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Is there a unique signature in the ULF response to sprite-associated lightning flashes?

Tilmann Bösinger,[1] Ágnes Mika,[2] Sergei L. Shalimov,[3] Christos Haldoupis,[2] and Torsten Neubert[4]

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[1] Using observations made by the Finnish chain of pulsation magnetometers, we select typical properties of the ULF response to sprite-associated lightning events taken from the EuroSprite 2003 summer campaign. We concentrate on frequencies below the Schumann resonance and compare the obtained results with properties obtained from positive cloud-to-ground lightning discharges which are not associated with sprites. The latter we take from listings of the Météorage Lightning Detection Network, which correlate with strong impulsive events seen in the Finnish chain. The evidence shows no unique and identifiable ULF signature relating to the sprite causative discharges.

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1. Introduction

[2] The first investigations on transient luminous events (TLE) started only about 15 years ago [see, e.g., *Sentman and Wescott*, 1993; *Wescott et al.*, 1995; *Fukunishi et al.*, 1996]. The most spectacular among TLEs are sprites with their large luminous body above an active thunderstorm, developing vertically upward between 40 and 80 km in a gas discharge-like fashion, lasting from several milliseconds to a few tens of milliseconds (e.g., see review by *Rowland* [1998]). Although sprites seem to occur in association with positive cloud-to-ground (+CG) lightning discharges [*Sentman et al.*, 1995; *Lyons*, 2001], very few of these lead to sprites; thus the exact nature of this relation and the characteristics of the sprite-causative +CG discharges are not well known and understood.

[3] The present paper makes an effort to identify if a characteristic property of the sprite-related +CG discharges is inherently present in the ULF band of the impulsive electromagnetic signals radiated from the lightning channels into the Earth-ionosphere waveguide. Our attention here is directed only to background EM noise frequencies below 10 Hz and the main interest is even below the first Schumann resonance (SR) at 7.8 Hz. The 25 ms time resolution of our experiment does not allow to investigate short timescale changes of milliseconds which could originate in the sprite discharges themselves as suggested by previous ELF [*Cummer et al.*, 1998] and ULF [*Cummer and Füllekrug*, 2001] studies. Instead, we focus on timescales larger than a few hundreds of milliseconds which are attributable to slowly varying (continuing) currents following the impulsive and dynamic +CG return strokes. Regarding the much more populous but weaker −CG flashes, recent theoretical results by *Surkov et al.* [2005] show that below 10 Hz they produce only a negligible magnetic noise background, not even strong enough to excite the ionospheric Alfvén resonator [*Belyaev et al.*, 1990]). Interestingly, and as a byproduct of the present study, we have confirmed the theoretical estimates of *Surkov et al.* [2005] rather nicely.

[4] Here we investigate longer timescale ULF variations related to sprites, but we are not the first to address this topic. Motivated by theoretical estimates carried out by *Sukhorukov et al.* [1996] and *Sukhorukov and Stubbe* [1997], the authors *Fukunishi et al.* [1997] and *Füllekrug et al.* [1998] have attempted to show that sprite-related +CG discharges can excite the ionospheric Alfvén resonator. This automatically implies time constants of some seconds, demonstrating that sprite-causative CG discharges could initiate processes characterized by much longer time constants than milliseconds. A possible VLF equivalent of this kind are the abrupt perturbations, referred often as "early/fast" events, detected on VLF transmissions with great circle paths passing over, or nearby, an active thunderstorm (e.g., see review by *Rodger* [2003]). Early/fast events occur infrequently right after a short-lived sferic (∼1 ms) and have short onset durations (<20 ms) followed by long recoveries ranging from 10 to more than 100 s [e.g., see *Inan et al.*, 1993]. Moreover, recent findings of *Haldoupis et al.* [2004] and *Mika et al.* [2005] obtained from EuroSprite 2003 observations show (1) a one-to-one relationship between sprites and early/fast, (2) the presence at times of "early/slow" events with onset durations lasting up to about a couple of seconds, and (3) the frequent presence of long delayed sprites (by 100 to 300 ms) relative to the preceding causative +CG discharges. These results, which implied sprite-related VLF signatures with relatively large time constants, motivated our present study in a search for similar responses at ULF.

