Journal of Atmospheric and Solar-Terrestrial Physics 71 (2009) 1254–1266

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

# ELF/VLF signatures of sprite-producing lightning discharges observed during the 2005 *EuroSprite* campaign

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ARTICLE INFO

*Article history:*
Received 11 January 2009
Received in revised form
28 April 2009
Accepted 6 May 2009
Available online 10 May 2009

*Keywords:*
Lightning
ELF
VLF
Schumann resonance
Sprites

ABSTRACT

During the summer of 2005, transient luminous events were optically imaged from the French Pyrénées as part of the *EuroSprite* campaign. Simultaneously, extremely low frequency (ELF: 3–3000 Hz) and broadband very low frequency (VLF: 3–30 kHz) data were recorded continuously at two separate receivers in Israel, located about 3300 km from the area of the parent lightning discharges responsible for the generation of sprites. Additionally, narrowband VLF data were collected in Crete, at about 2300 km away from the region of sprites.

The motivation for the present study was to identify the signature of the sprite-producing lightning discharges in the ELF and VLF electromagnetic frequency bands, to qualify and compare their parameters, and to study the influence of the thunderstorm-activated region on its overlaying ionosphere. For the 15 sprites analyzed, their causative positive cloud-to-ground (+CG) discharges had peak current intensities between +8 and +130 kA whereas their charge moment changes (CMC) ranged from 500 to 3500 C km. Furthermore, the peak current reported by the Météorage lightning network are well correlated with the amplitudes of the VLF bursts, while showing poor correlation with the CMCs which were estimated using ELF methods.

Additionally, more than one +CG was associated with six of the sprites, implying that lightning discharges that produce sprites can sometimes have multiple ground connections separated in time and space. Finally, for a significant number of events (33%) an ELF transient was not associated with sprite occurrence, suggesting that long continuing current of tens of ms may not always be a necessary condition for sprite production, a finding which influences the estimation of the global sprite rate based on Schumann resonance (SR) measurements.



## 1. Introduction

Sprites are short-lived optical flashes (<100 ms), which occur above active thunderstorm systems at altitudes between 40 and 90 km, having horizontal extents of a few tens of km (Lyons (2006) and references therein). Sprites are usually associated with a positive cloud-to-ground (+CG) lightning discharge which neutralizes large amounts of charge from cloud and generates an electric field in the mesosphere which drives the electric breakdown of sprites. This parent +CG lightning discharge produces powerful electromagnetic radiation bursts in the extremely low frequency (ELF: 3–3000 Hz) (Boccippio et al., 1995; Sentman et al., 1995; Füllekrug and Reising, 1998; Hobara et al., 2001; Williams, 2001) and in the very low frequency (VLF: 3–30 kHz) (Reising et al., 1996; Bell et al., 1998; Wood and Inan, 2002; Price et al., 2002) bands.

These waves can propagate over large distances and provide information about the charge moment changes (CMC) of the parent lightning discharge. In the lower part of the ELF band, the radio waves below 50 Hz can propagate globally within the Earth–ionosphere waveguide, leading to constructive interferences which establish the 'Schumann resonance' (SR) with eigenfrequencies near 8, 14, 20,…, Hz (Schumann, 1952). The CMC of the parent lightning discharge can be evaluated by measuring the contribution of each mode in the resonance pattern (Huang et al., 1999; Sato et al., 2003; Greenberg et al., 2007). In the VLF band, the CMC can be evaluated by integrating the current of the lightning discharge over time (Cummer and Inan, 1997; Hu et al., 2002).

Sprites are sometimes accompanied by subionospheric VLF perturbations, named "early VLF events", characterized by abrupt changes in the signal of powerful VLF transmissions detected with

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doi:10.1016/j.jastp.2009.05.005

receivers at far distances from the storm when the corresponding great circle paths (GCP) pass above or near the storm (Inan et al., 1995; Dowden et al., 1996; Rodger, 1999; Haldoupis et al., 2004; Marshall et al., 2006). A mechanism involving a quasi-electrostatic (QE) field generated above the cloud in the upper atmosphere soon after a +CG lightning discharge has been proposed for the excitation of sprites (Inan et al., 1991; Pasko et al., 1995). Moreover, the intra-cloud (IC) horizontal discharges are also believed to play a role in sprite initiation (Adachi et al., 2004; Ohkubo et al., 2005; Haldoupis et al., 2006; van der Velde et al., 2006) as theoretically proposed (Valdivia et al., 1997; Rycroft and Cho, 1998) but their role is not yet well understood.

During the summers of 2002–2006, a European Union Research Training Network (RTN) project, named "coupling of atmospheric layers", conducted several sprite observational campaigns in southern Europe (http://www.eurosprite.net), a new region of sprite observations. The aim of the *EuroSprite* campaigns was to perform complementary optical and electromagnetic measurements to investigate the physics of sprite formation and their effects on the mesosphere and lower ionosphere (Neubert et al., 2005). Sprites have been investigated in the US since the early 1990's while extensive research in Europe began only in 2000 (Neubert et al., 2001). Although the thunderstorms over Southern Europe are generally less intense compared to the mesoscale convective systems (MCS) over the US high plains, hundreds of sprites have been imaged throughout the *EuroSprite* campaigns over France with cameras placed at the Pic du Midi Observatory in the French Pyrénées (Mika et al., 2005; Haldoupis et al., 2006).

In the present study, we analyzed ELF and broadband (BB) VLF observations made in Israel (~3300 km away) associated with 15 sprites imaged during storms in the summer of 2005. In addition, concurrent narrowband VLF recordings, made in Crete (CR) at about 2300 km away from the sprite-producing storms, were also analyzed. This set of ELF and VLF observations allowed us to investigate the effects of the charges removed by the sprite-causative +CG lightning currents on sprite generation and perturbations in the ionosphere. These are crucial topics for understanding the impulsive reorganization of charge distributions in thunderclouds, the properties of the region of the atmosphere above them and the associated electric fields that lead to the generation of sprite discharges.

## 2. Instruments

The optical measurements were conducted from the Pyrénées Mountains in Southern France (42.90°N; 0.09°E) at the Observatoire Midi-Pyrénées (OMP) on Pic du Midi using a low light sensitive charge-coupled device (CCD) camera system (Chanrion et al., 2007). Two monochromatic CCD cameras were used—one with a 16 mm f/1.4 lens and horizontal field of view (FOV) of 36.5°, and the other with a 50 mm f/0.95 lens and horizontal FOV of 11.5°. The camera frame rate was 24 frames/s. Both camera systems were remotely controlled via the internet and included an automatic event detection algorithm to reduce the amount of data. The digitized video files were time-stamped using the PC system time which was synchronized to UT time using a GPS clock. The frame integration time of the images was 41.7 ms and the image time was correct to below 1 ms.

Several receivers were used for simultaneous ELF and VLF electromagnetic measurements. The ELF station is located at the Wise astronomical observatory (30.60°N, 34.76°E) near Mitzpe-Ramon (MR) in Israel, a remote site which has low man-made electromagnetic noise levels in the Negev desert (Greenberg and Price, 2004). The MR station is composed of two horizontal magnetic induction coils for receiving $H_{ns}$ and $H_{ew}$ which are oriented along the geographic north-south and west-east directions, respectively, and one vertical electric ball-antenna for receiving $E_r$. The three components of the electromagnetic field are sampled at 250 Hz with 12-bit resolution, using a notch filter at 50 Hz. The VLF station is located at the Ben-Gurion University Desert Research Institute (30.86°N, 34.78°E) at Sde-Boker (SB) in Israel, and consists of two orthogonal triangular loop-antennas of 9 m high with a baseline of 18 m (Price et al., 2002). The broadband VLF data are sampled at 100 kHz with 12-bit resolution using a bandpass filter in a range ~0.1–40 kHz, and were recorded in a continuous mode for 9 h periods during the nights of the *EuroSprite2005* campaign. The VLF receiver in Crete, Greece (35.31°N, 25.08°E) is a Stanford University receiver identical to those of the Holographic Array for Ionospheric Lightning (HAIL) which uses a $1.7\times1.7\,m^2$ magnetic loop antenna (Johnson et al., 1999). Its wideband signal is sampled at 100 kHz with 16-bit resolution and bandpass filtered to a range 9–45 kHz. The sampled waveform is then digitally filtered into a few narrow bands (NB) centered on selected frequencies of signals from specific ground transmitter stations. Two of these stations had their GCP links to Crete located within 100 km from the sprite-producing storms under consideration, namely those with signs HWU (18.3 kHz; Le Blanc, France; 46.62°N, 01.08°E) and NAA (24.0 kHz; Cutler, Maine, US; 44.63°N, 67.28°W). The NB amplitude and phase of the transmitter signals are digitized with a sampling interval of 20 ms and stored for further processing, while the BB data is not saved. All ELF and VLF receivers use accurate GPS timing for temporally correlating the detected electromagnetic signatures with the sprites observed from OMP.

