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More evidence for a one-to-one correlation between *Sprites* and *Early VLF* perturbations

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[1] Past studies have shown a correlation between sprites and early VLF perturbations, but the reported correlation varies widely from ~50% to 100%. The present study resolves these large discrepancies by analyzing several case studies of sprite and narrowband VLF observations, in which multiple transmitter-receiver VLF pairs with great circle paths (GCPs) passing near a sprite-producing thunderstorm were available. In this setup, the multiple paths act in a complementary way that makes the detection of early VLF perturbations much more probable compared to a single VLF path that can miss several of them, a fact that was overlooked in past studies. The evidence shows that visible sprite occurrences are accompanied by early VLF perturbations in a one-to-one correspondence. This implies that the sprite generation mechanism may cause also sub-ionospheric conductivity disturbances that produce early VLF events. However, the one-to-one visible sprite to early VLF event correspondence, if viewed conversely, appears not to be always reciprocal. This is because the number of early events detected in some case studies was considerably larger than the number of visible sprites. Since the great majority of the early events not accompanied by visible sprites appeared to be caused by positive cloud to ground (+CG) lightning discharges, it is possible that sprites or sprite halos were concurrently present in these events as well but were missed by the sprite-watch camera detection system. In order for this option to be resolved we need more studies using highly sensitive optical systems capable of detecting weaker sprites, sprite halos and elves.

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1. Introduction

[2] Sprites are electric discharges at ~50 to 90 km altitude above thunderstorms [Sentman and Wescott, 1993]. The optical emissions typically last 5–50 ms and may take the form of one or more vertical columns of a few hundred meter radius for the smaller column sprites or large jellyfish-shaped structures of tens of kilometers of radius and extending from the ionosphere D-region almost down to the thunderstorm cloud tops. Sprites are one of several types of optical emissions discovered during the past 20 years above thunderstorms, sometimes called Transient Luminous Events (TLEs). Besides the sprites, transient luminous emissions in

the upper atmosphere also include the sprite halo, blue jet, gigantic jet and the elve [Neubert, 2003].

[3] It is believed that sprites are manifestations of electrical breakdown in the mesosphere driven by quasi-electrostatic (QE) fields in the upper atmosphere generated overwhelmingly by positive cloud-to-ground (+CG) lightning discharges with large charge moment changes [e.g., see Pasko *et al.*, 1995, Cummer and Lyons, 2005]. Many aspects of the physics of the discharge process are inferred from theory and from various observations. The techniques that are available include optical imaging and photometer observations, ELF (extremely low frequency) electromagnetic observations that give information on the electric current in sprites and on the charge moment changes of the causative +CG, and the technique of monitoring impulsive perturbations to man-made sub-ionospheric VLF signal transmissions passing through or close to a thunderstorm. The VLF perturbations have been due to *D* region conductivity modifications caused in conjunction with lightning discharges [e.g., see Rodger, 2003, and a recent overview by Inan *et al.*, 2010, and references therein].

[4] Early VLF events are abrupt perturbations to the signal amplitude or phase occurring within <20 ms of a

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lightning event. They have been studied extensively in an effort to understand their properties, the physical mechanism behind their occurrence and their relation to TLEs. The question regarding the correlation between sprites and early VLF events has been a key topic of study for the last several years but also a matter of some controversy. *Inan et al.* [1995] were the first to report a relation between sprites and *far-storm*, or narrow-angle forward scattering, early VLF events, but the relation was found only for a small subset of sprites. On the other hand, *Dowden et al.* [1996] reported *near-storm*, or wide-angle scattering, early VLF events with a close association with concurrent sprites. These, seemingly conflicting, results led to a debate in *Dowden* [1996] and *Inan et al.* [1996] which did not provide clear answers regarding the causative mechanism but revealed the complexity of the scattering process and the instrumental limitations and demonstrated the need for more research.

[5] More recently, *Haldoupis et al.* [2004] and *Mika et al.* [2005] used *EuroSprite* observations to obtain evidence in favor of a close relation between sprites and forward scatter (far-storm) early VLF perturbations, suggesting a nearly one-to-one association. These findings prompted the Stanford University VLF group to test the relationship further by analyzing a sizable data set of concurrent sprite and narrow-angle, forward scatter, early VLF observations. The results presented by *Marshall et al.* [2006] suggested that sprites and early VLF perturbations are related, but not in a one-to-one correlation. Specifically, they reported ~50% of sprites to be accompanied by early VLF events, or, when viewed conversely, about 60% of early events were associated with sprites.

[6] Examination of the existing studies showed that the exact *sprite-early* event relation remains unresolved, thus the aim of the present work is to further investigate this relationship and determine the degree of its validity. For this purpose, additional *EuroSprite* observations of concurrent sprite and early VLF events were analyzed using multiple transmitter-receiver links. The present results show convincingly that the close correspondence of sprites to early events, suggested first by *Haldoupis et al.* [2004], is valid. On the other hand, the reciprocal association of early VLF events observed in conjunction with sprites, appears not to be clear and thus requires clarification by using more sensitive optical measurements and additional experiments.

2. Early VLF Event Characteristics

[7] Before presenting any observations, the measured and implied properties of early VLF events that are pertinent to the present study are summarized. The term *early* signifies the nature of these VLF perturbations, meaning that they occur right after a causative lightning discharge through the effects of its electrical impact into the lower ionosphere [*Inan et al.*, 1988]. The early VLF events refer to the signal perturbations in the amplitude and/or phase of VLF transmissions that scatter from lightning-induced conductivity disturbances as they propagate in the earth-ionosphere waveguide. They are detected when a transmitter-receiver great circle path (GCP) passes through or nearby a thunderstorm at distances typically less than ~200 km from the causative CG lightning strokes [see *Johnson et al.*, 1999,

and for more details *Johnson*, 2000]. Most early events are characterized by abrupt increases, rather than decreases, in the received signal amplitude of about 0.2 to 2.0 dB, having onset durations which range from *fast* (<20–50 ms) to *slow* (up to 2.5 s), as shown by *Haldoupis et al.* [2006]. Typically, the early event signal recoveries last from many seconds to many tens of seconds (say 10 to 200 s), whereas in rare cases, as shown by *Cotts and Inan* [2007], they can reach larger values up to many minutes.

[8] The present study is concerned with typical early VLF perturbations caused by narrow-angle forward scattering and measured at a receiver located far from the storm, say at distances greater than 1000 km. Since the *EuroSprite* VLF observations analyzed herein are far-storm, there is no concern with near-storm early VLF events seen at distances less than ~500 km and at large scattering angles. The latter is actually a controversial topic that involves rare cases of weak early events caused possibly through wide-angle scattering from currents induced in the sprite streamers themselves [see *Mika et al.*, 2005; *Marshall et al.*, 2006, and references therein].