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[1] Department of Physical Sciences, University of Oulu, Oulu, Finland.
[2] Department of Physics, University of Crete, Crete, Greece.
[3] Institute of Physics of the Earth, Moscow, Russia.
[4] Danish National Space Center, Copenhagen, Denmark.

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[5] The +CG precondition for sprites led us to investigate the ULF response to +CG lightning as such, irrespective of sprite association. In this direction there exist previous research studies under the headline of transient Schumann resonance or "Q-bursts" [e.g., see *Füllekrug and Fraser-Smith*, 1996; *Füllekrug et al.*, 1996; *Füllekrug and Reising*, 1998]. The term Q-burst was created as a label for large Schumann resonance bursts (transients) which exceed the usual magnetic background noise to such an extent that they can be treated as single, individual magnetic response signatures to exceptionally intense lightning discharges. According to the pioneering work of *Boccippio et al.* [1995], the large +CG discharges which are associate with red sprites tend to produce Q-bursts. More recently, *Sato and Fukunishi* [2003] have applied such inferences of Q-burst SR transients to obtain through triangulation estimates of global sprite occurrence location and rates.

[6] However, is there enough evidence to suggest that Q-bursts are indeed ULF sprite signatures? In other words, is there a unique ULF magnetic fingerprint of a sprite? The present study aims at providing an answer to these questions. For this purpose we use ULF magnetic noise measurements made with a sensitive search coil magnetometer in South Finland during sprite-producing storms in France which have been monitored during the EuroSprite 2003 summer campaign. To carry out this objective, we had to separate sprite associated +CGs from those not associated with sprites. The METEORAGE data of the French Lightning Detection Network in connection with the sprite images made with a camera operating at the Observatoire Pic du Midi in the French Pyrenees enable us to do this task and to prove that contrary to what has been believed so far, there is no specific ULF signature unique to sprite-associated +CG lightning.

2. Observations

2.1. Data Sets and Methodology

[7] The Finnish chain of pulsation magnetometers (http://spaceweb.oulu.fi/projects/pulsations/) has been operating on a continuous basis since the early seventies. At present it consists of six stations distributed along a geographic meridian ($\lambda \sim 25°$) covering an L-value range from 3.3 to 6.6. The instruments are of a search-coil type; thus measurements are made of the time derivative of the changing magnetic field in a frequency range from several mHz to 10 Hz. Data are recorded with a resolution of 16 bits for all three orthogonal components (magnetically northward, eastward, and downward). Thanks to a GPS clock the absolute time accuracy of single data points is better than ±5 ms. The sampling frequency is 40 Hz corresponding to samples every 25 ms. In this study, data from only the southernmost station Nurmijärvi (NUR, ϕ = 60.5°N and λ = 24.7°E) is used. Most recent quick-look summary spectra of the Finnish chain of pulsation magnetometers are available via http://www.sgo.fi/Data/Pulsation/latestPulsation.php. The average distance over a great circle from NUR to the thunderstorm centers under investigation was about 2000 km.

[8] The EuroSprite 2003 campaign, which has been funded by the European Union CAL project, resulted in a list of some hundred well-documented sprite events over central France, categorized by their optical images and the time and coordinates of the causative positive cloud-to-ground lightning flash (+CG) as well as its peak current intensity. This list, whose first five sprite events are shown as an example in Table 1, formed the most valuable information desk in our search for ULF response to sprites. For more details on EuroSprite 2003, see the Web page of the CAL project (http://www.dsri.dk/cal/) and an overview on the campaign and key results published by *Neubert et al.* [2005].