Lightning data from the French national lightning detection network Météorage was used to pinpoint the exact location of the sprite-producing lightning discharges and to estimate a few of their properties (http://www.meteorage.com). Based on radio triangulation from 17 sensors using direction finding and time of arrival techniques, the Météorage network is able to geolocate CGs with high detection efficiency (>90%) and to provide its time of occurrence (error<1 ms), geographic location (error<4 km), peak current intensity of the first return stroke (error ~5%), multiplicity, and CG discharge polarity (Morel and Sénési, 2000; Bonnet, 2004).

The locations of the +CGs associated with the sprites under consideration are shown in Fig. 1 along with the sites of the optical and electromagnetic sensors used in the present study. The

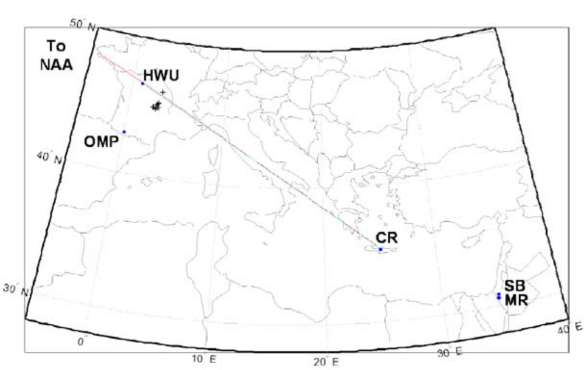


**Fig. 1.** Location of optical instruments at the Observatoire Midi-Pyrénées (OMP), the location of CGs which were associated with sprites as detected by the Météorage in the Southern Europe (with '+' sign), ELF station at Mitzpe-Ramon (MR) in Israel, broadband VLF station at Sde-Boker (SB) in Israel, and narrowband VLF station at Crete (CR) and its GCP links to HWU (cyan) and NAA (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

cameras at OMP were mounted on a motorized pan-and-tilt unit which allowed omnidirectional observations around OMP. The ELF and BB VLF stations in Israel (MR and SB, respectively) are close to each other (~30 km) and located ~3300 km from the region of sprites. Also shown in Fig. 1 is the NB VLF station in Crete, located at ~2300 km from the sprite regions, along with the GCPs for the HWU- and NAA-CR links.

## 3. Observations

From July to November 2005, 65 sprites were imaged during 14 different thunderstorm observation nights. ELF and VLF data were available for five nights (July 19th and 29th, August 16th, September 7th and 9th) when 15 sprites were imaged, see Table 1. These events allow us to investigate the ELF and VLF transient perturbations associated with sprites observed during European thunderstorms, and to quantify parameters related to its causative lightning discharges. In this section, five case studies of groups of column and carrot sprites and their corresponding ELF and VLF waveforms are presented. These events occurred during one night in a time period of about 40 min. The order of presentation below is not chronological but rather according to the electromagnetic features. All ELF and VLF waveforms presented in this section are related to the $H_{ns}$ magnetic field component, since both projections ($H_{ns}$ and $H_{ew}$) are with almost the same amplitude due to angle of arrival which was ~315°.

### 3.1. Case study 1—01:40:50 UT, July 29th, 2005

Fig. 2 shows sequential images of groups of carrot sprites that were observed on July 29th, 2005 at 01:40:50 UT. The transient luminous events were captured in five subsequent video frames for a total of 208 ms, from 01:40:50.204 to 01:40:50.412 UT. In this figure, five pairs of frames are presented. For each pair, the upper frame was captured by the wide FOV camera (*.0) while the lower frame related to the narrow FOV camera (*.1). The Météorage network detected two +CGs that occurred at 01:40:50.195 and 01:40:50.378 UT which were associated with this group of sprites, with measured peak currents of +61.4 and +115.6 kA, respectively, at locations separated by about 40 km.

Fig. 3 displays the ELF and BB VLF signals that were detected in Israel (MR and SB) during the time period of sprites shown in Fig. 2. The vertical dashed lines designate the time windows of the video frames, with the five sections marked with Latin numerals related to the images shown in Fig. 2. In Fig. 3(a), the VLF time series is presented for a time interval of 400 ms ($H_{ns}$ field component), starting at 01:40:50.100 UT. Superimposed upon the background noise are two intense bursts, which emit radiation in a wide frequency band, from the individual powerful +CG discharges that were detected by the Météorage network, implying that more than one +CG discharge is associated with the sprite sequence. The second discharge is stronger and has a longer tail as can be seen in both the VLF and ELF data, respectively. There is a positive correlation for the two +CG

**Table 1**
List of sprites; date, UT time and number of frames for sprites imaged from OMP; UT time, location and peak current of associated +CG as detected by the Météorage and values of CMCs evaluated using ELF methods.

| No. | Date | UT time of sprite | Num of frames | UT time of +CG | Location of +CG (Lat., Lon.) | Peak current (kA) | CMC (C km) |
|---|---|---|---|---|---|---|---|
| 1 | 19/07/2005 | 00:46:12.51 | 1 | 00:46:12.434 | 45°36, 9°99 | 70.7 | 900 |
| 2 | 29/07/2005 | 01:28:59.14 | 3 | 01:28:59.065/077 | 45°04, 2°26; 45°03, 2°29 | 197.4/38.7 | 1500 |
| 3a | 29/07/2005 | 01:32:51.33 | 3 | 01:32:51.246 | 44°92, 2°46 | 24.6 | 1000 |
| 3b | 29/07/2005 | 01:32:51.41 | 2 | 01:32:51.364 | 44°98, 2°24 | 35.5 | – |
| 4 | 29/07/2005 | 01:36:09.46 | 5 | 01:36:09.357/393 | 45°25, 2°68; 45°25, 2°67 | 66.7/29.4 | – |
| 5 | 29/07/2005 | 01:40:50.28 | 5 | 01:40:50.195/378 | 44°99, 2°68;45°06, 2° 19 | 61.4/115.6 | 3500 |
| 6 | 29/07/2005 | 01:43:52.66 | 4 | 01:43:52.525/736 | 45°22, 2°56; 45°35, 2°09 | 8.1/25.5 | – |
| 7 | 29/07/2005 | 01:46:04.82 | 3 | 01:46:04.739 | 45°26, 2°71 | 63.1 | – |
| 8 | 29/07/2005 | 01:48:08.39 | 5 | 01:48:08.267/383/418 | 45°33, 2°77; 45°27, 2°62; 45°32, 2°61 | 129.9/75.2/16.2 | 700 |
| 9 | 29/07/2005 | 01:54:35.20 | 2 | 01:54:35.157 | 46°21, 3°06 | 49.8 | 500 |
| 10a | 29/07/2005 | 01:54:38.16 | 2 | 01:54:38.078 | 45°06, 2°83 | 71.9 | 800 |
| 10b | 29/07/2005 | 01:54:38.53 | 3 | 01:54:38.444 | 45°49, 2°65 | 31 | – |
| 11a | 29/07/2005 | 02:04:10.30 | 2 | 02:04:10.255 | 45°33, 2°77 | 99.7 | 1500 |
| 11b | 29/07/2005 | 02:04:10.39 | 1 | 02:04:10.342/343 | 45°54, 2°58; 45°44, 2°53 | 66.2/32.9 | – |
| 12 | 16/08/2005 | 23:06:42.26 | 4 | 23:06:42.182 | 41°99, 0°83 | 24.5 | – |
| 13 | 07/09/2005 | 02:14:08.37 | 2 | 02:14:08.337 | 43°83, 6°24 | 57.6 | 2000 |
| 14 | 09/09/2005 | 20:35:42.35 | 2 | 20:25:42.292 | 44°64, –1°41 | 37.2 | 500 |
| 15 | 09/09/2005 | 21:18:39.33 | 2 | 21:18:39.220 | 45°00,–1°04 | 74.5 | – |

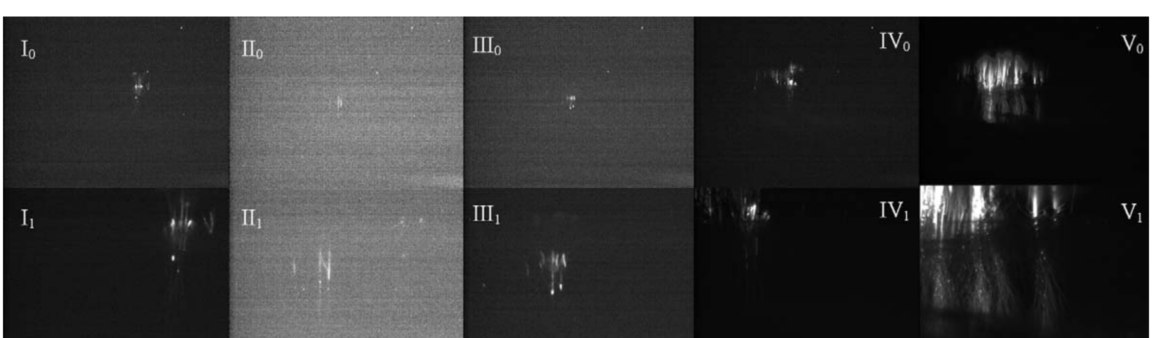


**Fig. 2.** Case study 1: images of groups of carrot sprites as were observed on July 29th, 2005. (I) 01:40:50.204 UT; (II) 01:40:50.246 UT; (III) 01:40:50.287 UT; (IV) 01:40:50.329 UT and (V) 01:40:50.370 UT. For each time two images are presented—the upper (*0) for wide FOV and the bottom (*1) for narrow FOV.