[9] Regarding the ionospheric conductivity perturbations responsible for the early events, one has to consider that the *D* region conductivity is overwhelmingly electronic, that is, $\sigma = e^2 N_e / m_e \nu_{en}$. Thus it is proportional to the ambient electron density N_e and inversely proportional to the square root of electron temperature T_e , which enters through the electron neutral collision frequency ν_{en} . Since the early event durations are much larger than the lifetimes of the *D* region electron gas heating (lasting a small fraction of a second), this implies that the majority of early VLF events are basically due to ambient electron density perturbations. Furthermore, the observed recoveries of tens of seconds imply that most early events associate with electron density increases in the upper *D* region, say between 70 and 90 km. This range of altitudes has been suggested by several studies. They include the results of *Haldoupis et al.* [2009] on modeling early event recoveries, the theory of *Poulsen et al.* [1993] on narrow-angle scattering from laterally elongated volumes of diffuse ionization enhancements in the upper *D* region, and the findings of *Johnson et al.* [1999] on the horizontal extent of the perturbed regions, from ~80 to 100 km. Such volumes of elevated electron density are likely also to co-locate with laterally extended diffuse glows seen often in sprites and sprite halos in upper *D* region altitudes between about 70 and 90 km [*Gerken et al.*, 2000; *Barrington-Leigh et al.*, 2001; *Moore et al.*, 2003; *Marshall et al.*, 2006]. All this is also in line with the quasi-electrostatic field theory of *Pasko et al.* [1997] on sprite generation and ionization production in the upper *D* region. These results and implications point to a close correlation between sprites and early VLF perturbations, a fact that is established clearly by the present study.

3. EuroSprite Optical and VLF Observations

[10] To investigate further the relationship between sprites and early VLF events, a series of case studies of simultaneous sprite and VLF measurements obtained from various *EuroSprite* campaigns will be presented. The *EuroSprite* experiments are detailed elsewhere [*Neubert et al.*, 2005; 2008], therefore here we include only some brief information.

[11] The experimental units that provided data for this study included: 1) Stanford-AWESOME network (<http://nova.stanford.edu/~vlf/awesome>) narrow-band VLF receivers, particularly those located in Crete, Greece (35.31°N, 25.08°E), and Algiers, Algeria (42.94°N, 0.14°E). 2) Automated sprite detection camera systems with an exposure image time of 20 ms operating independently at various locations, including: a) the Observatoire du Pic du Midi, France (42.90°N; 0.09°E), b) Corsica, France (42.46°N, 8.92°E), and c) San Vicente de Castellet, Spain (41.67°N 1.86°E). 3) Lightning detection measurements provided by Météorage, the French lightning detection network that measures positive and negative CG lightning flashes over all France with spatial and temporal accuracy of ~1 km and 1 ms, respectively, and with ~90% detection efficiency. Some operational aspects of these units and other experimental details are given elsewhere [e.g., see Neubert et al., 2005, 2008; Haldoupis et al., 2004; Mika et al., 2005, van der Velde et al., 2006; Mika and Haldoupis, 2008].

[12] In the following subsections, *EuroSprite* case studies from different years are presented and discussed. Each refers to a sprite-producing thunderstorm that happened to be located close to the GCPs of several VLF transmitter-receiver pairs. This was the only selection criterion and we have used all sprite-producing storms that happened to be available. The sprite-early VLF event relationship is investigated here by considering sprite-producing thunderstorm cases rather than using a statistical analysis based on a rather small assembly of individual storms that were available. This was preferred because the unknown and uncontrolled parameters/conditions, both physical and experimental, which affect either the optical or the VLF measurements, may introduce significant biases which can differ for different storms. Experience shows that such uncontrolled factors can be more severe in a statistical study of a few storms rather than a single storm study for which conditions can be at times favorable in revealing the physical mechanisms at work.

[13] Before presenting new observations we first refer, for the sake of completeness, to the previous *EuroSprite* studies on the sprite-early event association.

3.1. *EuroSprite*-2003 Case Studies and Results

[14] The first evidence in favor of a one-to-one relationship between sprites and early VLF perturbations was reported by Haldoupis et al. [2004]. This relied on *EuroSprite* measurements during a localized thunderstorm in France, which lasted for about 70 min and produced 28 sprites seen by a Pic du Midi camera, all triggered by +CG lightning flashes. The Crete VLF receiver at ~2200 km southeast of the storm observed 27 early VLF events all occurring in coincidence with sprites, that is, for ~96% of the observed sprites. These were detected only in the signal of a powerful (~500 kW) French transmitter (HWU-18.3 kHz) located ~150 km west of the storm and having its GCP to the Crete receiver passing through the storm. Interestingly, the many more (~200) non-sprite producing +CG and the numerous (~1270) -CG discharges during the storm did not associate in this case with any detectable early type VLF perturbations.

[15] It is interesting to note that the near 100% correlation seen on the HWU-18.3 kHz link was not observed on the

nearly identical GCP HWU-20.9 kHz link. This data set showed that only about half of the observed sprites were observed in conjunction with early VLF events. Thus, in the absence of the HWU-18.3 kHz link, one would have concluded (wrongly) that only 50% of the sprites were accompanied by VLF perturbations. The reasons behind the early event detection differences between the two HWU links could not be easily identified. For example, one reason would have been the lower transmitted power (~100 kW) of HWU-20.9 kHz and possibly transmitter frequency related propagation effects, particularly since the amplitude variations and mode structure dependence on VLF frequency are well known effects [e.g., Wait, 1996].

[16] Mika et al. [2005] tested further the association between sprites and early events by using more *EuroSprite* 2003 data, which included two storms that occurred at about the same location as the storm analyzed by Haldoupis et al. [2004]. The storms produced 15 sprites with 12 of them occurring in association with early VLF events seen again at HWU-18.3 kHz while the HWU-20.9 kHz link detected only 7 of those events. In addition, 10 cases of early VLF perturbations associated mostly with +CG discharges were detected which were not accompanied by sprites. An inspection of the optical raw images (available only for 3 of these early events) revealed one more sprite that was missed by the camera automatic detection system, while for the other two images the discharges were too low on the horizon for the camera to detect sprites. In summary, the *EuroSprite* 2003 case studies suggested that nearly 9 out of 10 sprites (~90%) did occur in association with early VLF events, which was taken to be suggestive of a one-to-one relation. Next, we present more case studies and results not published before.

