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Subionospheric VLF signatures and their association with sprites observed during *EuroSprite-2003*

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Abstract

In this study, VLF observations during *EuroSprite-2003* are analyzed in connection with many sprites observed above thunderstorms in central France. The sprites were detected with a sensitive camera from the Observatoire du Pic du Midi in the Pyrenees overlooking storms monitored by the French national lightning detection network. The VLF observations were made in Crete, Greece with a narrowband receiver, and in Nançay, France with a broadband receiver. The storms were in the vicinity of a VLF transmitter (HWV) at Le Blanc, France, whose signal was received on Crete, arriving over a great circle path that cut through the storms to the southeast. The Nançay broadband receiver was located near HWV to the northeast of the transmitter. This setup provided a unique observational set for investigation. The receiver in Crete observed early VLF perturbations in nearly one-to-one association with the sprites, which endorses the findings of earlier work based on *EuroSprite-2003* observations from a single storm. While part of the sprite-related VLF perturbations were of the early/fast type, many classified as "early/slow" having onset durations up to ~2 s and thus suggesting a new mechanism at work which may cause a slow build up of ionization after a sprite. The only elve in the data set was found to associate also with an early/fast VLF perturbation. Moreover, the analysis showed basically no early VLF events to occur in relation to the numerous ±CG discharges that did not lead to sprites. Bandpass filtering of the broadband VLF signal revealed that only about 5% of the sprites were escorted by early VLF perturbations, possibly due to backscatter. Finally, by using all 131 sprites captured during *EuroSprite-2003,* the time lags of the sprites to the preceding +CG discharges were computed and analyzed. The time-lag distribution had a well defined tail suggesting that at least one third of the sprites observed were lagging the +CG discharges by more than 30 up to 300 ms. In addition these "long-delayed" sprites were not accompanied by any radio-sferics during the sprite observation period, in sharp contrast to the short-delayed sprites which were escorted nearly always by enhanced, burst-like, sferic activity. These observations endorse the notion of long delayed sprites reported in past studies, but also show that their occurrence is much more frequent than it was thought before.

Keywords: Red sprite; Elve; Early VLF perturbation; Backscatter; Lightning; Lower ionosphere

1. Introduction

Early VLF perturbations, caused by lightning-induced conductivity changes in the lower ionosphere

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above thunderstorms, have been studied extensively since their first detection by Armstrong (1983). They are characterized by an abrupt onset in amplitude and/or phase of a VLF signal whose great circle path (GCP) to the receiver intersects, or passes near, the thunderstorm. They occur only occasionally, shortly after a sferic ($<$20–50 ms, i.e., "early") produced by a lightning discharge. At first, the perturbations were categorized as "early Trimpis" in order to contrast with the long-delayed classic Trimpis caused by whistler-induced precipitation of radiation belt electrons. The explanation of early VLF events relies on two different, but not necessarily independent, processes: (1) heating of the lower ionosphere by strong quasi-electrostatic fields generated by lightning (Inan et al., 1991, 1996a; Pasko et al., 1995), and (2) ionization production during transient luminous events (TLEs), such as sprites, sprite halos and elves (e.g., see Moore et al., 2003; Rodger, 2003 and more references therein).

The present paper deals with observations of early VLF perturbations in association with TLEs, a topic on which there exist only few observational studies. The first connection between sprites and early/fast VLF events ("fast" means having short onset durations $<\sim$20–50 ms) was reported by Inan et al. (1995). This relationship was observed only for a small subset of sprites occurring at large distances from the receiver ($>$2000 km). These early VLF events were attributed to directional forward scattering from enhanced ionization located near the GCP to the receiver and having lateral extents of ~100–150 km. On the other hand, Dowden et al. (1996) observed early VLF perturbations in one-to-one relationship with sprites located within ~500 km to the receiver. They attributed their occurrence to wide-angle (omnidirectional) scattering from columnar structures of ionization with scales shorter than the VLF wavelength. The differences between the two sets of observations stimulated a discussion between Dowden (1996) and Inan et al. (1996b), which revealed the complexity of the phenomenon and the need for more observations. Finally, and to our knowledge, there is a single event reported in the literature of a "rapid onset rapid decay" (RORD) VLF signature associated with an elve (Hobara et al., 2001).

In the present paper, narrow- and broadband VLF recordings collected during the *EuroSprite-2003* campaign are analyzed in relation with simultaneous optical observations of TLEs and CG lightning detection measurements. The aim of *EuroSprite-2003* was to perform complementary measurements in order to investigate the effects of sprites on the mesosphere and lower ionosphere. During the summer of 2003, various instruments were deployed in southern Europe and at magnetically conjugate locations in South Africa, which collected data concurrently with the detection of more than 130 sprites during 9 different storms. For details on *EuroSprite-2003,* the experiments and the measurements, see Neubert et al. (2005).

The first results on the relation of *EuroSprite-2003* VLF measurements taken from Crete and video images of sprites over a storm in central France taken from the Observatoire du Pic du Midi (OMP) in the Pyrenees, were reported in a brief paper by Haldoupis et al. (2004). They observed early VLF perturbations in a one-to-one relationship with the captured sprites, which is consistent with narrow-angle forward scattering from volumes of enhanced ionization above the thunderstorm. In addition, they reported for the first time sprite-related VLF perturbations which exhibited, besides their rapid onset, long-lasting onset durations ranging from about 0.5 to 2.0 s. These "early/slow" events suggested a new process at work, of slow ionization build-up in the lower ionosphere following the sprites. Finally, this initial *EuroSprite-2003* study found no early VLF perturbations in relation with the numerous and at times very energetic CG discharges which did not lead to sprites.

The present paper continues and expands the previous work on the *EuroSprite-2003* VLF measurements. First, the analysis used by Haldoupis et al. (2004) on a single storm with 28 sprites is now applied for the entire data set of three storms with a total of 47 sprites and one elve. In this way, in addition to testing the validity and generality of the previous results, the first statistics on the characteristics of the sprite-related early VLF perturbations are derived, and a VLF signature relating to an elve is reported. Moreover, broadband VLF observations from a station in the vicinity of the storms, but also near a VLF transmitter, are used to investigate the possible occurrence of backscatter from ionized structures with small spatial scales inside the volume of sprites. Finally, the entire number of *EuroSprite-2003* sprites (131 events) is used in conjunction with lightning detection data and broadband VLF recordings of the radio sferic activity, in order to investigate the topic of positive CG discharges causative to the sprites. Surprisingly, this led to some new findings which show that the relationship between sprites and causative +CG discharges is more complex than thought.

2. Experimental systems

In this section, a brief description is given of the experiments that provided observations for the present study. They include the sprite detection system in the French Pyrenees, the narrowband VLF receiver in Crete, the broadband VLF receiver in central France near Nançay, and the French lightning detection system. For more details on these and other instruments deployed during *Euro-Sprite-2003* see Neubert et al. (2005).

The optical measurements were made with an automated camera system operated in the OMP at 42.9° N, 0.09° E. The video equipment consisted of two unintensified low-light CCD cameras with identical 16 mm F1.4 lenses, having a field-of-view of 22.5°. The cameras were mounted on a motorized pan-tilt unit, which allowed observation within 360° of azimuth and from −35° to +35° elevation. The system was controlled via Internet through a personal computer (PC) with software for automatic event detection and image recording in digital form. The image files were timed by the PC clock, which was synchronized to UT through the Internet by making use of the network time protocol (NTP). The exposure time of the images was 20 ms and the image time was correct to within 12 ms.

The crete VLF receiver (35.31° N, 25.08° E) is identical to those of the Holographic Array for Ionospheric Lightning research (HAIL) network in the United States (e.g., see Johnson et al., 1999). The wideband signal detected by a north-south oriented 1.7×1.7 m magnetic loop antenna is bandpass filtered to a range of 9–45 kHz and sampled at 100 kHz with 16-bit resolution, with triggers provided by GPS timing. Next, the wideband signal is digitally down-converted into narrow bands, centered around six pre-selected frequencies of individual VLF transmitters chosen from those located around the globe for communication purposes. The demodulated amplitude and phase of the narrowband signals are recorded with 20 ms resolution, typically during 17:00–05:00 UT. For covering *EuroSprite-2003*, the Crete receiver was tuned onto six transmitters, five of them located in north-west Europe and one in Puerto Rico. The transmitter call signs, their frequencies and the GCPs to the Crete receiver are all shown in Fig. 1. Also shown in Fig. 1 are the locations of the OMP and the broadband VLF receiver at Nançay.