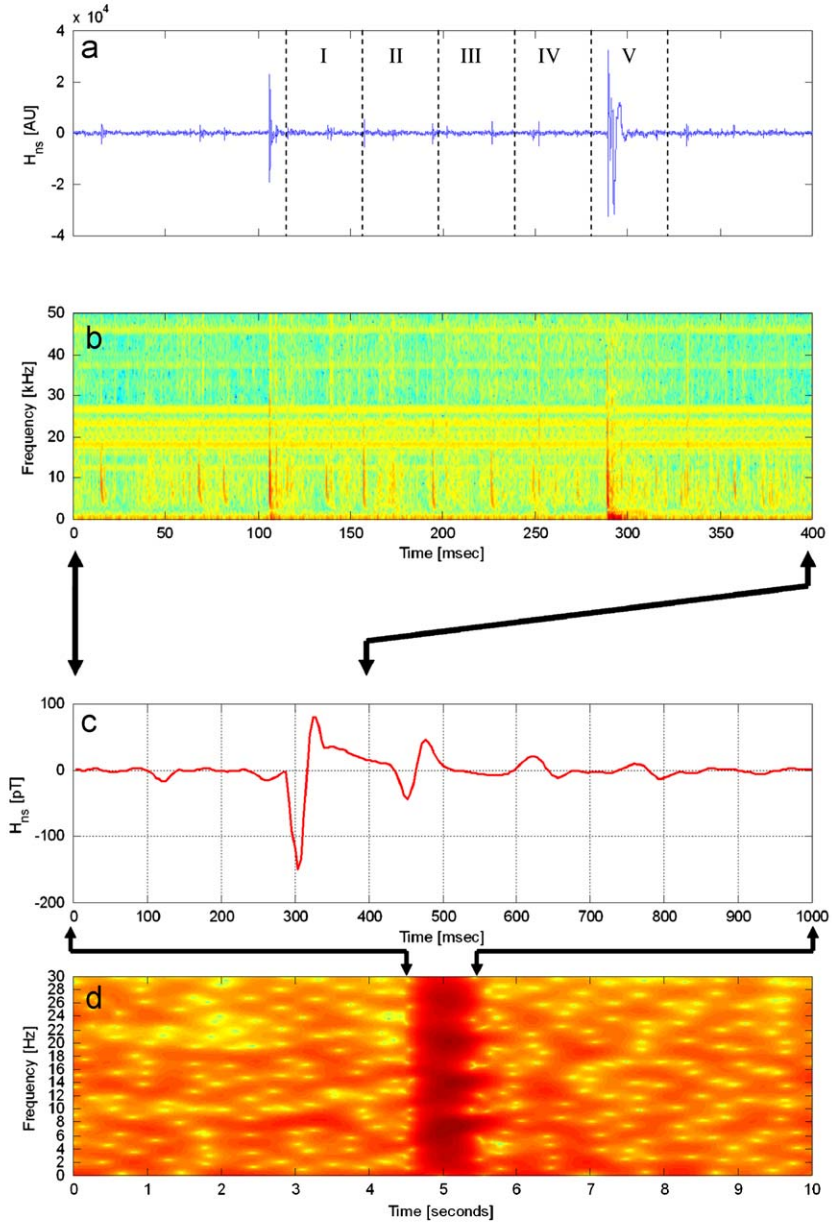


**Fig. 3.** Case study 1: time series and dynamic spectrum of the ELF and VLF signals associated with the groups of sprites as recorded in Israel (MR and SB, respectively), ~3300 km from lightning origin. (a) VLF time series starting at 01:40:50.100 UT; (b) VLF dynamic spectrum starting at 01:40:50.100 UT; (c) ELF time series starting at 01:40:50.100 UT and (d) ELF dynamic spectrum starting at 01:40:45.100 UT.

discharges between sprite brightness using qualitative observation, the ELF and VLF sferic amplitudes, and peak current detected by Météorage. The VLF dynamic spectrum is shown in Fig. 3(b), in which the horizontal lines are the frequencies of the ground-based VLF communications transmitters where HWU has the highest received power shown in the plot.

The vertical lines in the BB VLF bursts are due to atmosferics from lightning discharges, having a spectrum that peaks in the 5–10 kHz range, extending down to a cutoff frequency of ~1.7 kHz. In Fig. 3(c), the $H_{ns}$ field component of the ELF time series is shown for an interval of 1 s starting at 01:40:50.100 UT just as Fig. 3(a) and (b). At $t$~100 ms, the first +CG arrived with a low-amplitude ELF component, while at $t$~300 ms the second +CG arrived with a pronounced ELF transient indicating the existence of long-lasting continuing current with high value of CMC. Fig. 3(d) shows the ELF dynamic spectrum starting 5 s before the sprite occurrences, lasting for 10 s. The eigenfrequencies enhancement of the Earth–ionosphere waveguide can be observed with four initial SR modes at ~8, 14, 20 and 26 Hz (Schumann, 1952). The ELF and VLF transients were received at the observation sites in Israel ~11 ms after they were detected by the Météorage close to their point of origin due to a propagation distance of ~3300 km and, therefore, the dashed lines designating the images of sprites were shifted to be coherent with the time delay of ELF and VLF signals.

### 3.2. *Case study 2—01:28:59 UT, July 29th, 2005*

Fig. 4 shows sequential images of groups of column sprites that were observed on July 29th, 2005 at 01:28:59 UT. These transient luminous events were captured by the narrow FOV camera in three subsequent video frames from 01:28:59.065 to 01:28:59.188 UT. These groups of column sprites were captured by

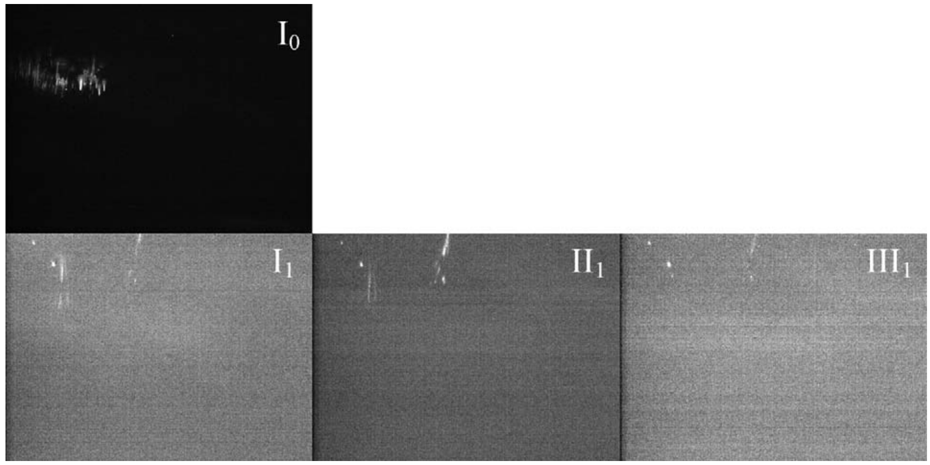


**Fig. 4.** Case study 2: images of groups of column sprites as were observed on July 29th, 2005. (I) 01:28:59.065 UT; (II) 01:28:59.107 UT and (III) 01:28:59.149 UT.