3.2. A *EuroSprite*-2005 Case Study

[17] In this case study, a sprite-producing storm happened to be intersected by 3 VLF transmissions all having nearly identical GCP distances to the Crete receiver. These included the two HWU transmitters at 18.3 kHz and 20.9 kHz, considered also in the 2003 case studies, plus the NAA transmitter, a very powerful VLF transmitter located in Maine, that transmits 1.2 MW at 24.0 kHz. By a mere coincidence, the GCP of the NAA transmitter to Crete happened to be superposed on top of the HWU GCPs links to Crete. Figure 1 depicts the GCPs of the VLF links recorded in Crete during a July 29, 2005 thunderstorm that produced 10 sprites between about 01:25 and 02:10 UT, all caused by +CG discharges. The sprite causative +CG discharges were located near the HWU transmitters about 200 km to the southeast, as shown by the open circles in Figure 1, whereas the many more small black crosses represent the +CG strokes that produced no observed sprites.

[18] Figure 2 shows time series of the signals received in Crete for the 3 VLF links under consideration. Inspection of the HWU-18.3 kHz VLF amplitude signal in the top panel reveals 11 early events, identified by the abrupt jumps in VLF amplitude of either positive or negative polarity and denoted in time by plus (+) signs. As seen, 9 out of the 10 observed sprites (marked in the plots by their count numbers) occur coincidentally with early event onsets. This suggests a close association between the two phenomena, in agreement

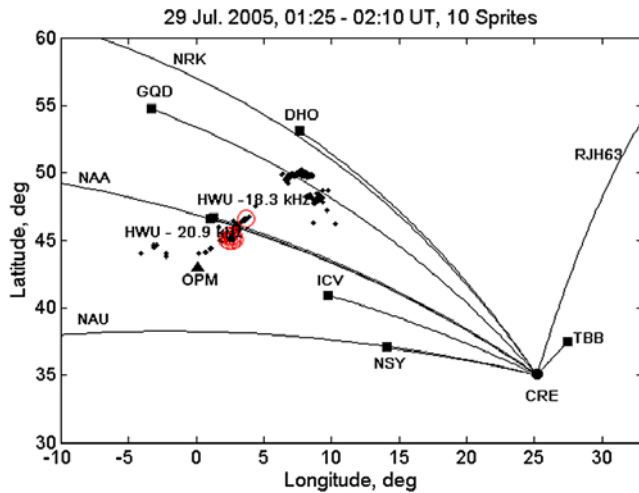


Figure 1. Geographic map showing the locations of the observed +CG lightning discharges during the interval 01:25 to 02:10 UT, 29 July, 2005, when a thunderstorm in southwest France produced at least 10 sprites seen by a camera located at Observatoire Pic du Midi (OPM). The open circles refer to the sprite causative +CG discharges having their radii scaled to the return-stroke current intensity. Shown also in Figure 1 are the VLF great circle paths (GCPs) of various VLF subionospheric transmitters monitored by the Crete VLF receiver. Note also a separate thunderstorm located to the northeast of the sprite producing storm, which produced neither sprites nor early VLF perturbations.

with the 2003 *EuroSprite* observations. On the other hand, and in sharp contrast with the 18.3 kHz link, the HWU-20.9 kHz link did not detect any early event in this case, as shown by the rather noisy signal amplitude in the bottom panel. The middle panel shows the signal of the powerful NAA-24.0 kHz transmission received in Crete, which detected only 3 early events, corresponding to some of the strongest ones seen at the HWU-18.3 kHz link. Inspection of the sprite images did not provide any systematic clue as to why NAA has detected these three sprite - early VLF event pairs out of the ten sprites. The NAA-Crete link alone would have suggested a 30% sprite-early event correlation which, however, would have been wrong.

[19] The HWU-18.3 kHz link observed in addition 2 early events not accompanied by sprites, although they both appeared to have been caused by +CG flashes. Finally, there was no early VLF perturbations detected in relation with any of the numerous (~1250) negative CG strokes and the other (158) positive CG strokes that caused no sprites, observed by Météorage from 01:25 to 02:10 UT. This case study shows that, as in the 2003 cases, it would have been impossible to identify the one-to-one sprite-early event correspondence if the HWU-18.3 kHz link had happened to be unavailable.

3.3. A *EuroSprite*-2007 Case Study

[20] The thunderstorm under consideration occurred over westernmost France and northern Italy on 15 November 2007. It produced 15 sprites from ~22:17 to 23:40 UT, all caused by + CG discharges. Figure 3, which is similar to Figure 1, depicts the VLF links monitored in Crete and the

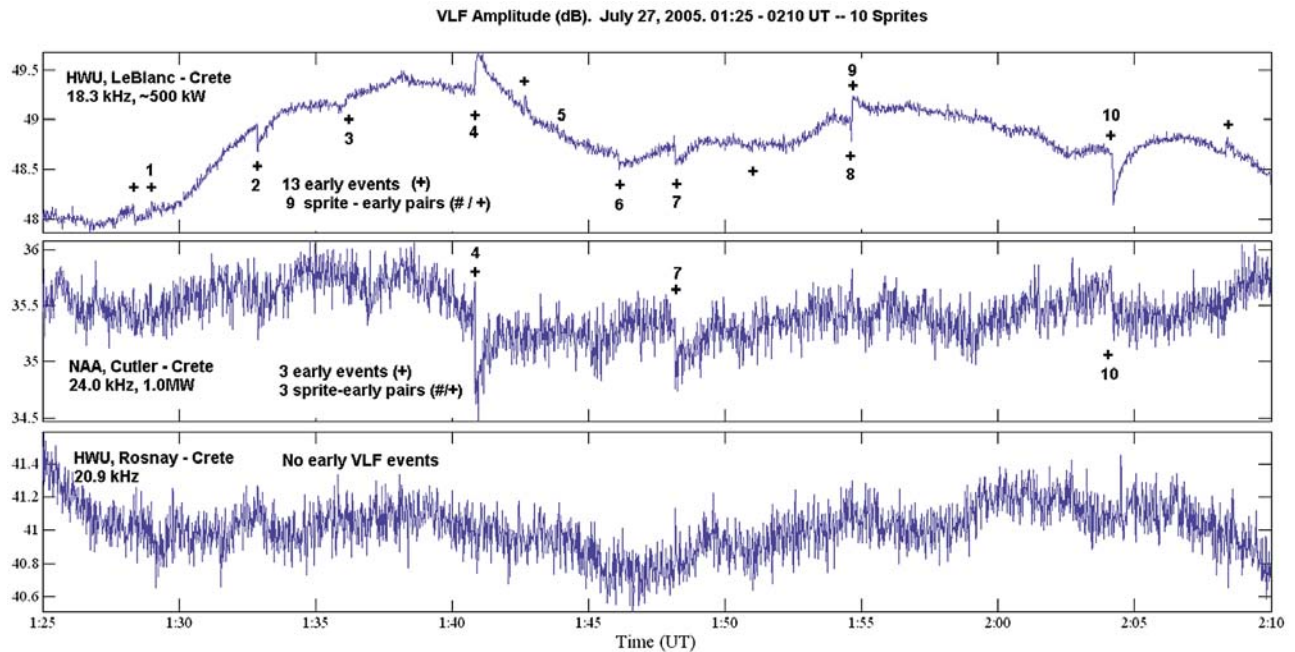


Figure 2. This refers to the case study of Figure 1 and shows narrowband amplitude recordings from 3 VLF transmitter-receiver links which had similar GCPs from the two French transmitters to the Crete receiver. The observed 10 sprites during this time interval are marked by their count number as compared to the observed early VLF events denoted the plus sign (+). See text in section 3.2 for details.