The Nançay VLF station (47.38° N, 2.19° E) near Orleans, France, is a two channel (north–south and east–west) broadband (~350 Hz–50 kHz) receiver, using two right-isosceles triangular antennas with 8.4 m base, 4.2 m height, mounted on a central pole. Both channels are sampled at 100 kHz with 16-bit accuracy to provide a high resolution digital waveform of lightning emitted sferics. During *Euro-*

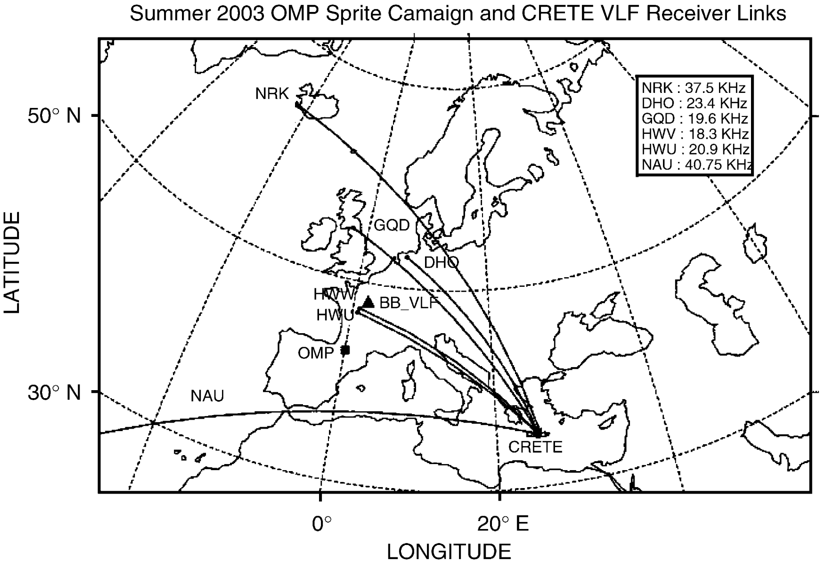

Fig. 1. Map, showing the GCPs of the Crete narrowband VLF receiver links. Also sown is the sprite measurement site at the OMP, and the location of the broadband VLF receiver (BB-VLF) near Nançay, France.

Sprite-2003, the Nançay VLF station was operating on a daily basis from 21:00 to 03:00 UT.

Finally, the cloud-to-ground (CG) lightning observations used in this study were made by MÉTÉORAGE, the French national lightning detection network. MÉTÉORAGE uses radio triangulation techniques to provide the characteristics of CG discharges, which include: time of occurrence with better than 1 ms accuracy, geographic location with at least 4 km precision, peak current intensity of the first return stroke, multiplicity, and CG discharge polarity. Note that the detection efficiency of MÉTÉORAGE is higher than 90% (Morel and Sénési, 2000), whereas the error of peak current intensity measurements is close to 5% (Bonnet, 2004).

3. Observations and analysis

During the two month duration of *EuroSprite-2003*, sprites were observed above 9 thunderstorms over central France, between July 21–27 and August 20–29. During these time periods, 131 sprites and 2 elves were captured (Neubert et al., 2005). The Crete VLF station did not operate from July 25 to 29, and from August 5 to 30, therefore most of the analysis here is based on the first few nights of the campaign when the OMP camera captured nearly 35% of the recorded sprites. More specifically, during the July 21–24 period 48 TLEs were observed over three separate thunderstorms: 29 sprites from 02:05 to 03:15 UT, July 21, 1 elve and 2 sprites from 21:50 to 21:58 UT, July 22, and 16 sprites from 21:10, July 23 to 00:34 UT, July 24. As for the lightning activity in these storms, MÉTÉORAGE reported 1274 –CG and 207 +CG discharges during the storm of July 21, 108 –CG and 18 +CG for the short storm period of July 22, and 5148 –CG and 247 +CG discharges during the storm of July 23–24.

Fig. 2 summarises the geographic distribution of +CG discharges measured by MÉTÉORAGE, where the symbols mark their locations while their sizes are scaled linearly to the peak current intensities. Shown also in Fig. 2 are the geographic projections of the great circle paths (GCPs) of the HWV (Le Blanc, 46.7°N, 1.26°E) VLF transmitter to the Crete narrowband receiver and to the Nançay broadband receiver. As seen, the storms were situated at distances between ~100 and 600 km to the southeast of the HWV transmitter, more or less along and near its GCP to Crete. This provided an excellent opportunity for the detection of VLF perturbations due to conductivity changes in the lower ionosphere above the storm, caused possibly

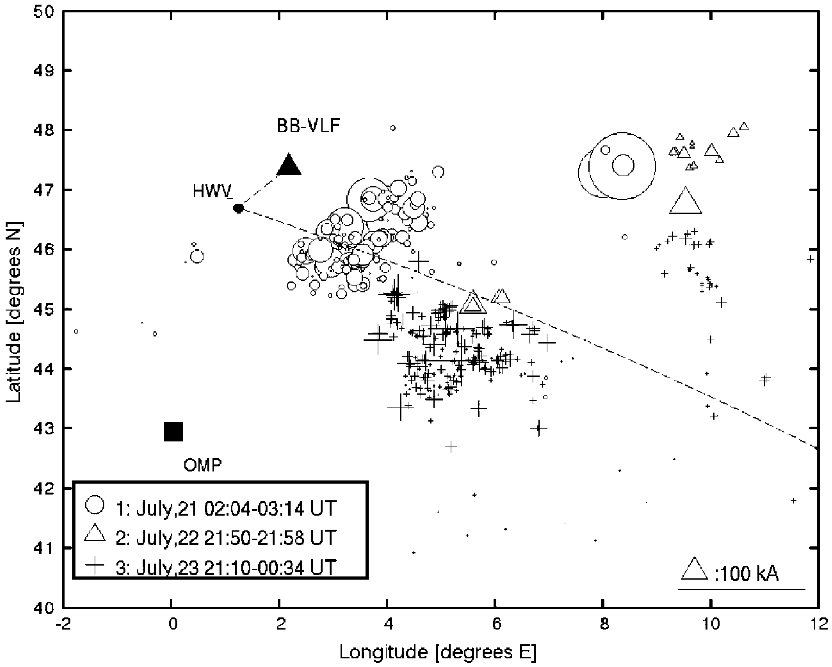

Fig. 2. Geographic locations of the +CG discharges, as recorded by MÉTÉORAGE during three different storms during July 21–24, 2003. The size of markers is scaled to the +CG peak current intensity. Shown also with a dashed line is the HWV-Crete link GCP, used in this study. Also seen there is the location of the BB-VLF which is near the storms to the southeast and the HWV transmitter.

by the electrostatic energy released during CG discharges and/or in situ by the sprites themselves. The most active storm areas were located at distances up to ~150 km in the perpendicular direction to the HWV-Crete GCP.

Note that the HWU-link, which as shown in Fig. 1 has its transmitter at Rosnay (46.6° N, 1.1° E), situated close to the HWV transmitter at Le Blanc, was not used in the present analysis because its sprite-related VLF perturbations were not always as clearly identifiable as in the HWV-link. We have no satisfactory explanation to offer for this discrepancy. A possible reason would have been the higher noise level present in the signal of the HWU-link, as evidenced by the time series themselves, caused probably by a relatively low transmitted power at Rosnay.

In searching for storm-related VLF perturbations, the amplitude time series of the HWV-link were averaged over 0.6 s in order to reduce the noise level. On the other hand, knowing the sprite occurrence times, the VLF time series were plotted for a period of 10 s each centered at the sprite time in an attempt to magnify the sprite-related VLF responses and their characteristics. Note that the phase time series of the narrowband signal were not analyzed because they displayed peculiar periodic changes. A possible explanation for this was that while the software used for extracting the phase information was tuned to work with 200-baud minimum shift keying (MSK) modulated data, the modulation scheme of the transmitter signal may not have been set at the same baud rate. Another difficulty was the high noise level present in the phase signals.