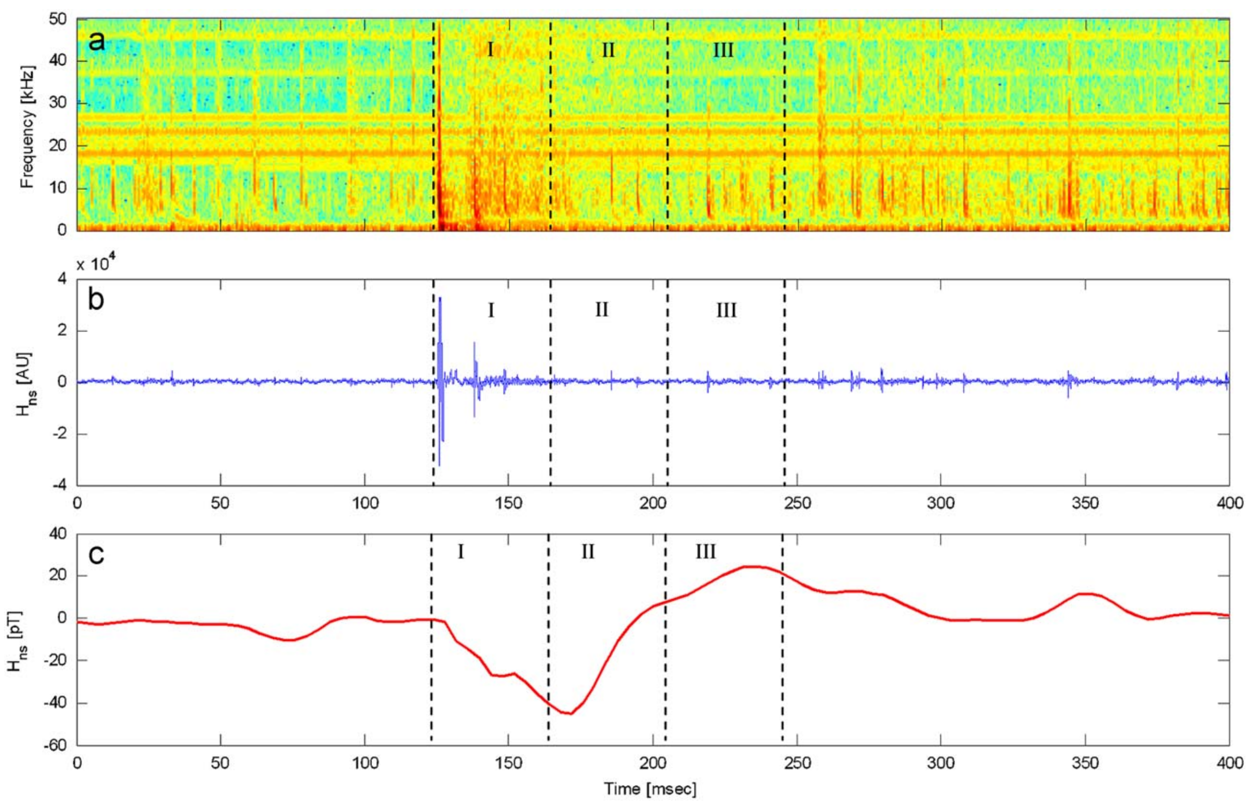


**Fig. 5.** Case study 2: (a) VLF dynamic spectrum, (b) VLF time series and (c) ELF time series associated with the groups of sprites during 400 ms, starting at 01:28:58.950 UT.

the wide FOV camera for only one video frame due to technical problems and, therefore, are absent in Fig. 4. The Météorage network detected two +CGs that occurred at 01:28:59.065 and 01:28:59.077 UT which were associated with this group of sprites, with measured peak currents of +197.4 and +38.7 kA, respectively, at locations separated by about 5 km.

Fig. 5(a)–(c) display the VLF dynamic spectrum, the VLF time series and the ELF time series, respectively, during the time period of 400 ms, starting at 01:28:58.950 UT. The amplitudes of the two intense VLF bursts are correlated with the peak currents reported by the Météorage. A weak pulse train followed the second burst and lasted for ~40 ms, with a spectral component below 20 kHz. The ELF transient for this case study is exceptional by its long continuing current and was associated with the first +CG discharge, with a peak current of +197.4 kA. The ELF signature of the second +CG discharge, which had a peak current of +38.7 kA, could not be resolved, although it may have left a sign at $t \sim 150$ ms. This case study is another example that more than one +CG discharge produced a group of sprites, but only one clear ELF transient detected.

### 3.3. *Case study 3—02:04:10 UT, July 29th, 2005*

Fig. 6 shows sequential images of groups of carrot sprites that were observed on July 29th, 2005 at 02:04:10 UT. The transient luminous events were captured in three subsequent video frames from 02:04:10.224 to 02:04:10.347 UT. The Météorage network

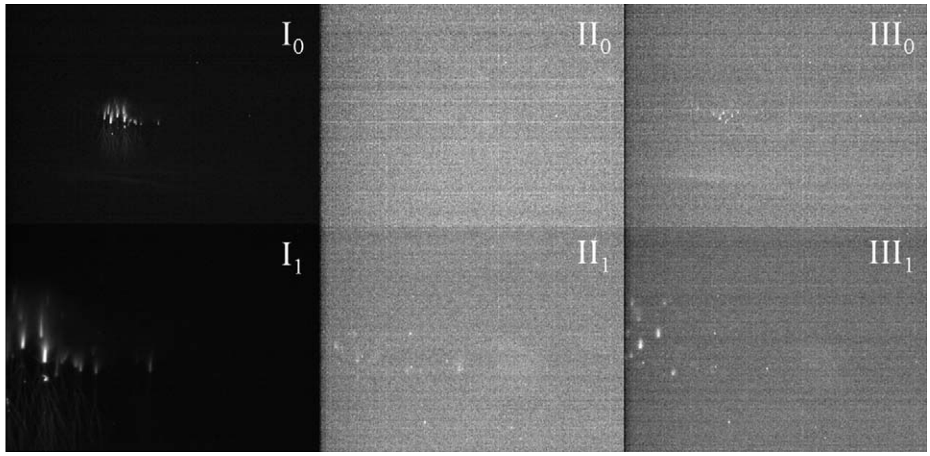


**Fig. 6.** Case study 3: images of groups of carrot sprites as were observed on July 29th, 2005. (I) 02:04:10.224 UT; (II) 02:04:10.266 UT; (III) 02:04:10.308 UT.

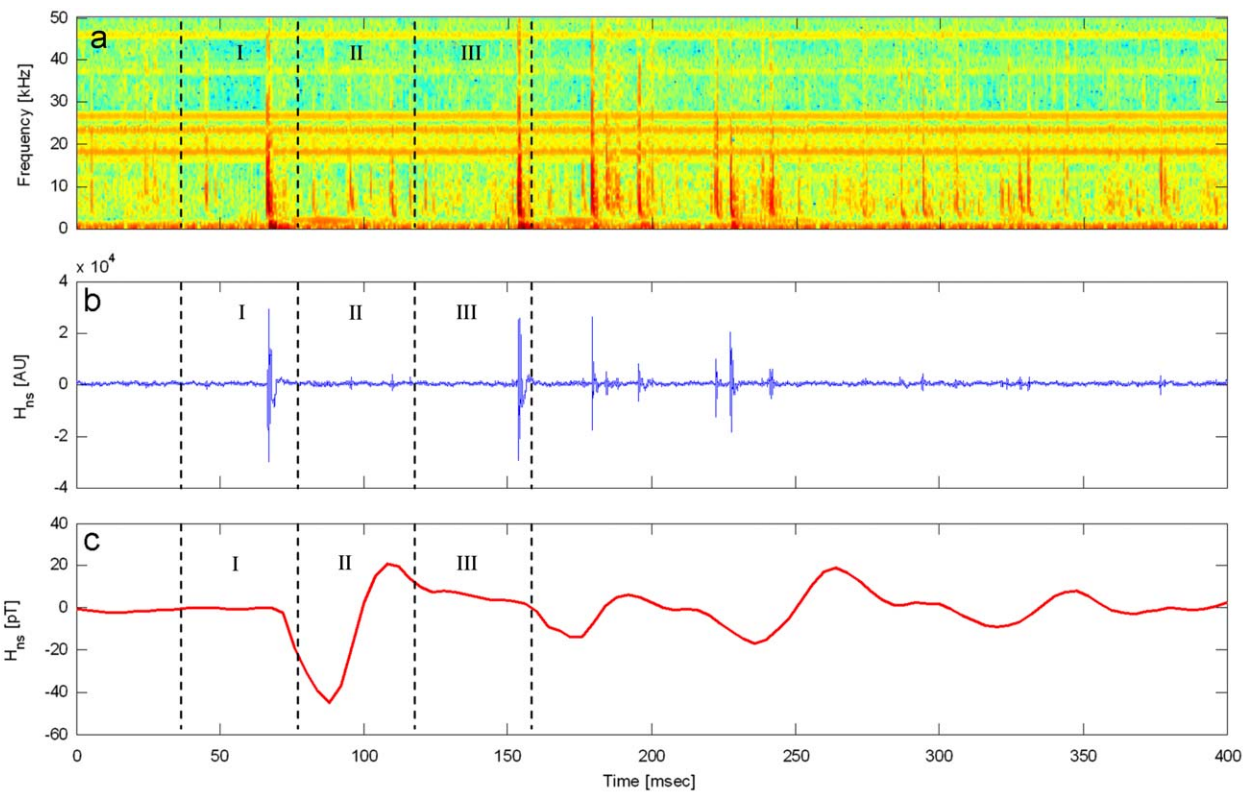


**Fig. 7.** Case study 3: (a) VLF dynamic spectrum, (b) VLF time series and (c) ELF time series associated with the groups of sprites during 400 ms, starting at 02:04:10.200 UT.

detected three +CG discharges that occurred at 02:04:10.255, 10.342 and 10.343 UT with measured peak currents of +99.7, +66.2 and +32.9 kA, respectively, in a thunderstorm cell with a radius of about 20 km. The luminosity of sprites in the first image is strongest compared to the other frames in the sequence. Fig. 7(a)–(c) depict the VLF dynamic spectrum, the VLF time series and the ELF time series, respectively, during the time period of 400 ms, starting at 02:04:10.200 UT. The amplitudes of the three intense VLF bursts are correlated with the peak currents reported by the Météorage. Note that the timing of the first +CG discharge is within the 41 ms of the first frame integration time period, and the second and third +CG discharges are separated by 1 ms and, therefore, cannot be easily distinguished in a time scale of 400 ms. The ELF transient is associated with the first +CG discharge and the signature of slow tail can be identified also in the VLF dynamic spectra, at $t\sim65$ ms. The two later +CG discharges at $t\sim152$ ms also exhibit a slow tail in the VLF dynamic spectra, but its ELF direct wave (from source to observer on the GCP) may have interfered with the antipodal wave of the first +CG discharge (from source to observer on the GCP but in the opposite and long way). Therefore, the second ELF transient at $t\sim152$ ms cannot be distinguished and it is hard to tell whether it is related to the first or to the later two +CG discharges. Such an ELF signature of a sequence of sprites which was associated with a few +CG discharges can lead to inaccuracies in geolocating the parent lightning and evaluating its CMC (and see Section 3.6).