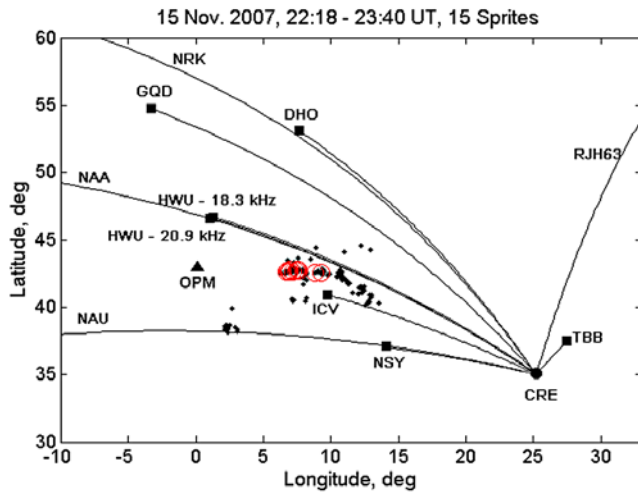


Figure 3. Same as Figure 1 but for the case study of the thunderstorm interval 22:18–23:40 UT, 15 November, 2007, when a camera at Observatoire Pic du Midi (OPM) captured 15 sprites, with 14 of these sprites accompanied by early VLF perturbations.

geographic location of a total of ~180 +CG discharges identified by Météorage. The red circles correspond to the 15 sprite causative +CG discharges which were located at distances ranging from about 150 to 300 km to the south of the GCPs to Crete of the HWU-18.3 kHz, HWU-20.9 kHz and the NAA-24 kHz transmitters. As in the 2005 case, these VLF links have nearly identical GCPs (from the storm) to the receiver in Crete, which makes them all equally suitable for early event detection.

[21] Figure 4, which is similar to Figure 2, shows the narrow-band signals in Crete for the 3 VLF aforementioned links during the sprite occurrence interval from 22:17 to 23:40 UT. As inferred by the flat noisy signal level in the upper panel and its diurnal variation pattern (not shown here), the HWU-18.3 kHz transmitter was inactive for this time period. Fortunately however, the anticipated one-to-one sprite-early correspondence was depicted in the NAA-24 kHz VLF link signal, shown in the middle panel. Remarkably, 14 out of the 15 sprites were all accompanied by early VLF events (marked by “+”) of either positive or negative amplitude onset polarity. The HWU-20.9 kHz link amplitude (lower panel) detected only 6 sprite-early event pairs, that is, ~40% of the observed sprites, as compared to the 93% for the NAA-24.0 kHz link, were matched by early event perturbations.

[22] The present case study supports again the one-to-one correspondence of sprites to early VLF events. There is only one sprite (number 12) out of the 15 detected that was not accompanied by an observable early VLF event in either of the two active links. Further inspection of the NAA and HWU-23.9 kHz signals in Figure 4 shows that in addition to the sprite-early pairs, there were 4 more early events that occurred without sprites, 2 of them seen by both links. Notably, at least 3 of these 4 early events appear to be caused by +CG discharges, thus the possibility exists that corresponding sprites might have occurred but somehow had been missed by the camera’s automatic detection software.

3.4. A EuroSprite-2008 Case Study

[23] Here, a localized thunderstorm that occurred over southwest France is considered. It produced 35 observable sprites from 19:28 to 02:06 UT, 3–4 September 2008, all

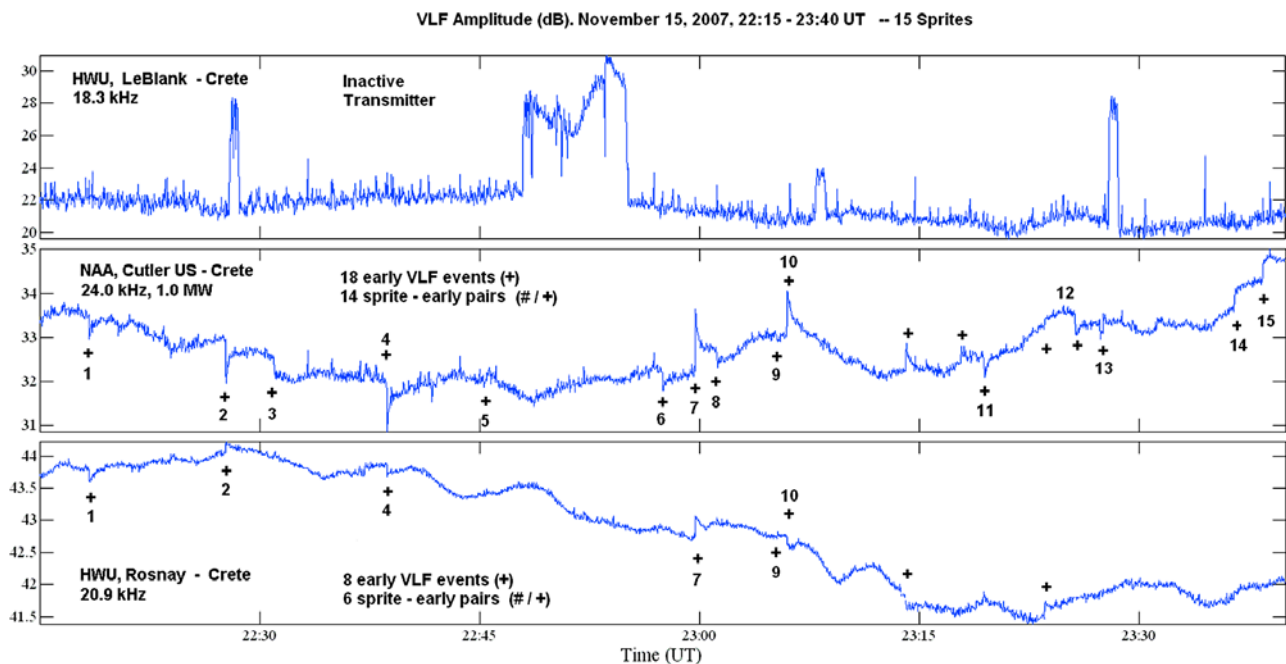


Figure 4. Same as Figure 2 but for the case study of 22:18–23:40 UT, 15 November, 2007 when a total of 15 sprites were captured by a camera at Pic du Midi, with 14 of the sprites (~93%) accompanied by early VLF perturbations (marked here by crosses +).

