairly long, ∼2.5 s.

the north (GQD-CR, upper panel), both associated with the sprite shown in the lower panel. The onset of the early event coincides with the optical sprite, marked in the middle and upper panels by the dashed line at 0238:40.660 UT (time of image integration start) and a strong sferic from a +CG lightning flash of 161 kA on 0238:40.664 UT. The onset of the LEP event is delayed relative to the sprite by ∼0.7 to 0.9 s, whereas its onset duration lasts for ∼1.5 s.

[19] An interesting observation in Figure 4 relates to the duration of the perturbation onset time of the early VLF event. The onset duration is fairly long nearing ∼2.5 s, which classifies this sprite-related signature as "early/slow," in contrast to "early/fast" VLF events having onset durations typically less than 100 ms [e.g., see *Rodger*, 1999, 2003]. At least 18 of the early VLF events have onset durations between 0.5 and 2.5 s. VLF events which are "early" but not "fast" with onset durations of ∼500 ms have been also observed before [*Inan et al.*, 1995, 1996].

[20] Nearly all sprites, 26 out of the 28, are associated with perturbations in VLF amplitudes ranging from 0.2 to 3.0 dB. Only one early VLF signature was not accompanied by an optical sprite. No VLF perturbation signatures were observed in relation with the numerous lighting discharges not producing sprites, which included 179 +CG and the 1274 −CG flashes in the time interval under consideration.

4. Summary and Concluding Comments

[21] We have presented unique results on VLF ground transmitter signal amplitude perturbations observed during

the postmidnight of 21 July 2003, when 28 sprites were detected over an active mesoscale convective system in central France. The main findings are as follows.

[22] 1. Abrupt perturbations in the amplitude of VLF transmitter signals arriving over paths intersecting the storm are observed only in conjunction with those +CG flashes that lead to the production of sprites. No VLF events are observed in connection with the numerous +CG and −CG lightning discharges that did not lead to sprites, even when these are energetic and occur near the GCPs intersecting the storm. The perturbation onsets of the VLF events are "early," that is, they occur within the resolution of the measurement (∼20 ms) relative to the sprites.

[23] 2. The sprite-related early VLF perturbations are seen at distances larger than 2000 km from the storm and have well-defined amplitude perturbations reaching values as high as 3.0 dB.

[24] 3. Many of the VLF events have slow onset durations ranging from 0.5 to 2.5 s, indicating that while the events have early onsets, they are not necessarily "fast."

[25] 4. A few of the lightning flashes that led to sprites and early VLF events also led to nonducted whistler-induced electron precipitation, or classic Trimpi, events seen a few hundred kilometers north of the storm. The data suggest that this combination occurs for the strongest +CG discharges.

[26] The characteristics of the early VLF events reported here resemble in many ways those reported by *Inan et al.* [1995]. One exception is that the VLF events in our case are observed for all sprites and not for a subset of sprites. We attribute this difference to the proximity of the present storm to the VLF transmitter, which allows the traverse of the storm-affected lower ionospheric volume by the subionospheric VLF wave while it is still constituted by a large number of higher-order waveguide modes. Subionospheric VLF signals launched by a ground-based transmitter are generally constituted by a large number of higher-order waveguide modes initially which decay away rapidly with distance [*Poulsen et al.*, 1993], and it is possible that electric field distribution of some of these higher-order modes are better disposed to be perturbed by a given ionization profile. In view of the fact that coupling between waveguide modes does occur, perturbations of these higher-order modes may then be manifested as signal amplitude changes on the lower-order modes, which survive the propagation distance to the receiver [e.g., see *Wait*, 1996]. In this way, the proximity of the ionospheric disturbance to the transmitter may well have enhanced the overall sensitivity of detection of relatively small ionization changes.

[27] The long onset durations of 0.5 to 2.5 s measured for several of the observed early VLF events may imply a mechanism at work that causes ionization to build up during all this time. In one way, this slow buildup of the sprite-related early VLF events resembles the long onset times of classic VLF signatures of LEP events, which involve a much larger timescale driven by the relatively slower timescales of the magnetospheric wave-particle interaction and the resulting durations of electron precipitation bursts. Nevertheless, the early/slow VLF signatures reported here constitute a new observation that awaits explanation.

[28] Finally, it is interesting that the numerous and at times very energetic CG flashes which did not generate observed sprites were also not associated with early or early/fast VLF perturbations. This result implies that the CG discharges that do not lead to sprites may not have a direct detectable effect on the ionosphere above the storm. On the other hand, early/fast VLF events have clearly been observed with no sprite-related CG discharges, even with −CG discharges [*Inan et al.*, 1993, 1996] which are known to not produce sprites, [e.g., see *Rodger*, 1999]. At present, the nature of the association between sprites and early and/or early/fast VLF events thus remains unclear, even though our data indicate a nearly one-to-one relationship.

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