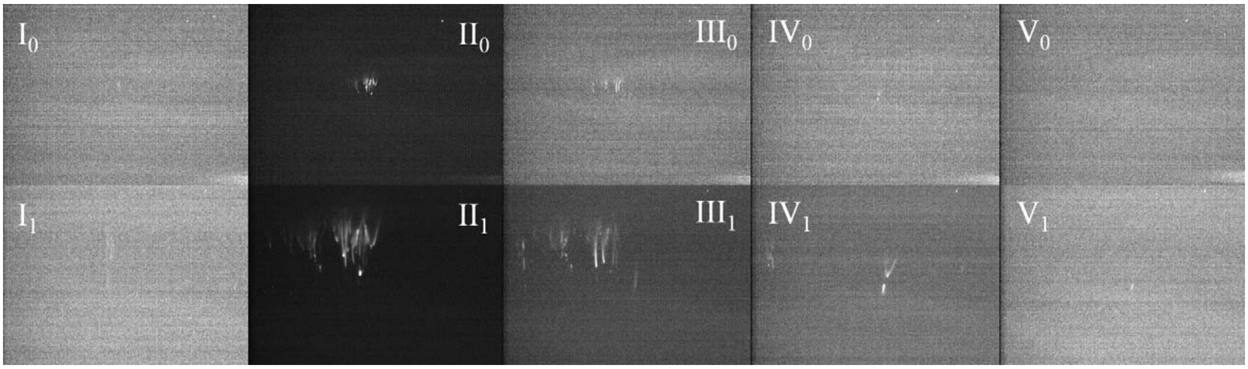


**Fig. 8.** Case study 4: images of groups of column sprites as were observed on July 29th, 2005. (I) 01:36:09.382 UT; (II) 01:36:09.424 UT; (III) 01:36:09.465 UT; (IV) 01:36:09.507 UT and (V) 01:36:09.548 UT.

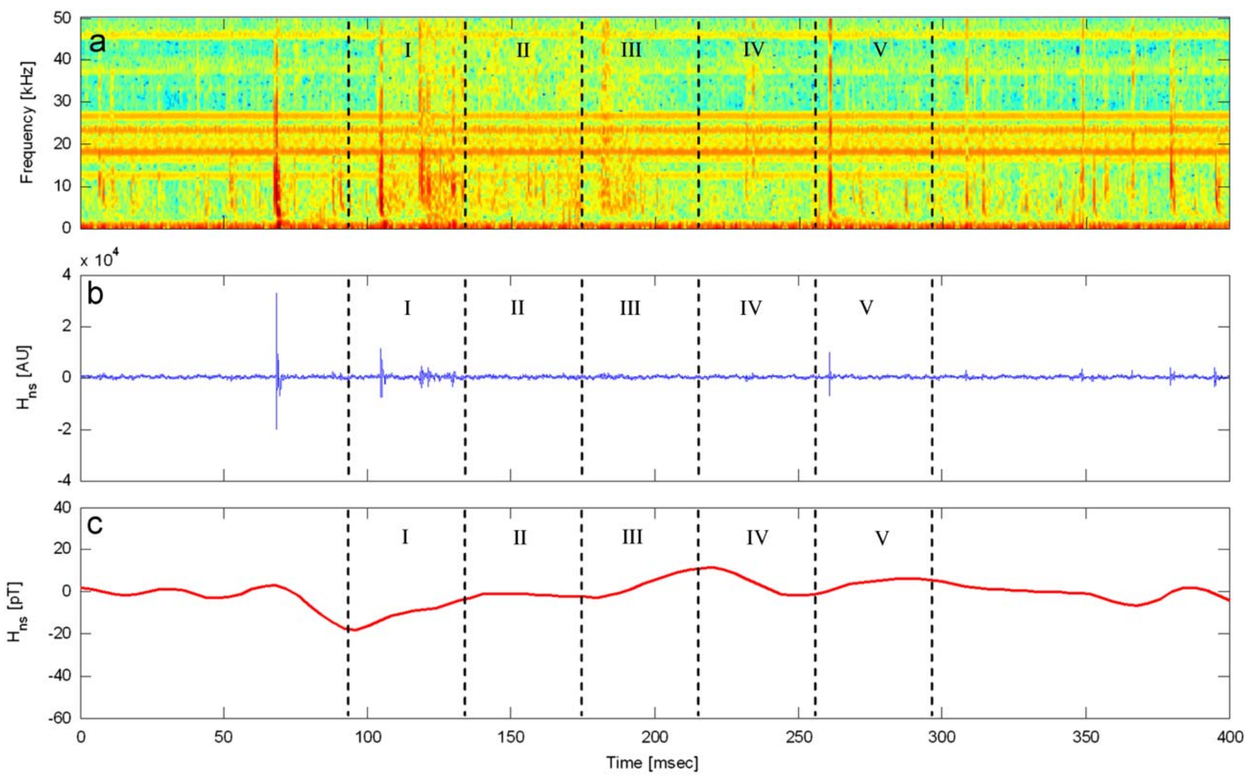


**Fig. 9.** Case study 4: (a) VLF dynamic spectrum, (b) VLF time series and (c) ELF time series associated with the groups of sprites during 400 ms, starting at 01:36:09.300 UT.

### *3.4. Case study 4—01:36:09 UT, July 29th, 2005*

Fig. 8 shows sequential images of groups of column sprites that were observed on July 29th, 2005 at 01:36:09 UT. The transient luminous events were captured in five subsequent video frames from 01:36:09.382 to 01:36:09.589 UT. The Météorage network detected two +CG discharges that occurred at 01:36:09.357 and 01:36:09.393 UT with measured peak currents of +66.7 and +29.4 kA, respectively, at locations separated by about 1 km. The luminosity of the sprites in the second image is the highest among the frames in the entire sequence. Fig. 9(a) and (b) display the VLF dynamic spectrum and the VLF time series, respectively, during a time period of 400 ms, starting at 01:36:09.300 UT.

The ELF time series, which is presented at Fig. 9(c) starts at the same time as the VLF signal and shows no significant transient above the background noise levels produced by the global lightning activity. Evidence for continuing current is also absent in the VLF dynamic spectra lowest frequency region. The amplitudes of the two intense VLF bursts are correlated with the peak currents reported by the Météorage. A weak pulse train arrived after the second burst and lasted for ~20 ms. Note that the luminosity of the first frame is less than the second frame suggesting the group of column sprites imaged in the second frame may have been re-initiated by the second +CG discharge or by the weak pulse train.

### *3.5. Case study 5—01:46:04 UT, July 29th, 2005*

Fig. 10 shows sequential images of groups of column sprites that were observed on July 29th, 2005 at 01:46:04 UT. The transient luminous events were captured in three subsequent video frames from 01:46:04.740 to 01:46:04.865 UT. The Météorage network detected a single +CG that occurred at 01:46:04.739 UT with measured peak current of +63.1 kA. The luminosity of the second image is the most powerful in the

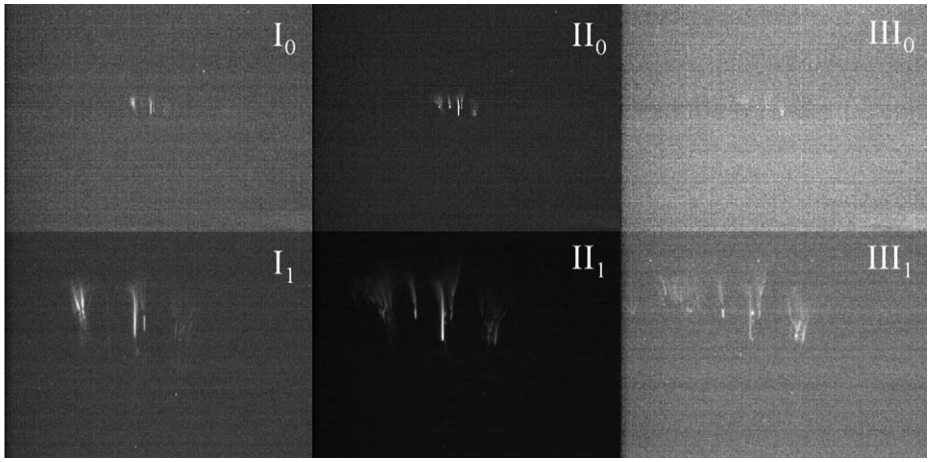


**Fig. 10.** Case study 5: images of groups of column sprites as were observed on July 29th, 2005. (I) 01:46:04.740 UT; (II) 01:46:04.782 UT and (III) 01:46:04.824 UT.