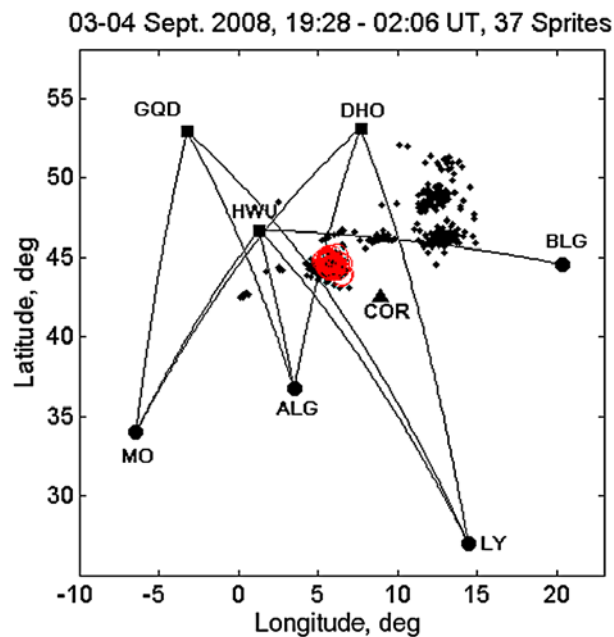


Figure 5. Map showing the +CG discharges of a localized thunderstorm in southwest France during 19:28–02:06 UT, 03–04 September, 2008, which produced at least 37 sprites caused by an equal number of +CG flashes (denoted by the circles). The sprites were captured by a camera located in Corsica (COR). Also shown are the great circle paths of various AWESOME network VLF links used for the identification of early VLF perturbations during the above sprite observation interval.

associated with +CG lightning discharges. The sprites were captured by a *EuroSprite* camera located in the highest mountain peak in Corsica (~ 2150 m altitude, 41.67°N ; 1.86°E), ~ 300 km away from the storm core to the southeast. The Crete VLF receiver did not operate in this case, thus VLF recordings provided by the AWESOME receivers at Rabat-Morocco, Algiers-Algeria, Sebha-Libya and Belgrade-Serbia, were inspected for early VLF event occurrences. Figure 5 shows the geographic location of the storm with +CG discharge locations marked by a plus (+), and the circles identifying the sprite causative +CG discharges. As seen, the storm that produced the sprites remained very localized during the 6-h period of observations. Shown in Figure 5 are the locations of the Corsica sprite-watch camera, the aforementioned AWESOME VLF receivers (marked by solid circles), and the GQD-22.1 kHz, DHO-23.4 kHz and HWU-18.3 kHz transmitters (marked by solid squares) along with the GCPs of the transmitter-receiver VLF links, used here to search for early VLF event occurrences.

[24] According to the findings of *Johnson et al.* [1999], the most suitable VLF links for early VLF event detection are those with GCPs passing nearby the storm at distances less than ~ 200 km from its center. In this respect, those meeting this proximity criterion are the DHO to Algiers link, the GQD and HWU to Sebha links, and the HWU-Belgrade link. Indeed, careful inspection of the DHO-Algiers narrow

band signal revealed that 33 out of the 35 sprites did coincide with early event onsets, which means that $\sim 95\%$ of the sprites were accompanied by early VLF perturbations. This endorses again the one-to-one correspondence of sprites to early events. On the other hand, the Sebha VLF links for both the GQD and the HWU transmitters, despite having GCPs passing fairly close to the storm did not detect any early VLF events. As for the HWU-Belgrade signal, inspection of the VLF time series showed only about 7 out of the 35 sprites, that is $\sim 20\%$ of them were accompanied by early VLF perturbations. Again, if the DHO-Algiers link were not available here, the very close association of sprites to early VLF perturbations would have been missed.

[25] For the rest of the VLF links shown in Figure 5 that pass too far from the storm there were no early VLF events detected, as anticipated, with one exception. Surprisingly, the HWU-Algiers link that passes ~ 350 km away from the storm center and forms a fairly large scattering angle of $\sim 70^{\circ}$, did show that 28 of the 35 sprites, (80%) had associated early VLF perturbations. To appreciate this we provide Figure 6, which includes the VLF recordings for the DHO (top panel) and HWU (bottom panel) paths to Algiers for the 50-min period from 20:20 to 21:10 UT when the Corsica camera observed 9 sprites. As seen in this case, all sprites, marked by their occurrence number from 5 to 13, are accompanied by VLF perturbations in both links, their onset marked by “+” signs. Notably, the DHO link to Algiers, which provided a fairly small scattering angle of a few degrees, observed rather stronger perturbations (of about 0.4 to 1.5 dB), relative to those seen simultaneously in the HWU-Algiers path (of about 0.2 to 1.2 dB).

[26] The “wide-angle” scattering seen in the HWU-Algiers path is an interesting new observation because it contrasts with the narrow-angle observations of $< 20^{\circ}$ observed by *Johnson et al.* [1999]. These studies have established that early VLF perturbations are due to forward scattering from laterally elongated diffuse regions of enhanced ionization, in line also with the theory of *Paulsen et al.* [1993]. The large scattering angles observed here suggest that this may not always be valid and thus there is need for more experimental work on this matter, which can be implemented now with the AWESOME network in Southern Europe, Northern Africa and the Middle East.