The broadband VLF data collected at Nançay were used in two ways. First, they were bandpass filtered at exactly the HWV transmitter frequency in order to produce narrowband signals (amplitude and phase) similar to those obtained by the Crete VLF station. The narrowband time series were then analyzed and inspected in the same way as the Crete station recordings for sprite related VLF perturbations. The idea here was to examine if the signals are also backscattered, in addition to being forward scattered, by ionization structures produced by the sprites above the storm. Second, high resolution (10 μs) time series of the broadband VLF data were plotted shortly before and after the sprite image times, in order to resolve the details of the radio-sferic activity in relation to the sprite, and also compare the recorded sferics with MÉTÉORAGE observations in an effort to identify the presence or not of sprite causative CG discharges.

4. Presentation of results

The results are presented in four subsections as follows: first, the association between sprites and the occurrence of early VLF perturbations is discussed and the statistical properties of the sprite-related VLF signatures are documented. Second, the back-scatter from sprite-related sub-ionospheric perturbations is investigated by presenting the filtering analysis results of the Nançay broadband VLF observations. Third, the widely accepted relationship between sprites and +CG discharge times is investigated by comparing the sprite observation times with the +CG discharges detected by MÉTÉORAGE. Fourth, the radio-sferic activity in the broadband VLF recordings is examined during the sprite observation time in conjunction also with the lightning detection data.

4.1. Association between sprites and VLF perturbations

In this section, the analysis focuses on the identification of the occurrence of VLF perturbations in association with sprites and the presentation of statistics of their characteristics, which include onset time relative to the sprite, perturbation magnitude, onset duration, and recovery time. Although data from the storm of July 21 were already analyzed in this respect by Haldoupis et al. (2004), these observations were also included in the present study for completeness and for improving the statistical accuracy.

Inspection of the entire dataset for all three storms during 21–24 July, 2003, revealed that the HWV-Crete signal amplitude underwent abrupt perturbations, both negative and positive, in association with the observed sprites. This is illustrated in Fig. 3, which shows HWV signal amplitude time series that cover most of the observation periods under consideration, when 29 out of a total of 48 sprites occurred at times marked by arrows along the ordinate. The VLF perturbation onsets were found to coincide with the sprite times within the 20 ms time resolution of the optical observations, therefore this confirms the "early" character of the sprite-related VLF signatures. Fig. 3 suggests a near one-to-one relationship between sprites and early VLF perturbations.

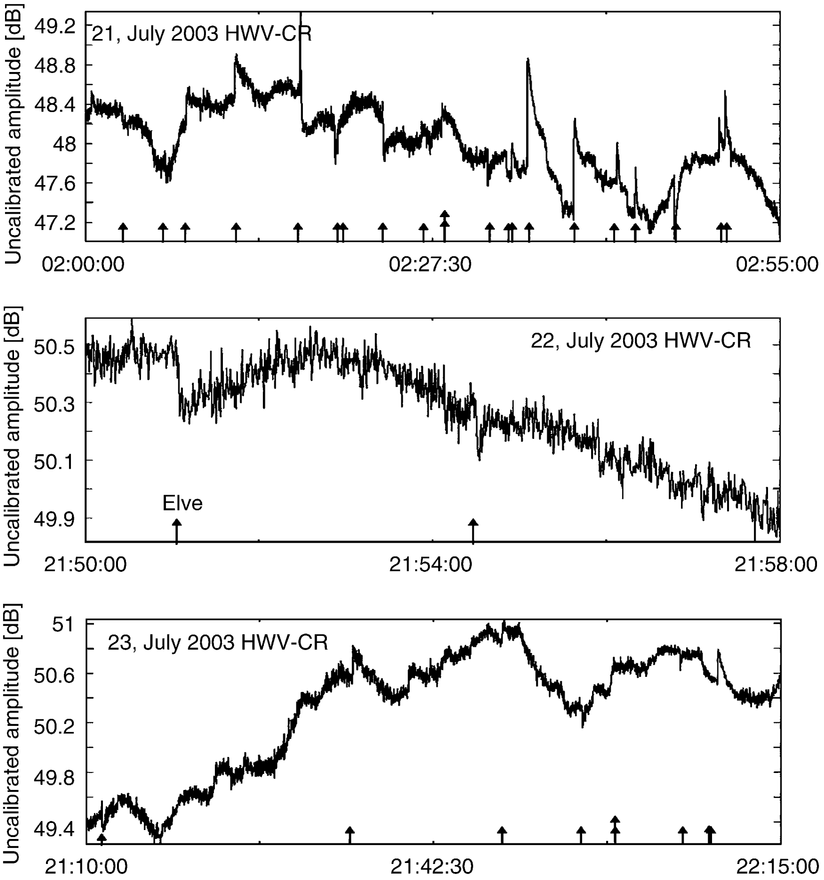

Fig. 3. Sample sections of the HWV (18.3 kHz)—Crete signal amplitude time series for each of the three sprite-producing storms during the July 21–24, 2003 observation period. The times of sprites are marked approximately by arrows. Nearly all sprites coincide with the onsets of early VLF perturbations. Note also the occurrence of an elve indicated in the middle panel.

In comparing the occurrence of early VLF signatures in relation with the sprites, the events are summarized as follows: for the storm of July 21, 26 out of a total of 29 sprites were accompanied by early VLF amplitude perturbations, as reported also by Haldoupis et al. (2004). For the storm of July 22, the occurrence of one elve and one of the two observed sprites coincided with early VLF events, whereas for the storm of July 23–24, 14 out of the 16 sprites detected were also escorted by early VLF perturbations. These results indicate that about 90% of the observed sprites had early VLF perturbations coincident to them, a fact that statistically signifies a one-to-one relationship.

A close inspection of the entire data set revealed only 10 cases of early-like VLF perturbations which were not accompanied by sprites. For 8 of those events MÉTÉORAGE detected positive cloud-to-ground discharges near the onset of the perturbations, whereas in one case a negative CG discharge was observed, while for the last case left there was no any CG lightning present despite that sferics did exist in the VLF broadband recordings at about the event's onset. A re-examination of the CCD optical images, which was possible only for three out of the ten events under consideration, led to the discovery of one more sprite which, obviously, has been missed originally. This reinforced further the possibility of a one-to-one relationship between early VLF perturbations and sprites.

High resolution plots of the sprite-related early VLF events identified two types of signatures. These are characterized by a short and long "onset duration", and thus have been categorized as "early/fast" and "early/slow", respectively. The early/fast events, which have onset durations less than about 100 ms, are well known and documented in the literature (e.g., see review articles by Rodger, 1999, 2003 and references therein). On the other hand, the existence of early/slow events, with onset durations ranging from 100 ms to a couple of seconds, is a surprising result whose importance was first recognized by Haldoupis et al. (2004). Fig. 4 shows typical examples of sprite-related signatures, which have been identified as early/fast (bottom panel) and early/slow (top panel, having in this case an onset duration of about 1.5 s).

In order to assess the statistical properties of the sprite-related VLF signatures, only 26 events were considered for this purpose which had amplitudes higher than about 0.2 dB and relatively low-level sferic contamination. These “clear-cut” VLF events were used to compute the onset durations and perturbation amplitudes. The onset duration was measured simply as the time between the abrupt onset and the time of the maximum mean amplitude