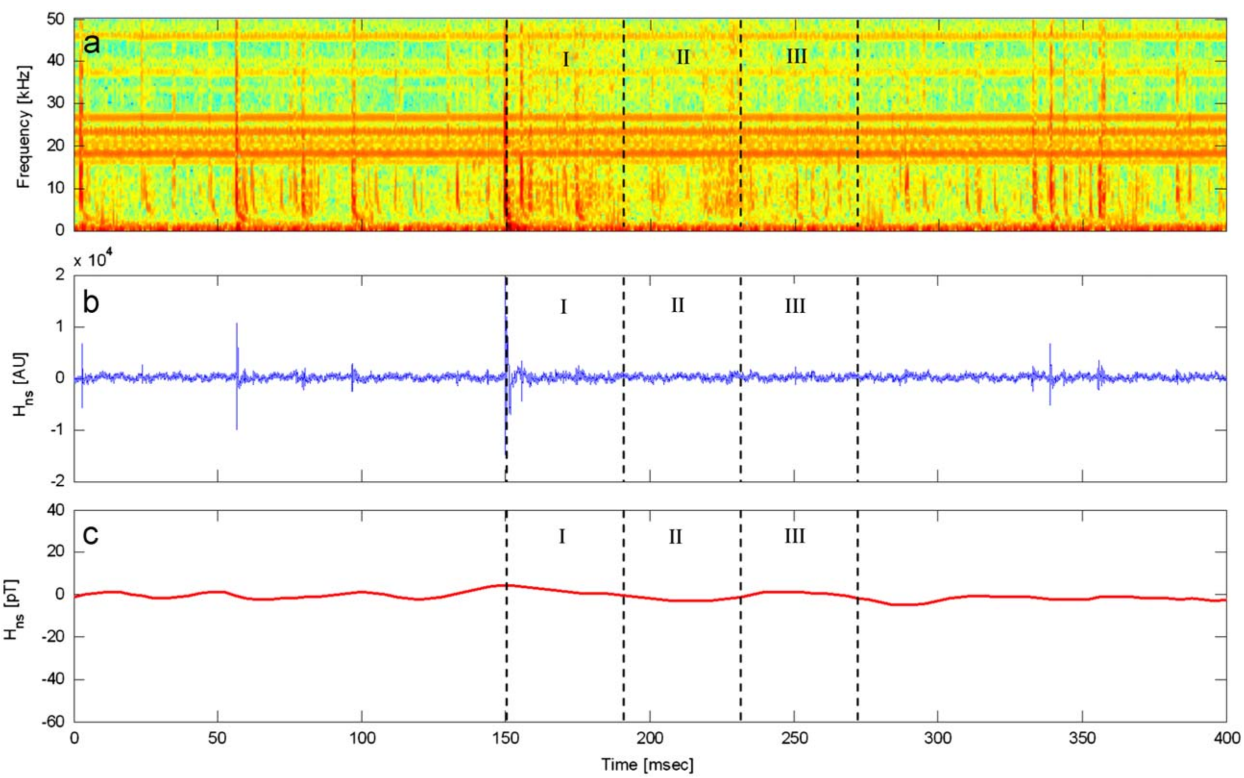


**Fig. 11.** Case study 5: (a) VLF dynamic spectrum, (b) VLF time series and (c) ELF time series associated with the groups of sprites during 400 ms, starting at 01:46:04.600 UT.

sequence of adjacent frames. This pattern may suggest that the QE field induced by the parent +CG intensified gradually on time-scales of the order of tens of milliseconds, supporting sprite propagation at altitudes below ~60 km. Fig. 11(a) and 11(b) display the VLF dynamic spectrum and the VLF time series, respectively, during the time period of 400 ms, starting at 01:46:04.600 UT. In this case, no ELF transient was observed in the time ELF series, see Fig. 11(c). As for case study 4, when no ELF transient was detected, no evidence was found in the VLF dynamic spectra lowest frequency region as well. Among the five case studies presented in this contribution, only in this case study the groups of column sprites were associated with just a single +CG discharge, although this is the more common behavior since nine out 15 sprites analyzed in this current study followed such a pattern.

### 3.6. CMCs, peak currents and VLF perturbations

To calculate the CMC values, we assume that the quasi-transverse electromagnetic mode (q-TEM) is the only mode effectively radiated (radial $E_r$ and horizontal $H_\varphi$) with the normal mode expansion of SR waves (Jones and Kemp, 1970) and by assuming that the lightning current moment in the time domain acts as an exponentially decaying function (Huang et al., 1999; Sato et al., 2003; Greenberg et al., 2007). Fig. 12 shows a simulation of the zonal harmonic series representation of the ELF radio wave for the electric field component (Nickolaenko and Hayakawa, 2002) assuming that the source–observer distance (SOD) is 3000 km. This theoretical spectrum was best fitted to the measurement although the actual SOD is 3300 km (see detailed discussion in Greenberg and Price, 2004).

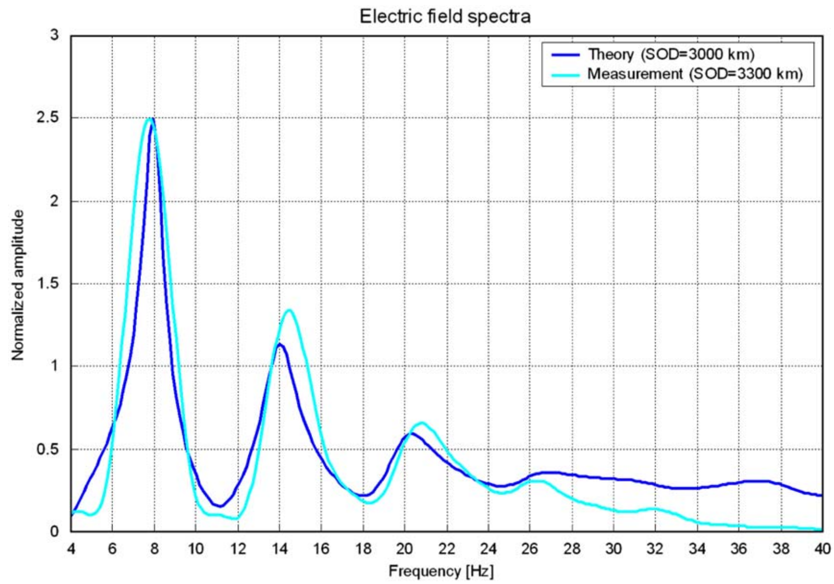


**Fig. 12.** Simulation of the q-TEM mode equations for the electric field component (assuming SOD ~3000 km), and measurement of the signal (actual SOD ~3300 km).

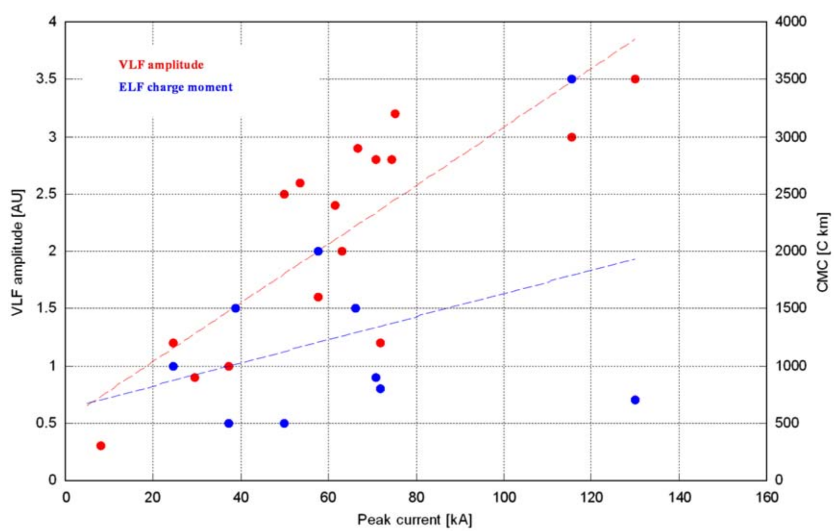


**Fig. 13.** VLF amplitudes (left *y*-axis, 15 data points) and CMCs based on ELF measurements (right *y*-axis, 10 data points) as a function of the peak currents as reported by the Météorage for the 15 sprite-producing lightning discharges. Note: the VLF amplitudes are presented as Arbitrary Units as no exact calibration was preformed at the SB site.

For 10 out of 15 sprites intense ELF transients were detected and its parent lightning CMC was calculated. The CMC of these events ranged from 500 to 3500 C km (mean value and standard deviation is 1250±915 C km). All of these ELF transients arrived from an azimuth of about 315° as deduced from the associated Lissajous figures, and their polarities were positive based on the $E_r$ field component. Note that the minimum CMC which can be evaluated from the data due to local signal-to-noise ratio (SNR) is about 50 C km. As presented in Fig. 3(c), the first ELF event suffers from low SNR and, therefore, the CMC cannot be deduced; however, the value of the second ELF transient was estimated to be 3500 C km. For all 15 sprites, the Météorage network detected a +CG and clear VLF bursts were received at the Sde-Boker VLF antennas. The peak current intensities ranged between 8 and 130 kA (mean value and standard deviation was +65±33 kA), all with positive polarity. Fig. 13 shows the VLF relative amplitudes (left *y*-axis) and CMCs based on ELF measurements (right *y*-axis) as a function of the peak currents as reported by the Météorage for the 15 sprite-producing lightning discharges. The relative amplitudes of the VLF bursts are well correlated with the peak currents ($r$~0.8), while the correlation of the CMCs with the peak currents is poor ($r$~0.4).