[27] Furthermore, Figure 6 shows that the DHO-Algiers link detected 9 more early VLF events not accompanied by sprites as compared to two such events in the HWU link. It is important to stress that for the entire interval of observation, that is, from 19:30 to 02:10 UT, the DHO link detected at least 60 early events in addition to the 33 ones which occurred concurrently with the observed sprites. Viewing it conversely, it means that only 35% of the early events observed here were accompanied by sprites, which hints that the one-to-one sprite-early event correspondence may not be reciprocal. Interestingly, however, the majority of the non-sprite related early events, that is $\sim 70\%$ were identified to be caused by +CG discharges. This could not be inferred with certainty for the remaining 30%, since the early event onsets in the VLF data cannot be identified with the same time accuracy present in the Météorage CG lightning measurements. These facts raise the possibility that many of the non-sprite early VLF events may have occurred

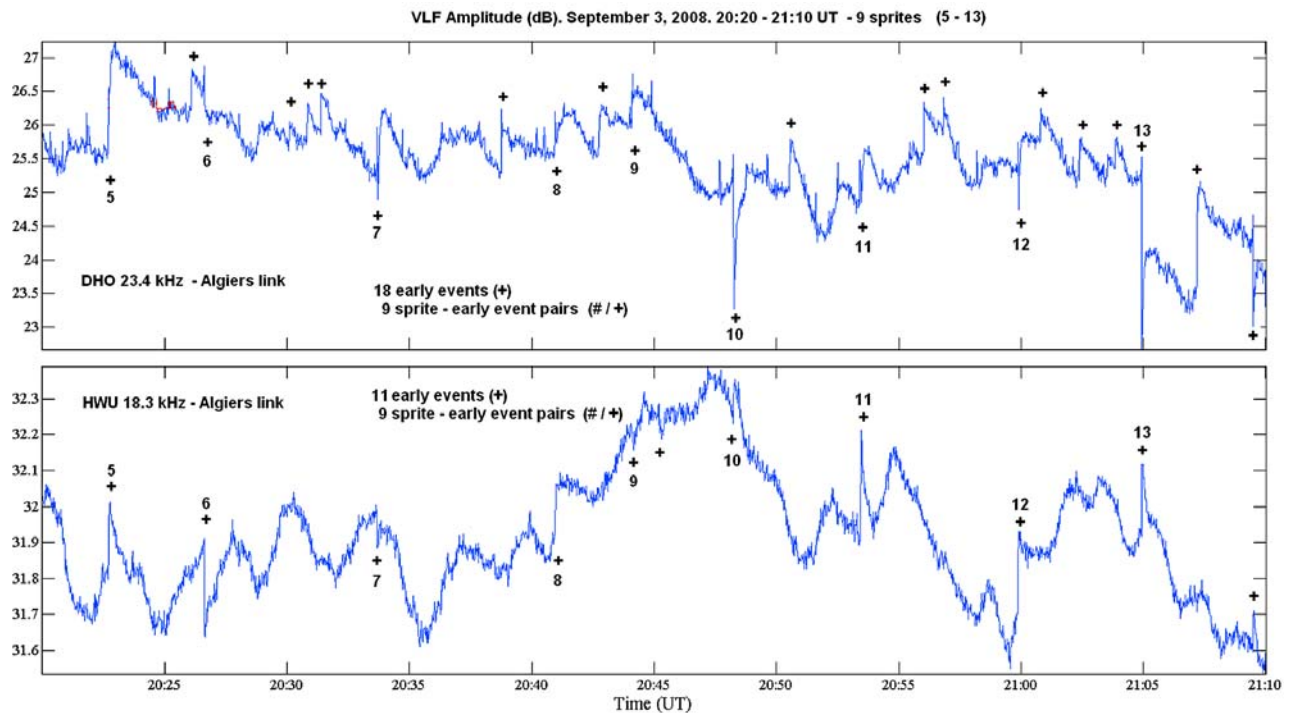


Figure 6. Narrowband VLF amplitude recordings observed by the Algiers AWESOME receiver for the DHO-23.4 kHz and HWU-18.3 kHz transmitters, during the interval from 22:20–21:10 UT, September 3, 2008, of the thunderstorm mapped in Figure 5. Despite their widely different scattering geometry, both links have observed early events to correspond to all the 9 sprites captured during this time interval. The small scattering angle link (DHO-Algiers) at the top panel observed in addition 9 more early events not accompanied by sprites as compared to two such cases for the large scattering angle signal link (HWU) in the lower panel.

in relation with sprites as well, which, for one reason or the other, might have not been captured.

3.5. A EuroSprite-2009 Case Study

[28] The thunderstorm under consideration started west of Toulouse in the early evening of October 8, 2009 and moved across South France eastward, crossing into Italy in the early hours of October 9. A sprite-watch camera in Spain, at San Vicente de Castellet (190m altitude, 41.67°N 1.86°E), captured 77 sprites during an observing period of about 7 h from 18:10 to 00:50 UT of 8–9 October 2009. Figure 7 maps the storm during this time interval by plotting the +CG discharges observed by Météorage. The small crosses represent the +CG discharges not accompanied by sprites whereas the open circles identify the sprite causative +CG discharges. The latter are color-coded according to time in order to depict the location and eastward movement of the storm as time progresses during the night. Shown also in Figure 7 are GCPs of transmitter-receiver VLF links passing through and near the storm, whose signals were inspected for early VLF events. These include four VLF transmitter links (NRK, GQD, HWU and DHO) to the Algiers receiver crossing the storm from north to south, and two transmitter links (HWU and NAA) to Crete and one (HWU) to Belgrade receivers, all passing north of the storm.

[29] The search for early VLF perturbations accompanying the observed sprites led to the following: 1) The westernmost NRK and GQD-Algiers links did not observe

any early events despite the fact that their GCPs passed fairly close to the location of several sprite-causative +CG discharges during the storm's earlier stages. 2) The HWU to Algiers link detected 53 early VLF events concurrently with sprites, corresponding to ~70% of the total number of sprites. This was the only link to identify early events in relation with 21 out of 23 sprites observed prior to 20:30 UT. The two sprites missed during this time were the first two observed by the camera prior to 18:40 UT and this happened because the VLF signal was rather noisy as it was going through solar terminator semi-dark conditions. As expected, the HWU to Algiers link did not detect any early VLF events after about 23:50 UT when the storm moved far to the east more than ~250 km away from its great circle path. 3) The eastward DHO-Algiers link detected 21 sprite-early pairs after about 21:00 UT when the storm approached its GCP. This corresponds to ~60% of the total number of sprites observed between 21:00 and 00:50 UT. 4) The HWU-Crete link started detecting early VLF perturbations after about 20:30 UT because the storm moved sufficiently close to its GCP for forward scattering to take place. It detected 37 sprite-early pairs, corresponding to about 82% of the sprites observed after 20:30 UT. 5) The NAA-Crete link observed 15 sprite-early pairs that occurred the last hour of the observation period, which corresponds to 90% of the sprites detected during this hour. 6) the HWU-Belgrade link observed only 4 sprite-early pairs the last 40 min of the observation period, but in one case it was the only link to