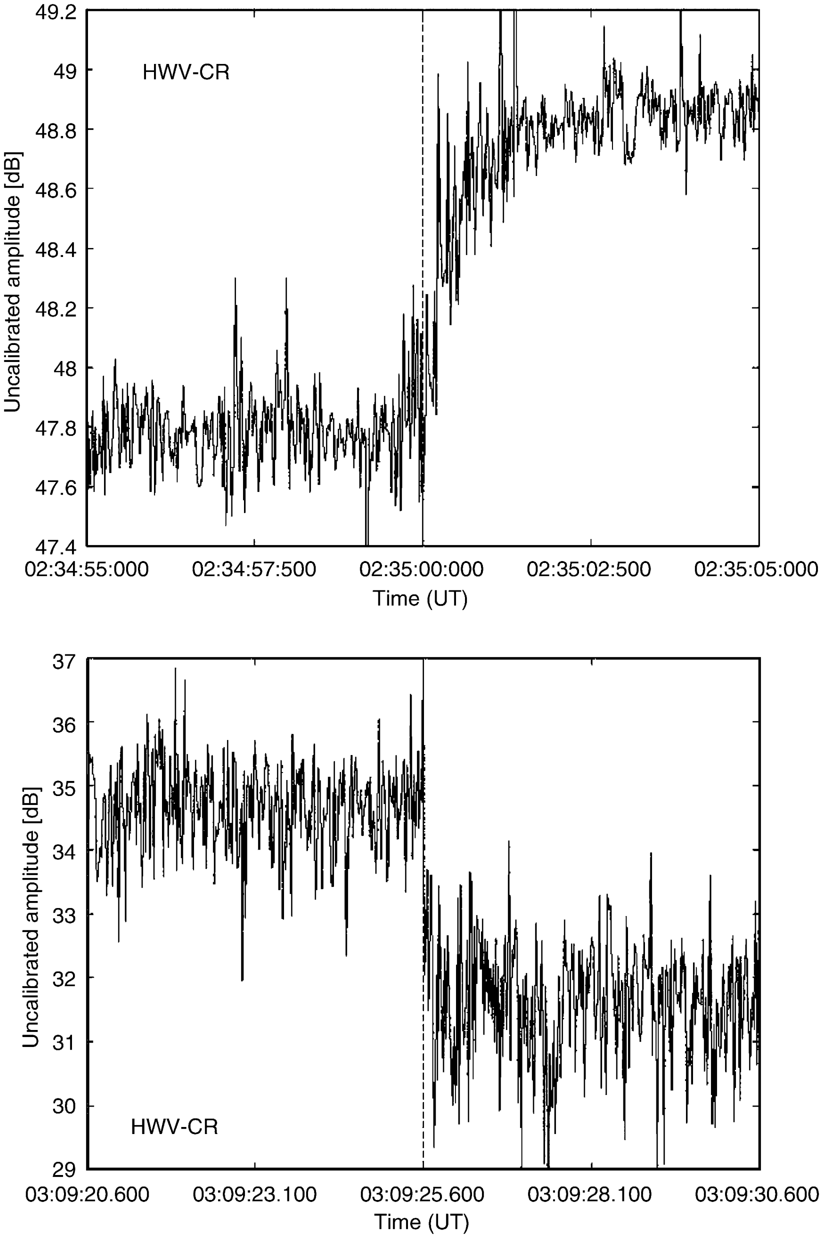

Fig. 4. Examples of early/slow (top panel) and early/fast (bottom panel) VLF amplitude perturbations observed on the HWV signal received in Crete.

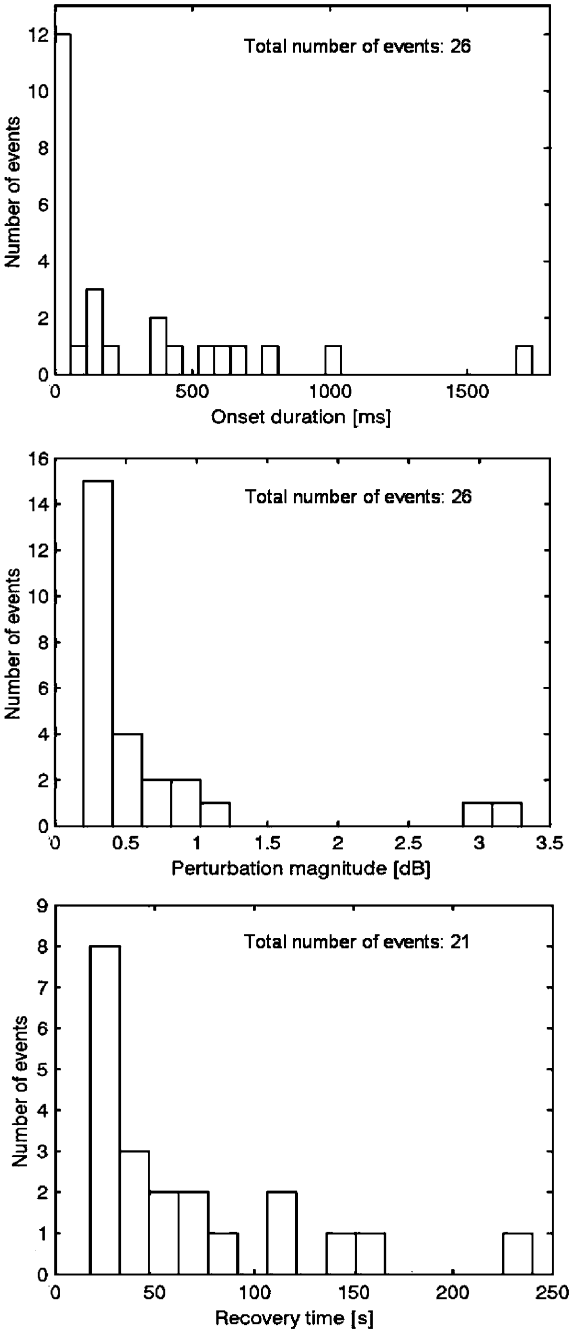

Fig. 5. Histograms presenting the onset duration (top), magnitude (middle) and recovery time (bottom) of well defined early VLF perturbations, observed on the HWV—Crete link.

level of the perturbation. The event magnitude was computed in dB as the absolute difference between the pre-event mean amplitude level and the maximum mean perturbation level. Finally, the "recovery times", that is, the times needed for the perturbation to set back to pre-event amplitude levels, were also measured for 21 sprite-related early VLF events that were suitable for this purpose because their relaxation phase was not obscured by other VLF perturbations.

The occurrence distributions for the onset duration, the perturbation magnitude and recovery time are presented in Fig. 5, in the top, middle and bottom panels, respectively. From the top panel, we observe that in 12 cases the onset duration was larger than 100 ms, whereas at least 6 sprite-related VLF early/slow events had onset durations greater than 500 ms reaching values up to about 2 s. The middle histogram in Fig. 5 shows that most of the perturbation magnitudes are between 0.2 and 1.0 dB in line also with existing statistics for early/fast events (e.g., see Moore et al., 2003); also seen are two events whose magnitudes reached values near 3.0 dB, departing considerably from the rest. As for the histogram in the bottom panel, the recovery times measured are mostly between 20 and 150 s, which compare well with those of early/fast events reported elsewhere (e.g., see Inan et al., 1996b). Also note that, no relationship or trend was found between the measured onset durations and perturbation magnitudes, and/or recovery times.

Finally, we comment on the VLF signature accompanying the only elve available in the present data, which, as indicated in Fig. 3, was observed during the storm of July 22. Based on theoretical grounds, elves, which occur at altitudes between 75 and 105 km and last for about 1–2 ms, should produce step-like changes in the VLF signal followed by a very slow relaxation due to the long lifetimes of electrons at elve-altitudes (Rodger, 2003). On the other hand, since elves are located higher up in the ionosphere and thus can be above VLF reflection heights, it is thought that the elve-related VLF perturbations may be of the rapid onset rapid decay (RORD) type, caused by subionospheric heating due to a lightning-induced electromagnetic pulse (EMP) rather than scattering from ionization changes in the lower D region (C. Rodger, personal communication, 2004). Indeed, a single RORD type VLF signature associated with an elve has been reported by Hobara et al. (2001, 2003). Our observations, however, do not agree with these findings because, as seen from the top panel of Fig. 6 and the middle panel of Fig. 3, the VLF signature accompanying the elve is not of a "RORD" but rather of "early/fast" type similar to those seen in association with several of the