In Fig. 14 are presented the NB VLF amplitude data from CR and the ELF data from MR in the time domain, during a period of 45 min from 01:25:00 to 02:10:00 UT, July 29th, 2005. The two upper panels show the amplitude changes of HWU and NAA ground transmitter signals, while the three lower panels show the three ELF field components $H_{ns}$, $H_{ew}$ and $E_r$. During this time period, 10 out of the 15 sprites were imaged, and they are marked with arrows and a serial number according to their occurrence times. Additionally, the peak currents and the CMCs of the parent lightning discharges are also indicated in the figure. A clear abrupt change in the amplitude of the detected signal can be observed for events no. 3, 5, 8, 9 and 11, and most of them were associated with +CGs with significant values of CMCs and peak currents. The most pronounced event is no. 5 (see Fig. 2), which left a clear signature on both HWU- and NAA-CR amplitudes. The luminosity was the strongest by means of visual size and brightness, and its parent

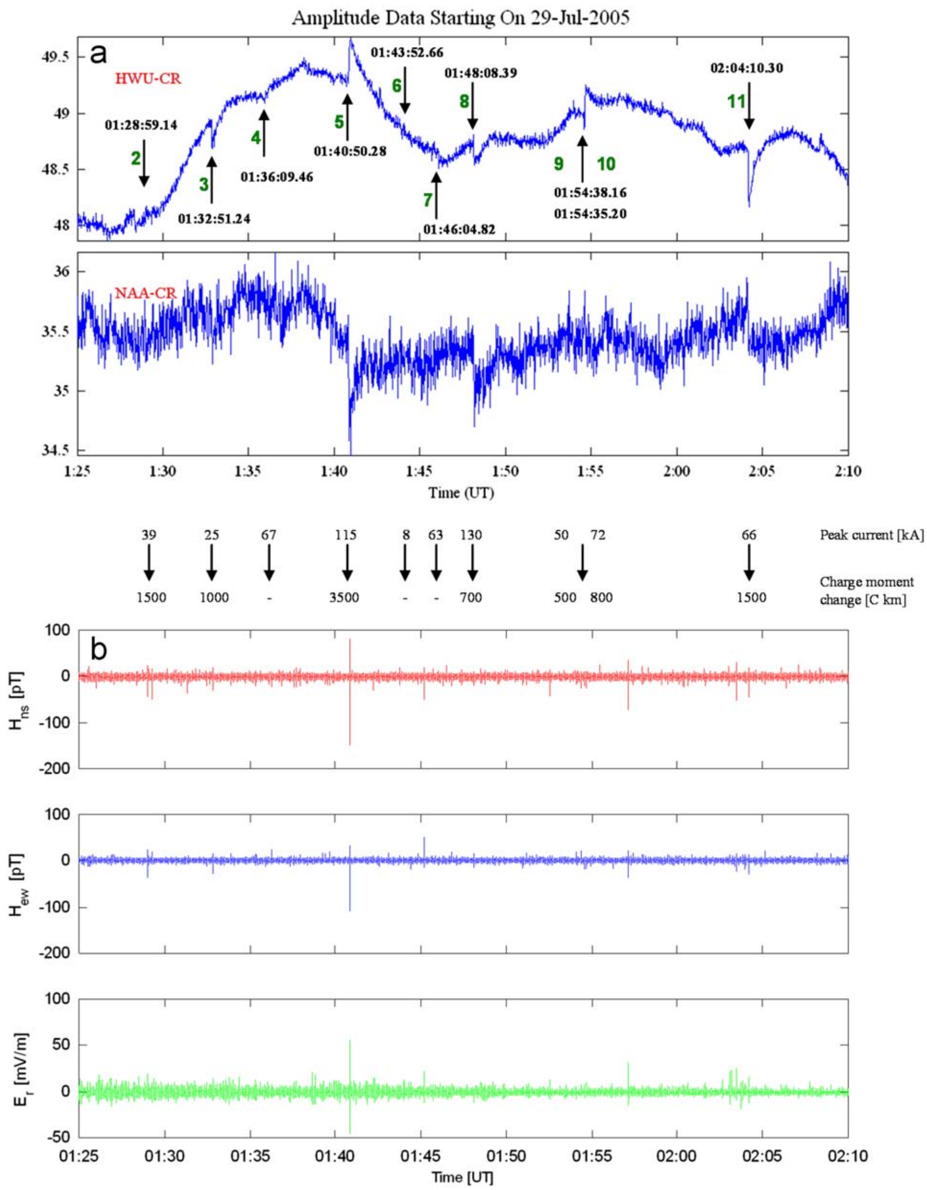


**Fig. 14.** Time series of VLF NB (CR) and ELF (MR) data for 45 min (from 01:25:00 to 02:10:00 UT, 29/07/2005). The arrows indicating the time occurrences of 10 sprites during this time period, and also the peak current and charge moment change values of its parent lightning discharges. (a) VLF NB amplitude changes of HWU (18.3 kHz) and NAA (24.0 kHz) ground station transmitters. (b) ELF field components $H_{ns}$, $H_{ew}$ and $E_r$.

lightning had high values of CMC (3500 C km) and peak current (115 kA). Nevertheless, the correlation between the amount of change in the amplitude and CMC and/or peak current is not consistent. The CMC of events no. 3, 8 and 9 ranges from 500 to 1000 C km which is lower than the CMC of event no. 2 with 1500 C km, while the amplitude change for events no. 3, 8 and 9 is clear but not so for event no. 2 as could be expected. The peak current of events no. 3, 9, and 11 ranged from 25 to 66 kA and a clear change is observed, while events no. 2, 4, and 7 had almost the same values of 39–67 kA but for the last three only very minor onsets can be observed.

## 4. Discussion

As found for sprites produced by MCSs over the US high plains, sprites produced by generally less intense thunderstorms over Southern Europe are also commonly associated with intense +CG discharges which leave their signature in ELF and VLF signals remotely detected in Israel, more than 3000 km from the sprite-producing storms. In the BB VLF time series, an intense burst was clearly observed close to the times of the optical recordings for all of the sprites, and the burst amplitudes were well correlated with the peak currents reported by the Météorage lightning network. The ELF transients were used to compute the CMCs associated with the+CG lightning discharges based on SR methods. Our finding of CMC values of 500 to 3500 C km is comparable with previous reports for sprites produced by MCS over the US high plains. Huang et al. (1999) suggested a CMC criterion of 200–2000 C km for sprite production. Hu et al. (2002) computed that the probability of sprite generation for +CG lightning with CMC greater than 1000 C km in less than 6 ms is more than 90%, while the sprite probability for lightning with CMC less than 600 C km in less than 6 ms is less than 10%. Furthermore, the peak current intensities of $65 \pm 33$ kA are consistent with earlier studies for sprites produced by MCS over the US high plains. São-Sabbas et al. (2003) found an average peak current of 60 kA for sprite-producing lightning discharges, while Bell et al. (1998) suggested that current intensities can span a wide range. The relationship of ELF and VLF data as presented in Fig. 13 shows a poor correlation between the values of peak current intensity and the values of CMC and supports similar results reported by Adachi et al. (2004) for sprites produced over the sea of Japan or the Pacific Ocean, suggesting that the EMP and the QE field play independent roles in the generation of sprites.

Our comprehensive optical and electromagnetic observations revealed that for four sprites two +CG discharges were associated with each sprite and for two sprites three +CG discharges were associated with each sprite. In each of these instances, the sprites lasted for several 10 s of ms in some cases brightening with consecutive strokes. The rest of the nine sprites were associated with a single +CG discharge. This finding implies that lightning discharges that produce sprites can sometimes have multiple ground connections separated in time and space, probably from the same flash. This finding implies that when remotely sensed +CG discharges serve as a proxy, ground lightning networks may overestimate the number of sprites produced in a given thunderstorm.

In a previous study by Greenberg et al. (2007), we investigated ELF transients and estimated CMCs of +CG discharges which were associated with sprites at a comparatively short distance (500 km) observed over the Eastern Mediterranean against a "no sprite" control group of +CG discharges. We have also examined the ELF waveform shapes of the three EM field components ($H_{ns}$, $H_{ew}$ and $E_r$) for 30 sprites that produced a characteristic pattern, compared with dozens of +CGs originating in the same time and space, and we demonstrated that the ELF signature of sprite and non-sprite-producing +CGs (including CMCs) cannot be distinguished from each other. A similar study, but of distant sprites, was reported on EM signals in the ultra low frequency (ULF) band below the first SR mode with the same conclusion (Bösinger et al., 2006). The present research extends previous studies by considering distant sprites produced by thunderstorms over Southern Europe and their electromagnetic signatures in the ELF and VLF bands. In this contribution, we have demonstrated that not all sprites produce ELF transient.