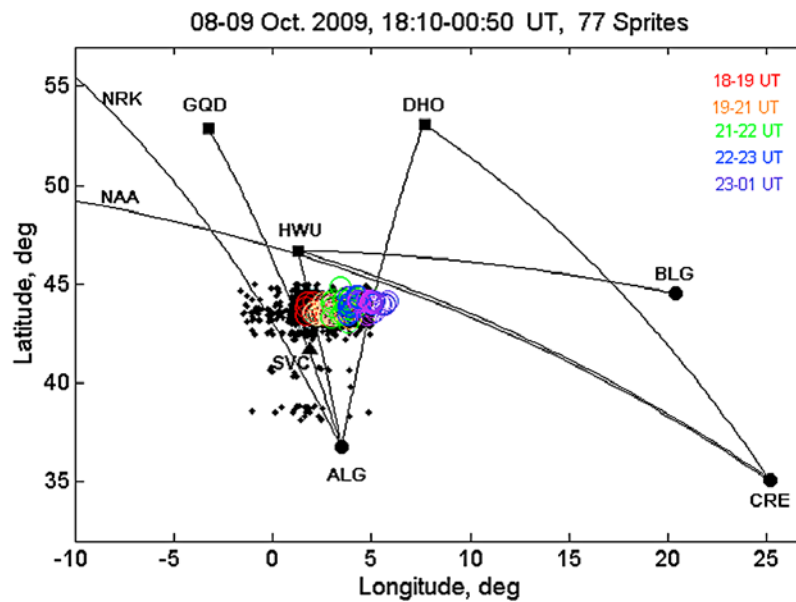


Figure 7. Same as Figure 6 but for a localized sprite producing storm, which started west of Toulouse and moved eastward across south France into Italy. During this time from 18:10 to 00:50, 8–9 October 2009, a sprite-watch camera at San Vicente de Castellet, Catalonia, detected 77 sprites. Also shown here are the GCPs of various AWESOME network transmitter-receiver VLF links, whose narrowband signals were used for the identification of early event occurrences in relation with the sprites.

have detected the anticipated early VLF perturbation in association with an observed sprite.

[30] The present case study shows that the detection of a sprite-related early VLF perturbation depends on the proximity of the affected region relative to the link's GCP, a necessary condition that agrees with the findings of *Johnson et al.* [1999]. However, the evidence here suggests, like in our previous case studies, that the proximity condition is not sufficient for the detection of all early VLF perturbations present during an active thunderstorm. In this respect, it was found that none of the single links examined here was capable of confirming the one-to-one correspondence of sprites to early VLF perturbations. On the other hand, the combined inspection of all the links shown in Figure 7 revealed that 75 out of the 77 sprites observed, that is, ~98%, were accompanied by early events seen at least in one link. This again leads to the conclusion that the sprite-early one-to-one correlation was valid in the present case study as well.

[31] Notably, all sprites observed here are found to be matched by early VLF perturbations thanks to the availability of several links fulfilling the storm proximity criterion for early VLF event detection. This can be appreciated in Figure 8, which shows concurrent VLF data from 3 links during the interval from 22:00 to 22:30 UT when the camera captured 13 sprites numbered in sequence from 42 to 54. Although each individual link detected only part of the 13 sprite-early pairs, with a maximum of nine pairs seen by the HWU-Algiers link, the combination of all 3 links revealed that the 13 sprites observed were all matched by early VLF perturbations. Finally, a total of 45 early VLF events have been identified which were not accompanied by sprites, with most of them seen by the HWU-Algiers link. It is important to note, however, that 38 of these events, that is, ~85% of

the total were caused by +CG discharges, while this was not certain for the remaining 15%.

4. Discussion and Concluding Comments

[32] The motivation for the present study was prompted by the existing discrepancies on the exact association between sprites and early VLF events. While all past studies recognized the connection between the two phenomena they disagreed on the extent of their correlation with estimates ranging from ~50% to 100%, the latter implying a one-to-one correspondence. In order to resolve this discrepancy, we considered here for analysis more optical and VLF observations obtained simultaneously during several *Euro-Sprite* campaigns carried out routinely the last several years. The decisive factor for this work was not the use of additional good quality data for analysis but the utilization of multiple VLF transmitter-receiver links that all happened to have great circle paths crossing through, or passing by, a sprite-producing thunderstorm. With this setup, it was possible to have three or more links fulfilling the storm-proximity condition that is necessary for early VLF event detection, thus we had several simultaneous VLF receiver links available to search for early VLF perturbations occurring in relation with the observed sprites. This has proven to be useful because it made early event detection, for all the reasons mentioned in the previous sections, more probable. Also, particularly advantageous for the purpose of this study was that some of the VLF links happened to have nearly identical GCPs.

[33] The evidence obtained is fairly conclusive and thus capable of clarifying the degree of correlation between sprites and early VLF events. By using several *EuroSprite* case studies of sprite-producing storms, we found that that