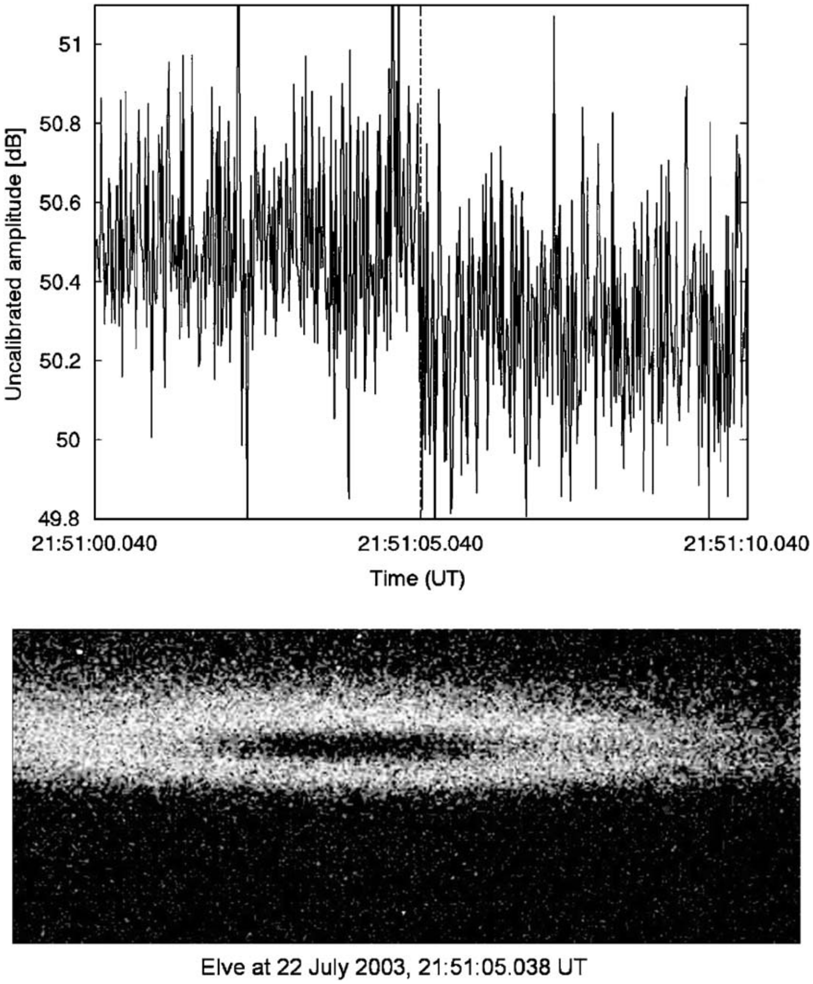

Fig. 6. Optical image of the elve (bottom panel) and the early VLF perturbation observed simultaneously on the HWV—Crete link (top panel).

captured sprites. The elve VLF perturbation in Fig. 6 has a magnitude of ~0.4 dB and a recovery time much larger than the 0.5 s reported by Hobara et al. (2001, 2003).

4.2. Possible VLF backscatter signatures associated with sprites

The early HWV-Crete perturbations were detected at distances more than 2000 km from the sprite producing storms. This, in addition to the assumed ~150 km diameter of the affected ionospheric region (Johnson et al., 1999; Inan et al., 1996b), should imply "narrow-angle" forward scattering from diffuse regions of ionization situated near the great circle path to the receiver with dimensions greater than the VLF radio wavelength (Inan et al., 1995). On the other hand, Dowden and co-workers (Dowden et al., 1996; Rodger, 1999, 2003 for more references) measured early VLF perturbations in one-to-one relation with sprites at distances less than 500 km from the storm and in various directions around it, even towards the transmitter (backscatter). These perturbations, which apparently are too weak to be detected at large distances, were attributed to "wide-angle" scattering from column-like ionization structures, possibly impacted by the sprites themselves and thus having small lateral dimensions relative to the VLF wavelength (Wait, 1991; Rodger, 2003). This contrasted with the concept of spatially extended diffuse regions of ionization needed to produce strong forward scatter of the VLF signal, and since it has been a topic of debate (Dowden, 1996; Inan et al., 1996b). More recently, Inan (2001) reported VLF measurements made at short distances from the sprites, similar to those reported previously by Dowden et al. (1996), but found no evidence in favor of backscatter events relating to sprites.

The location of the broadband VLF receiver near the HWV transmitter and the proximity of the July 21–24 sprite storms at distances less than 500 km to the southeast (e.g., see Fig. 2), motivated here the search for VLF backscatter perturbations in association with the observed sprites. In order to identify any VLF backscatter signatures in the Nançay recordings, the HWV signal was extracted from the broadband time series by applying the same narrow band digital filter employed in real time at the Crete receiver. Then, these narrowband signals were examined for sprite-related early VLF perturbations.

Inspection of the HWV-Nançay narrowband time series revealed only five cases out of the 44 TLEs, for which broadband data were available, to be accompanied by weak early-like VLF perturbations having onsets coincident to the sprites. Note that all five events occurred during the storm of July 21, which was the nearest one to Nançay, at about 100–200 km to the southeast. No similar perturbations were identified with the sprites captured during the July 22–24 storms, possibly because these were located further away from Nançay, at distances between about 230 and 500 km. Note that Corcuff (1998) reported early/fast VLF perturbations in association with lightning discharges situated over France at about 350 km distances in perpendicular direction to the observing GCP.

Fig. 7 shows 23 min of recordings when 4 out of the 5 early VLF events were seen at the HWV-Nançay link (bottom panel). Also shown for comparison in the top panel are simultaneous records from the HWV-Crete link. The sprite-related early VLF events, detected in both the Crete and Nançay data, are marked by arrows. As seen, there are 10 early VLF perturbations in the HWV-Crete link, all in relation with sprites, but only four of these had counterparts in the HWV-Nançay signal. As evidenced from Fig. 7, the Nançay perturbations were considerably weaker than those observed at Crete, having magnitudes less than 0.2 dB. In addition, these few backscatter events observed here did not appear to have any preference to either the early/fast or early/slow VLF perturbations. Fig. 8 displays high resolution views of the strongest event recorded at Nançay. Shown also there is its Crete counterpart in the top panel, whereas the sprite time is marked by a vertical dashed line in both panels. Note that both events are of the early/fast type, having positive polarity and magnitudes of ~0.15 and 0.5 dB, respectively.

Since broadband VLF observations were made during the entire campaign, the HWV recordings were investigated, for backscatter-like signatures, also for the storms of July 27, August 22, 24, 25 and 28–29 when the Crete VLF station was not in operation. The geographic locations of the +CG discharges measured by MÉTÉORAGE during these storms are marked with different symbols in Fig. 9, having sizes which are scaled linearly to the lightning peak current intensities. The results of this search were negative, that is, no early VLF perturbations were identified during the entire duration of these storms and in particular during the sprite onset occurrences. This may be attributed to the large distances of the sprite producing +CG discharge locations from the HWV-Nançay link, which were estimated to be larger than about 400 km. It is important to note that the August 28–29 storm (marked by crosses on Fig. 9) consisted of two separate electrically active centers, one around 0.5°W, 47.5°N, at distances of about 90–170 km, and another around 6°E, 46°N at distances of 360–450 km from the HWV-Nançay GCP. Among these two active regions, however, only the latter and more distant one produced sprites.

In summary, and taking into consideration the entire number of sprites recorded, only about 5% of the sprites were escorted by identifiable backscatter-like VLF perturbations, a figure which departs considerably form the one-to-one relationship reported by Dowden et al. (1996). Note that the weak backscatter-like perturbations were observed during a single storm situated near the Nançay broadband receiver at distances less than 200 km.

Alternatively, there might be another explanation for the presumed backscatter perturbations observed at Nançay. Note that the distances of 100–200 km from the +CG location to the Nançay receiver, in addition to a maximum 50 km horizontal offset of the sprite location relative to the +CG discharge (Wescott et al., 1998), can place these events in an ionospheric region that may overlap the receiver. Then, in this case, the observed early VLF signatures at Nançay may be the result of a direct change in the local propagation conditions and thus not associate necessarily with VLF backscatter.