Since the initiation of sprites by the conventional breakdown mechanism requires that a significant amount of charge be removed from a certain altitude (Pasko et al., 1995), not observing an ELF transient implies that this physical process must have occurred on a time scale of ms, since a VLF burst was clearly associated with all imaged sprites. Furthermore, if more than one +CG discharge are associated with the generation of sprites, then their ELF components can interfere with each other and cause significant inaccuracies when fitting SR spectra to evaluate its CMC. These findings suggest that the CMC of a sprite-producing +CG discharge, as deduced from the lower ELF band based on SR methods, cannot be used unambiguously to identify whether a specific +CG discharge can lead to the generation of sprites. This conclusion has a direct impact on methods evaluating the global rate of sprites based on SR measurements and automatic analysis (Sato and Fukunishi, 2003). One should further notice that another possible uncertainly apparently originates from IC activity which can also contribute, along with a +CG discharges, to a large charge removal, and thus to the generation of sizable QE fields in the upper atmosphere which may be strong enough to initiate sprite discharges. The process of charge removal and sprite generation is complex and not sufficiently quantified by the CMC of the causative +CG discharge. This conclusion is supported by models of Asano et al. (2008), suggesting that both the CMC and the current rise time, i.e. the QE and the EMP fields, are important in sprite generation.

In this context, our finding may complement the results reported by Cummer and Lyons (2005) on the basis of 36 sprites imaged in the US high plains in three different storms, where their measurements were consistent with charge moment change being by far the main driver of sprite production. However, the discrepancy can be explained by differences in the estimation technique of the CMC. While Cummer and Lyons (2005) calculated the impulsive CMCs of +CG discharges during the first 2 ms after return stroke onset, our method is based on SR measurements and considers tens of ms with lower sampling rate, and hence might miss the initial fast impulsive spike.

While investigating the BB VLF spectrogram we did not observe sferic clusters, which are characterized by long durations up to 100 ms and higher frequency components after the initial impulsive sferic burst associated with the return stroke, as reported by Johnson and Inan (2000). Therefore, no familiar evidence was found for the generation of sprites by intra-cloud activity as suggested in previous investigations (Adachi et al., 2004; Ohkubo et al., 2005; Haldoupis et al., 2006; van der Velde et al., 2006). This is likely due to the high attenuation rate of sferic clusters with propagation distances (Johnson and Inan, 2000), since clusters are presumably due to weaker horizontal IC discharges. In our case the propagation distance (region of sprites from SB) is ~3300 km, leading to severe attenuation of higher modes during their propagation along the path, so that no high-frequency components around several tens of kHz can be detected at the observing station. A previous study by Haldoupis et al. (2006), where BB VLF data from Crete was compared with BB VLF observations at Nançay, which was located near the sprite-producing thunderstorms, demonstrated that sferic cluster activity was present at Nançay and absent at Crete, because of severe attenuation of the IC lighting EM pulses at large distances, greater than about 500 km from the storm. Still, for some events a weak pulse train was present after the VLF burst which lasted for tens of ms, evident in a spectral band below 20 kHz.

Furthermore, we have investigated the distant ELF and VLF signatures of different types of sprites and found that column and carrot sprites cannot be identified by the ELF or VLF signature of their parent flash alone, as found by van der Velde et al. (2006).

As shown in Fig. 14, sprites affected the amplitudes of the HWU and NAA signals received in Crete by producing early VLF events, caused by the impulsive changes in the electric conductivity of the lower ionosphere, apparently because their GCP to CR were located within 100 km from the sprite-producing +CG lightning discharges (Johnson et al., 1999; Moore et al., 2003; Marshall et al., 2006). No effect was found on the amplitude of other transmitter signals such as NRK (Iceland) and GQD (Great Britain) and NAU (Puerto Rico), for which the sprite-producing CGs are located hundreds of km away from its GCP links to CR (Haldoupis et al., 2004; Mika et al., 2006). Furthermore, the correlation between the VLF perturbation amplitude and the CMC and/or the +CG peak current was not conclusive. We suggest that this is due to the presence of other factors in addition to the properties of the lightning discharges which may play a role in determining the strength of early VLF perturbations, such as interference of the direct and scattered waves that add constructively or destructively at the receiver, depending on their phase difference (Dowden et al. 1996; Johnson et al., 1999). Although Hobara et al. (2001) found a positive correlation between the magnitudes of the ionospheric disturbances and the charge transfer, they noted that this relation is sensitive to the ionospheric condition.

## 5. Conclusions

In this paper, we applied coordinated optical and distant electromagnetic observations to investigate the characteristics of sprite-inducing lightning discharges during thunderstorms activity over Southern Europe, a new region of sprite observation, and compare its related parameters with sprites produced by much more intense MCSs over the US high plains and other sprite observation regions (the Sea of Japan, the Pacific Ocean and the Eastern Mediterranean). A few case studies presented in this contribution demonstrated the variety of electromagnetic signals prior to, and in the course of, the luminous life time of groups of column and carrot sprites. The use of simultaneous measurements made in both the ELF and VLF bands allow a more thorough investigation and detailed characterization of the electromagnetic radiation produced by sprite-causative +CG lightning discharges and their effects on the upper atmosphere and lower ionosphere.

More than one +CG was associated with six out of 15 imaged sprites, implying that lightning discharges that produce sprites may sometimes have multiple ground connections separated in time and space (a few tens of ms and a few km, respectively). Therefore, to evaluate the rate of sprites produced by lightning activity originating from a specific thunderstorm by remote sensing the VLF radiation it produced, one should consider that sometimes more than one +CG discharge can be associated with sprite occurrence, and hence the number of VLF burst counts may overestimate the number of sprites.

We have also found that an ELF transient was associated with sprite occurrence only for 10 out of 15 transient luminous events, suggesting that long continuing current of tens of ms may not always be necessary for sprite production. Ground-base single station SR measurements are potentially a valuable tool to estimate the global rate of sprite due to the low attenuation rates of ELF waves and their ability to propagate over thousands and tens of thousands of km. During continuous ELF measurements of SR transients for geolocating and estimating their CMCs to evaluate the global sprite rate, one should consider two effects with opposite impacts: (1) ELF transients produced by lightning flashes with large CMC values which were or were not associated with sprites are indistinguishable, a fact that may lead to an overestimation of the global rate of sprite. (2) Not all sprites are associated with intense ELF signature, which may lead to an underestimation of the global rate of sprite. Furthermore, if relatively long-lived sprites are initiated by a group of +CG discharges then their ELF components can interfere and cause inaccuracies when fitting the SR spectra. The analysis presented in this contribution demonstrates the complexities of the ELF and VLF signatures associated with sprite events and shows the difficulties in basing global estimates of sprite rates solely on ELF and VLF observations, at least on the level of our current understanding.

We found that the values of CMCs and peak currents of the +CG discharges which were associated with the imaged groups of sprites are in agreement with previous reports for sprites produced by MCSs over the US high plains. The same is true for the time duration of sprites (number of frames) and time delays between sprites and their causative +CG discharges. Those results imply that the intensity of a thunderstorm may define the number of sprites it can generate, but the criteria for production of a specific sprite is almost the same no matter the intensity of the parent thunderstorm.

Furthermore, a good correlation ($r\sim0.8$) was found between BB VLF signal amplitudes and lightning peak currents, while comparison between CMCs and peak currents revealed poor correlation ($r\sim0.4$). Similar results were observed by Adachi et al. (2004) for sprites produced over the Sea of Japan and the Pacific Ocean. The weather systems that produced sprites over Southern Europe during the summer and over the sea Japan during the winter are of the same order of size in their horizontal and vertical extent (and smaller in size compared to the most prolific sprite-producing summer continental MCSs and equatorial tropical storms). Nevertheless, in both weather systems the EMP and the QE field play independent roles in the generation of sprites.

No direct evidence for intra-cloud activity was found, because high-frequency components are damped with distance after traveling within the earth–ionosphere waveguide, although for some events weak pulse trains were observed after the main VLF sferic which lasted for tens of ms with spectral components below 20 kHz. Another finding is that in sprite images, the first frame in a sequence of adjacent frames may not always be the brightest one (as in case studies 4 and 5; see Figs. 8 and 10), and generally good correlation was found between the peak currents of the parent lightning and sprite luminosities. Additionally, no correlation was found between the magnitudes of VLF subionospheric perturbations as deduced from NB data with values of CMC. Finally, we found that column and carrot sprites cannot be identified by the ELF or VLF signature of their parent flash alone, at least not at ranges to the source of several thousand km, as preformed in the present study.

To reinforce these conclusions and achieve a better understanding of the electrodynamic coupling processes between the lower and upper atmospheric layers, the present data set will be enlarged due to more *EuroSprite* campaigns currently under way and planned in the future.

## Acknowledgments

This research was partially supported by the Israel Science Foundation Grant #145/03, and the Tel-Aviv University Research Fund. We would like to thank the Wise Observatory in Mitzpe Ramon, and the Solar Energy Research Center at Sde Boker, for allowing us to use their facilities for the ELF and VLF measurements. We are grateful to Umran Inan of Stanford University for providing the Crete VLF receiver, and for his continuous support. The *Eurosprite2005* campaign was conducted by the CAL research training network sponsored by the European Commission under the Contract HPRN-CT-2002-00216. The authors thank all the CAL members involved in the optical observations, and the Météorage Company for providing the lightning data.

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