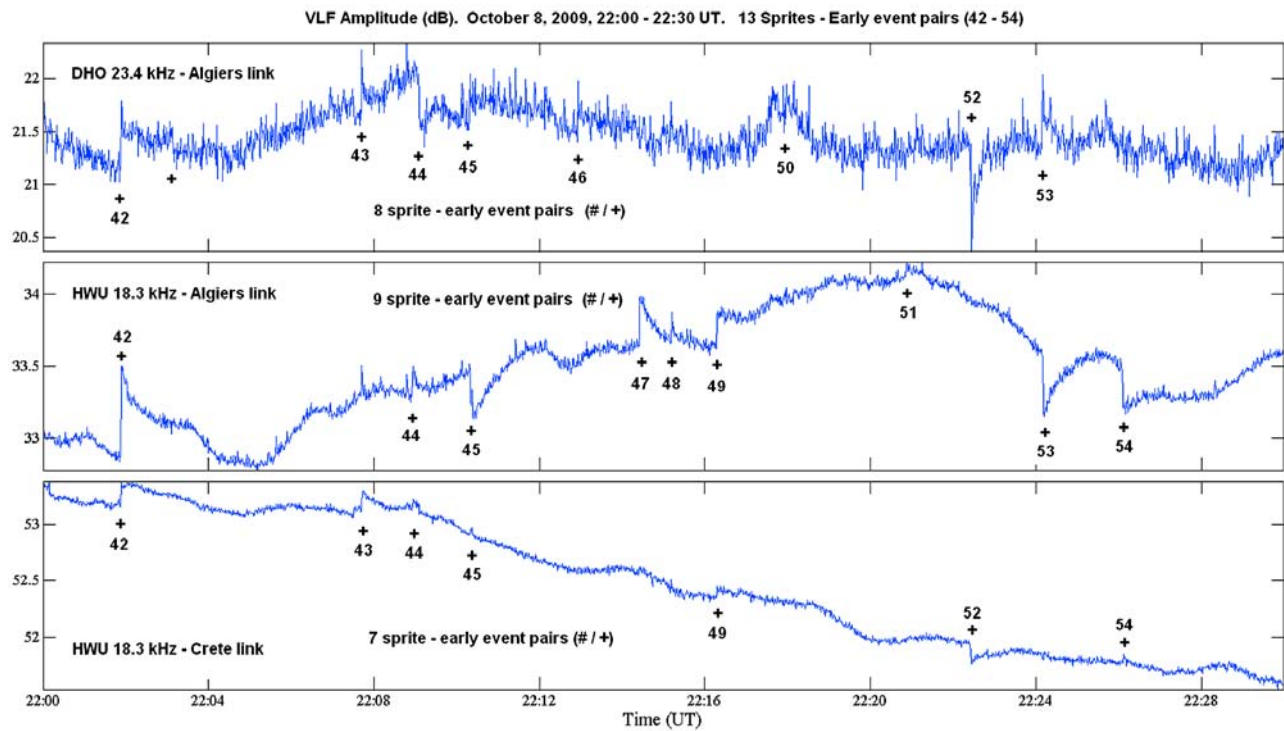


Figure 8. This refers to the case study of Figure 7 and shows narrowband VLF amplitude recordings at the Algiers AWESOME receiver (top and mid panels) and the Crete receiver (bottom panel). They have been observed during the half-hour interval of 22:00–22:30 UT, 8 October, 2009, when the storm produced at least 13 sprites. Although individual VLF links observed only part of the sprites to be accompanied by early VLF events, combination of all the links shows that all 13 sprites have early event counterparts. This supports the one-to-one correspondence of sprites to early VLF events. See text in section 3.5 for more details.

sprites were nearly always accompanied by early VLF perturbations. The degree of “one-to-one” correlation ranged from 90% to 98%, indicating that sprite occurrences are coincidental with perturbations in electron density in the lower ionosphere that produce early VLF events. This is an important result because it implies that the mechanism producing sprites is always responsible for the generation of ionization disturbances in the *D* region.

[34] Furthermore, it was shown that the close proximity of the VLF link GCP to a sprite - producing thunderstorm is necessary but not sufficient for early event detection. This is because VLF propagation and scattering in the earth-ionosphere waveguide are fairly complex physical processes that depend on several uncontrolled physical parameters and VLF transmitter signal characteristics, as discussed next. Their combination can affect the different VLF link signal properties at a receiver differently so that an early event may occur in one link but not in another, even though the links have GCPs equally suitable for early event detection. The significance of this fact has been overlooked before, therefore one may explain why several studies before, and possibly others to come, have been inconclusive or even contradictory in quantifying the exact sprite-early event correspondence.

[35] As for the kind of conditions needed for an early event to be detected in a VLF link, besides the need for having a GCP suitably close to the storm, they can neither

be deduced nor quantified from the available data alone. At this stage of research one can only speculate on various possible reasons. These may include the complexity of VLF mode-coupling and propagation in the imperfect and changeable earth-ionosphere waveguide, the position of the storm relative to the VLF transmitter and receiver, the size and properties of the disturbance regions that scatter the incident VLF waves, the scattering process itself, the phase difference at the receiver between the direct and the scattered signal, etc. In addition, the transmitter frequency and power, and interference from external noise sources are likely to play a role as well. The identification and understanding of the mechanisms behind the selective process of early VLF event detection is a challenging research problem that needs to be addressed.

[36] The present study suggests that there is need for a theoretical model to explain how nearby frequencies with similar paths can have different responses to a sprite-related ionospheric disturbance that is capable of producing early VLF perturbations. This could be a scattering model that can simulate the modal pattern of subionospheric VLF transmitter signals with distance at different frequencies. Then when observing what modal structure is present at a specific location you can begin to constrain the exact ionization profile which must have been present in order for scattering to take place, and what ionization profiles could be “missed” by a specific modal structure. For example at some places

along the paths the dominant mode of the two signal paths will be nearly orthogonal which could easily explain the observed results. A full analysis can also take into account further constraints, but such a detailed analysis is beyond the scope of the present paper.

[37] We stress that the one-to-one relation between sprites and early events, established by the present study, refers to a sprite being accompanied by an early VLF perturbation and not necessarily vice versa. If we are to view the sprite-early relationship conversely, then this correlation remains inconclusive because in some of the analyzed case studies there were many more early events observed than sprites. That is, the “early to sprite” correspondence, as compared to the “sprite to early” one-to-one association, was found to vary widely from ~35% to 95%, which means that the one-to-one sprite-early association seems not to be reciprocal always. This would have been anticipated because early VLF events are known to associate also with transient luminous types other than sprites, that is, mostly sprite halos [e.g., see *Barrington-Leigh et al.*, 2001; *Moore et al.*, 2003; *Marshall and Inan*, 2006], and occasionally with elves [e.g., see *Mika et al.*, 2006]. Halos and elves are often dimmer than sprites and live much shorter, thus it becomes difficult to be captured from the ground with low-light *EuroSprite* type cameras having relatively large frame-integration times (commonly 20 ms).

[38] On the other hand, it is important to stress that the majority (~70 to 90%) of the early events not accompanied by sprites were estimated to be caused by +CG discharges. This raises the possibility that sprites were also simultaneously present with these early VLF events but had been missed by the sprite-watch cameras. This could happen either because the meteorological observing conditions near the cameras were not optimal, or sprites failed to be recognized and captured by the camera automatic detection software. According to experienced sprite observers like *S. Cummer* (personal communication, Sopron, Hungary IAGA meeting, August 2009) and co-author *O. van der Velde*, “sprite misses” are fairly common in automatic sprite-watch camera systems, because optical sensitivity and the computerized algorithms used to identify the sprites in real time are strongly limited by signal-to-noise ratios. In conclusion, the reciprocal correspondence between early events and sprites, and also with sprite halos and elves, remains an open question that needs further investigation by using optical measurements of increased sensitivity and of optimized efficiency, supplemented also by charge moment change measurements which can contribute in sprite occurrence identification. On the other hand, there are indications in recent sprite theory suggesting that sprite luminosity is a very sensitive function of the applied electric field due to the exponential growth of luminosity in sprite streamers [e.g., see *Pasko*, 2010, and *Liu et al.*, 2009]. This means that some sprites may not achieve sufficient luminous strength in order to become visible and be detected, whereas they would produce electron density perturbations and thus conductivity changes strong enough to affect VLF waves and thus produce early events.

[39] The present study provides a definitive answer to the long-standing question: Are sprites accompanied by ionization production in the D region ionosphere? The nearly one-to-one correspondence of visible sprites to typical early VLF events implies clearly that sprites are indeed accom-

panied almost always with electron density production in the D region. However, this sprite-related ionization production still remains to be quantified.

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