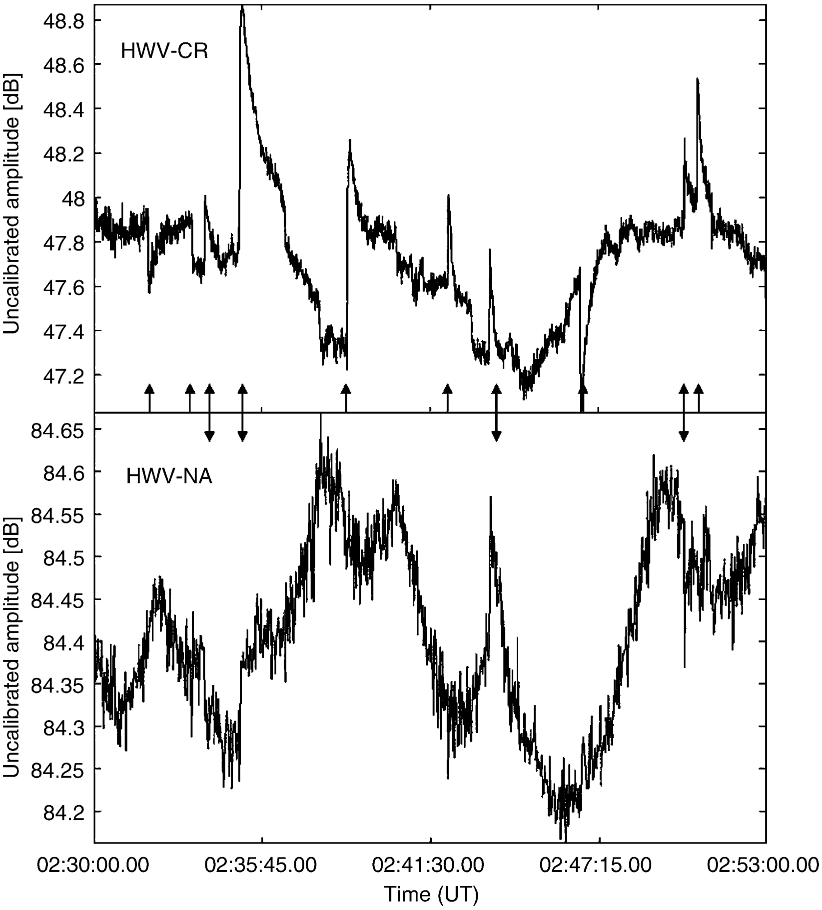

Fig. 7. Concurrent intervals of HWV (18.3 kHz) signal amplitude time series received in Crete through forward scattering (top), and in Nançay possibly through backscatter (bottom), from conductivity changes in the lower ionosphere during sprite occurrences. The observed early VLF perturbations are marked by arrows, showing that in few cases, backscatter and forward scatter early perturbations occur simultaneously.

4.3. Sprites and positive CG discharges

It is widely accepted that sprites initiate a few milliseconds after a positive cloud to ground (+CG) discharge, accompanied by charge moment changes sufficiently large to cause electrical breakdown in the lower ionosphere (e.g., see Rodger, 1999; Boccippio et al., 1995; Lyons, 1996, among several others). These +CG discharges are considered as causative to the sprites. Despite this conviction, however, the nature of the relation between sprites and causative +CGs is not well understood. This is particularly true for the so-called "long-delayed sprites", which are delayed relative to the lightning discharge by more than 30 ms (e.g., see Bell et al., 1998; Cummer and Füllekrug, 2001). In the following we investigate the relation between the observed sprites and the +CG discharges preceding their occurrence.

Fig. 10 displays the distribution of the time difference between the sprite time and the time of the nearest +CG discharge preceding it up to ~300 ms. Here, a total of 131 sprites were used, observed during the storms of July 21–24 (48 sprites) and of late August (83 sprites). Since the sprite images were taken over 20 ms and their times were correct to within ±12 ms, positive CG discharges preceding or following the sprite time by about 25–30 ms are taken to be nearly coincident, and thus were considered as causative to the sprites. In this respect, and as evidenced from Fig. 10, 73 out of the 131 sprites observed, that is 55%, were accompanied by +CG discharges occurring near their onset time. In the following

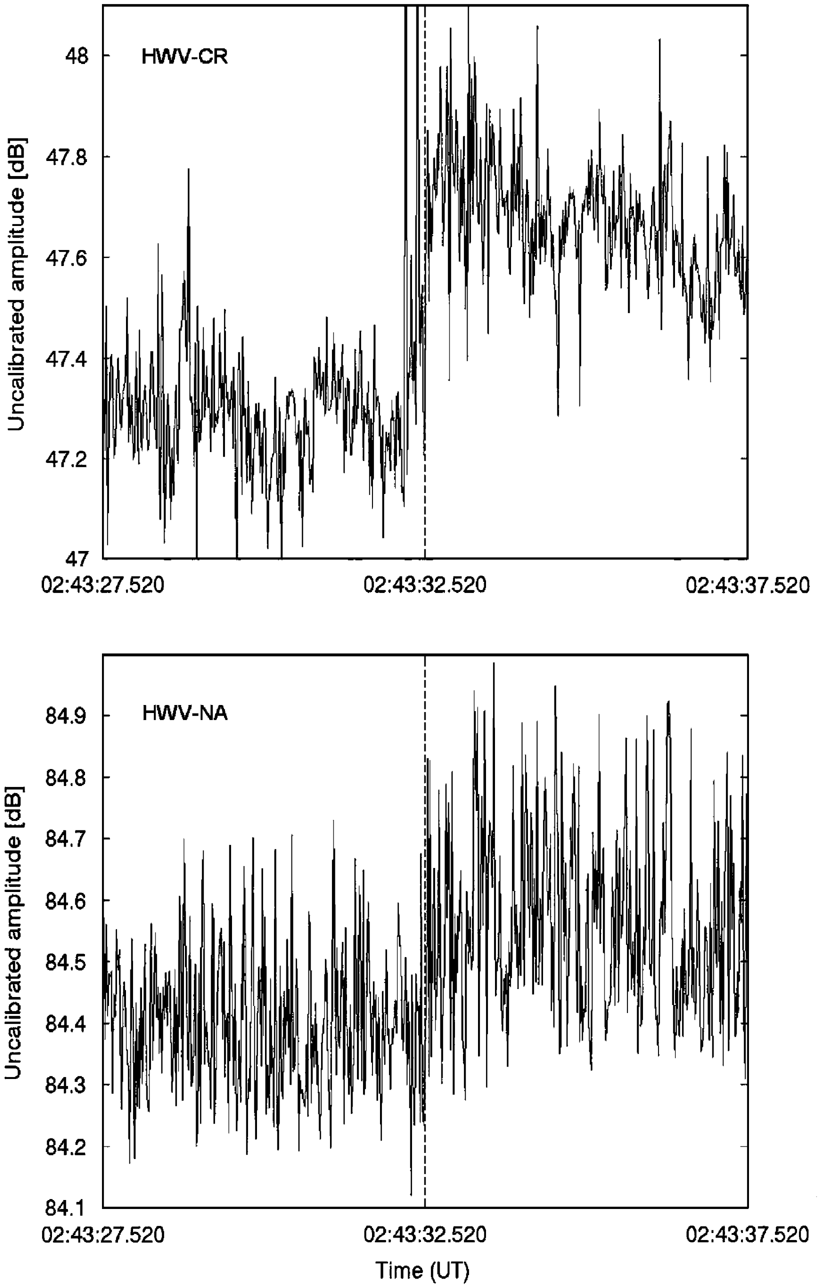

Fig. 8. High resolution displays of simultaneous early VLF amplitude perturbations received in Crete (top) and Nançay (bottom) for the HWV (18.3 kHz) narrowband signal. The perturbation magnitude measured at Nançay is much weaker than that of the forward scatter received in Crete.

we refer to these as "short-delayed" sprites. From the rest, 45 sprites (~35%) were lagging the +CG discharge by times ranging from about 30–280 ms, whereas 13 sprites (~10%) were not preceded by any +CG discharges up to at least 2.5 s prior to their occurrence. This means that nearly 45% of the observed sprites are either long-delayed or have no relation to a causative +CG discharge. MÉTÉORAGE records the time of the discharge as being the time of the first return stroke. In addition MÉTÉORAGE also measures the multiplicity of strokes, which has also been examined and found

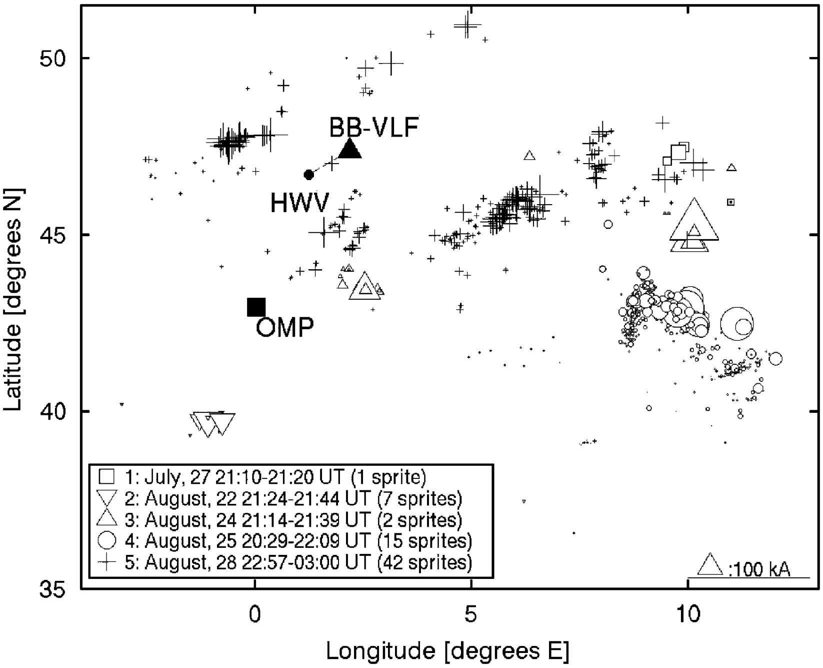

Fig. 9. Geographic locations of the +CG discharges, as recorded by MÉTÉORAGE during five different storms on July 27 and August 22, 24, 25 and 28–29, 2003. The size of the marking symbols is scaled to the +CG peak current intensity, similarly as in Fig. 2. All the +CG discharges causative to the sprites are located at distances larger than 400 km from the HWV-Nançay (BB-VLF) link. Note that the Crete VLF receiver was not in operation during these storms.

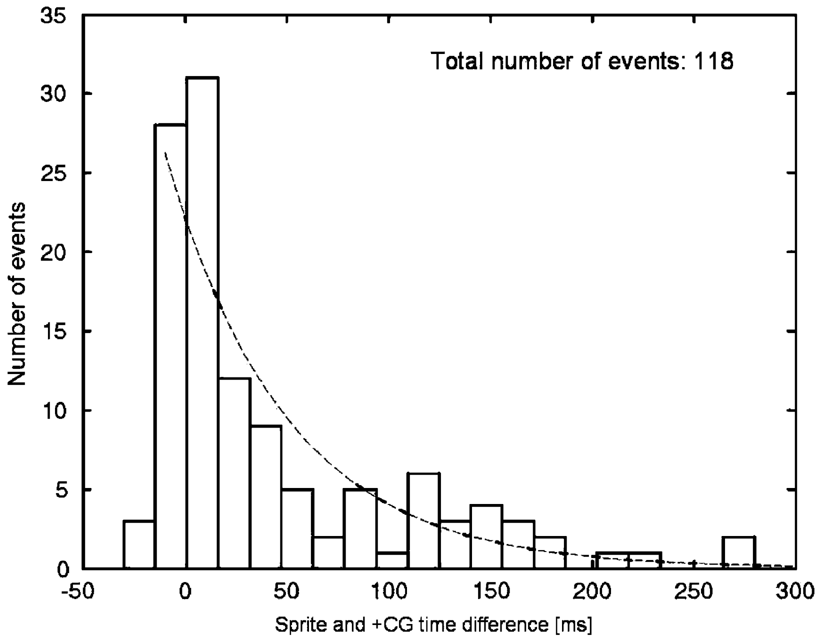

Fig. 10. Histogram showing the differences between the occurrence times of sprites and the nearest positive cloud-to-ground discharges preceding the sprites. There is a well defined tail in the distribution as evidenced also by an exponential fit (dashed line).

equal to 1 in all but two cases, therefore this parameter does not appear to have any effect on the processes under consideration.

Surprisingly, there is a large number of sprites in the present data set which depart from the widely accepted scheme of causative +CG discharges leading the sprites by a few milliseconds. This is an important observational fact that needs to be considered. Of course one may attribute this discrepancy to MÉTÉORAGE's efficiency which means that it has somehow missed more than 40% of the sprite causative +CG flashes. This is very unlikely, however, because MÉTÉORAGE is a state of-the-art lightning detection system having adequate coverage which provides high precision in both time (1 ms) and space (<4 km) and has a reasonably high detection efficiency of more than 90%, e.g., see Morel and Sénési (2000).

Another interesting aspect seen in Fig. 10 is the shape of the distribution. Besides the anticipated dominant peak about zero, there is also a well defined tail stretching out from about 30–280 ms. This was approximated by an exponential least squares fit, represented in Fig. 10 by the dashed line and having an e-fold delay time of −0.17 ms. If the +CG discharges leading the sprites by more than 30 ms had no relation to the sprites themselves, then their time difference would have been equally distributed, which is obviously not happening. Therefore, the exponential tail of the distribution in Fig. 10 must be of significance. This points to a relationship between the corresponding +CG discharges and the sprites, and thus endorses the notion of "long-delayed" sprites. If this is indeed the case, then our data shows for first time that the "short-" and "long-delayed" sprites occur with a ratio of about 5:4, which is much smaller than expected.

4.4. Sprites and radio atmospherics

In view of the observed large time differences between many sprites and preceding +CG flashes, the Nançay broadband VLF time series were also inspected in order to identify and assess the radio-sferic activity present during the sprites and how this may relate to the +CG discharges relating to the sprites. These observations can more accurately link lightning activity to sprite occurrence, since all lightning discharges produce sferics, virtually no other source is known to produce similar pulses, and the receiver sferic-detection efficiency is precisely 1. In such a way, sferic detection could also locate the ~10% of CG discharges which were apparently missed by the lightning detection network.

Since broadband measurements were carried out only from 21:00 to 03:00 UT, VLF records were available only for 60 short-delayed, 42 long-delayed and 8 no +CG-related sprites. Since the sprite producing storms of *EuroSprite-2003* were in proximity with the Nançay receiver (distances were from about 100 to 1000 km), it is probable that the wideband sferic recordings contain contributions from intracloud lightning (e.g., see Johnson and Inan, 2000), in addition to sferics produced by CG lightning. On the other hand, one needs to be cautious because the picture may be obscured by the presence of sferics coming from elsewhere around the globe.

We need to clarify that here the sprites were grouped into two categories, the short- and long-delayed ones, because of convenience rather than of real physical significance, since the latter cannot be substantiated by our data alone. On the other hand, published reports (Bell et al., 1998; Reising et al., 1999) and also the shape of the histogram in Fig. 10 suggest the possibility that these two categories of sprites are indeed significant. Moreover, as shown below, the presence of two categories of sprites, labeled here as short- and long-delayed, is also reinforced by the radio sferic activity present in the broadband VLF records.

Close inspection of the Nançay VLF time series revealed the presence of a burst-like sferic action coincident with the +CG discharge always in relation with the short-delayed sprites. This situation was valid for 58 out of the 60 events, therefore this fact cannot be coincidental. Note that, similar observations of sferic clusters accompanying early/fast VLF events, were reported by Johnson and Inan (2000). On the other hand, and in sharp contrast to the short-delayed sprites, there was no significant level of sferic activity present in the broadband VLF signal during the observation times of the long-delayed sprites. Again, this was true for the vast majority of the events under consideration. As for the 8 sprites which, according to MÉTÉORAGE, were not preceded by a +CG discharge up to at least 2.5 s prior to their occurrence, the broadband VLF records revealed sferic clusters occurring simultaneously with all these 8 sprites. This suggests the possibility that MÉTÉORAGE had indeed missed the CG discharges which would have been causative to the sprites.

Typical examples for the two cases, that is, the radio-sferic activity for the short-delayed and long-delayed sprites are shown in Figs. 11 and 12, respectively. Shown there is the broadband VLF noise recorded at Nançay for a time interval of ±250 ms around the sprite observation time which is marked by two dashed lines, accounting for the ±25 ms timing uncertainty. The cloud-to-ground discharges, either positive or negative, detected by MÉTÉORAGE during the same interval, are also presented below by solid lines scaled to their peak current intensities. Fig. 11 shows the presence of a strong burst of sferics in connection with the sprite and the causative positive cloud-to-ground discharge. On the other hand, the example in Fig. 12 is representative of the long-delayed sprites showing no sferic activity been present during the sprite observation time.

The absence of any sferic activity within ±25 ms of many sprites, labeled here as "long-delayed", is quite intriguing. For some reason there are no VLF electromagnetic emissions produced in the time span of these sprites, which is by itself interesting. This points to the possibility that we deal here with long-delayed sprites in accord with previous reports (Bell et al., 1998; Reising et al., 1999) and also the histogram tail in Fig. 10. An explanation put forward for the long delayed sprites assumes the

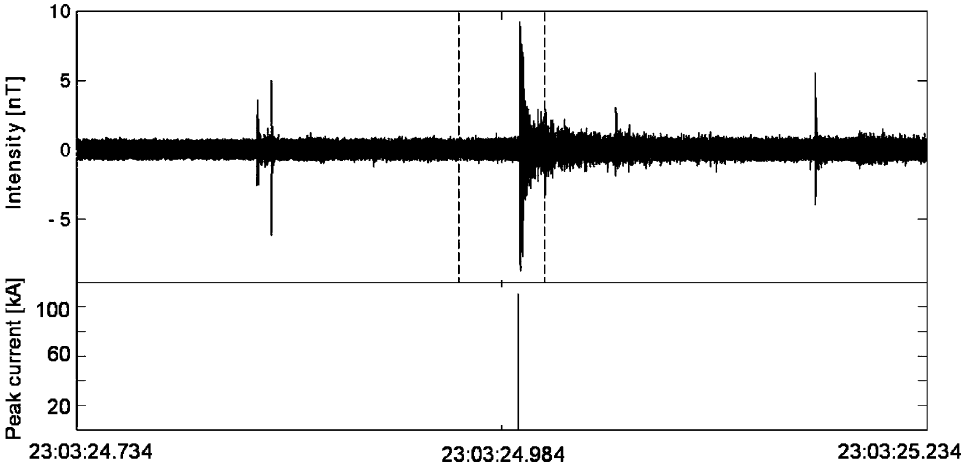

Fig. 11. Typical example of high time resolution broadband VLF data recorded at Nançay 250 ms before and after a short-delayed sprite. The sprite observation time is marked by two vertical dashed lines accounting for both, the image exposure time of 20 ms plus the time uncertainty of 12 ms. Note the strong, burst-like sferic activity during the sprite observation time, initiated by a +CG discharge measured by the lightning detection system.

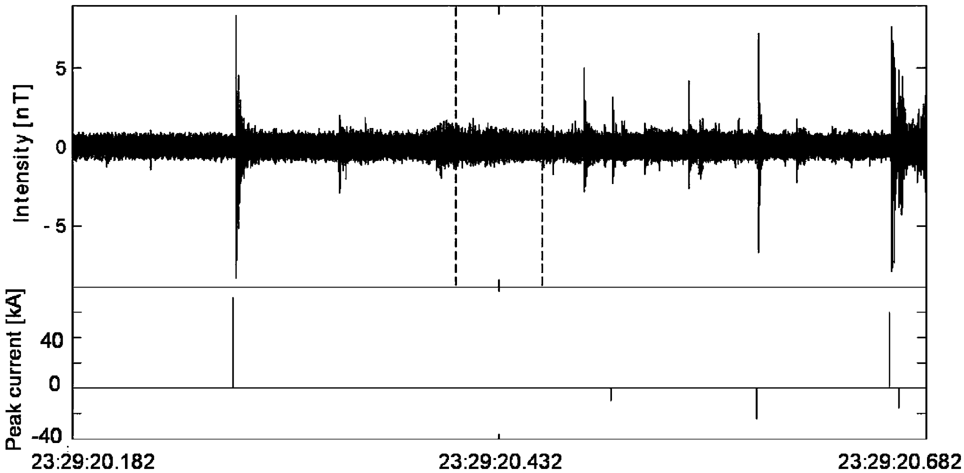

Fig. 12. Same as in Fig. 11 but this is typical of a "long-delayed" sprite event. As seen, the sprite occurred about 130 ms after a +CG discharge. Note the absence of any sferic activity during the sprite observation time, in line also with the observations of the lightning detection system.

presence of strong cloud-to-ground continuing currents flowing before, during and after the +CG discharge (Bell et al., 1998; Reising et al., 1999). This option was tested by Cummer and Füllekrug (2001), for three cases of long-delayed sprites with delays up to 160 ms and found to be feasible. Our data alone cannot provide evidence either for or against this mechanism.

5. Summary and concluding comments

The results of the present study are summarized and commented as follows:

1. The narrowband receiver in Crete detected characteristic VLF amplitude perturbations in nearly one-to-one association with the observed sprites, that is, 9 out of 10 sprites were accompanied by a well-defined VLF signature. These perturbations were "early", meaning that their onsets were coincident with the sprites within the time resolution (20 ms) of the measurements. The amplitudes of the early VLF perturbations ranged from 0.2 up to 3.3 dB and their recovery times were between 20 and 150 s. Although some of these signatures can be classified as "early/fast", having onset durations less than 100 ms, many have long onset durations of several hundreds of milliseconds, which categorizes them as "early/slow". Another interesting aspect is that only about 10 early VLF perturbations were observed not to be accompanied with sprites. Close examination of the optical recordings for three of these cases revealed the presence of a sprite which has been missed, originally. The present results agree with the findings reported by Haldoupis et al. (2004), which were based on a single sprite-producing storm, and thus support both their validity and generality.

The identification of the early/slow VLF events in association with sprites is an intriguing observation and constitutes a new element in sprite research that needs to be studied. Early/slow events with onset durations up to 500 ms were reported before by Inan et al. (1995) and attributed to the continuous presence of CG discharges which kept on altering the conductivity in the lower ionosphere above the storm. However, this explanation does not apply for the early/slow events described here, because there is no significant CG lightning activity seen during the event onsets for nearly all of the cases. For example only two CG discharges were seen during the second and a half onset duration of the early/slow event presented in the top panel of Fig. 4, that is, a positive CG discharge at 145 ms and a negative one at ~830 ms after the perturbation onset. Thus the nature of the process which causes a gradual change in conductivity during the onset duration of the sprite-related early/slow VLF events remains a mystery.

2. There was only one elve in the present data set. This was accompanied by an early/fast-like VLF perturbation, having 0.3 dB magnitude, less than 50 ms onset duration, and a recovery time of about 60 s. These characteristics are similar to those of the sprite-related early/fast signatures, and depart from theoretical predictions and the RORD-like VLF signature reported by Hobara et al. (2001, 2003) for a single elve event.

3. The position of the storms relative to the Nançay VLF receiver and the HWV transmitter made possible the search for VLF backscatter signatures, which are thought to associate also with sprites (Dowden et al., 1996). In the present study, there were only 5 cases found of possible early VLF backscatter perturbations at Nançay which occurred concurrently with sprites, representing only 5% of the data. All were detected during the July 21 storm, which was the nearest to the Nançay receiver, and had weak perturbation amplitudes between about 0.1 and 0.2 dB. The occasional detection of these signatures suggests the possibility of backscatter, meaning that at times, but not always, the ionization produced by the sprite can be spatially extended but also highly structured having within its volume scales less than the VLF wavelength. However, an alternate explanation is suggested by the possibility that the ionization region above the sprite extends over the receiver, and thus the observed perturbations could be caused by direct changes in the local propagation conditions.

4. In order to test and quantify the relationship between sprites and +CG discharges preceding them, the differences between the sprite occurrence time and the time of the nearest +CG discharge preceding the sprite were computed for the entire data base of *EuroSprite-2003*, consisting of 131 sprites. The distribution of the measured time differences had a strong peak at zero, as expected, but also a well defined tail towards larger values reaching 300 ms. Overall, it was found that ~35% of the sprites are delayed to the nearest +CG discharge by more than 30–40 ms up to about 280 ms. The observed distribution is a surprising result which apparently endorses the presence of the

so called "long-delayed" sprites, and suggests that they may occur in much larger numbers than was thought previously. Also, nearly 10% of the sprites were not preceded by any +CG discharges up to ~2.5 s prior to the sprite, apparently because these have been missed by MÉTÉORAGE.

5. Inspection of broadband VLF recordings shows that the sprites preceded by causative +CG discharges, that is, those with time delays less than 30 ms, were escorted nearly always by burst-like sferic activity during the sprite observation time which is initiated at the +CG discharge. On the other hand, the long delayed sprites, preceded by +CG discharges with leading times ranging between 30 and 300 ms, were not accompanied by individual and/or any burst-like sferic activity during the sprite observation time of 20 ± 12 ms. This is an interesting trend which seems to be compatible with the notion of "long-delayed" sprites that has been reported in the literature. According to Cummer and Füllekrug (2001), a possible reason for the long-delayed sprites is the existence of large continuing currents right after a +CG discharge. This may lead at times to charge moment changes large enough to trigger a sprite many milliseconds later.

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