[9] Another list of lightning events of equal importance for our investigation is provided by the French Lightning Detection network "Météorage" which is designed to effectively detect cloud to ground lightning over the whole French territory. By cooperation with the neighboring countries Italy and Spain, "Météorage" sets up an extended network that covers the southwestern Europe and the western Mediterranean Sea. From the original "Météorage" list a refined one was created including only those +CG and −CG events which stem from the same thunderstorm centers which are optically envisaged by the CAL cameras and form the base for the CAL list of sprite-associated +CG events. Thus the CAL sprite list is already a composite of sprite detection by optical means and lightning detection by triangulation of radio waves (VHF). For details of the "Météorage" network, see its Web page (http://www.meteorage.com).

[10] Both lists put us in a unique position. We are able to effectively differentiate between those +CG events which are followed by a sprite and those which are not. This procedure implies a time window defining what is considered as the causative +CG of a sprite and what is not. This does not come without some arbitrariness. For example, sprites can sometimes be delayed with respect to their initiating cloud-to-ground lightning flashes by up to 400 ms [*Mika et al.*, 2005]; however, these are exceptions. In our statistical findings, exceptional behavior should not falsify traits of the average.

[11] With this input information we have adopted a simple and straightforward methodology: General properties of the ULF response to sprite-associated lightning flashes are collected and analyzed. These properties are then compared with the properties of a control group. This consists of those +CGs which are not associated with a sprite. The question is then whether the properties of both classes are alike or differ in one or another aspect.

2.2. Event Selection

[12] Not all sprite-associated +CG lightning flashes of the CAL list (cf. Table 1) were equally suitable for our purpose. For the extraction of typical properties of the ULF response "clean events" are needed. This means first "a good timing" and second an "isolated event." Global thunderstorm activity implies 100 lightnings per second, on average. In general one deals therefore with a superposition of several responses at a time when looking at ULF data. The main background magnetic noise in the ULF frequency range is in fact caused by world-wide thunderstorm activity. Its best witness is the Schumann resonance. Note that we are looking at frequencies just below its fundamental frequency of 7.8 Hz. An "isolated event" implies that the ULF response of a single lightning happens to be so intense

Table 1. First Five Lines of a Composite Listing of Sprite Observations and Causative +CG Lightning Built By Integrating Data From the French Lightning Detection Network "Météorage" Into the Optical Records[a]

Symbol	Sprite Time	Comment	+CG Time	Delay	Current	Lat	Log	Distance
S1plus	0205:14.680	no tendrils	0205:14.668	12	82.5	45.7	2.8447	380.9
S2	0207:59.920	clouds	0207:59.912	8	56.5	45.8298	2.2901	369.8
S3	0209:20.080		0209:20.153	−73	46	45.7318	3.2764	404.5
S4	0211:51.800		0211:51.718	82	57.6	45.5929	2.4438	353.4
S5plus	0217:00.880	beauty	0217:00.880	0	111.3	45.9801	2.5017	392.4

[a] The list of more than 100 sprites covers almost the entire period of the EuroSprite 2003 summer campaign from 21 July to 25 August. Times are given in UT, the time delay between causative +CG and the sprite are given in milliseconds, return current peak intensity is given in kA, the geographic coordinates are given in degree, and the distance between the +CG and the camera on top of Pic du Midi is given in kilometers. For details see text.

that it overrules by far the average background. These relatively rare occasions have been called in the context of Schumann resonance transients "Q-bursts." It is already an important observational result of our study that all sprite-associated +CG lightning flashes of the CAL list produced very large ULF signatures in our recording at NUR so that most of them could be addressed as Q-bursts. As an example for our event selection, we show in Figure 1 a "clean" event. It happens to be the first event (referred to as S1; S standing for sprite) in the CAL list (cf. Table 1).

[13] Already the second event of the list (S2) shown in Figure 2 does not meet the criteria of an "isolated event." Clearly, event S2 follows an earlier impulsive event in fast succession so that its waveform is a superposition of the wake of the foregoing impulse and its own signature.

[14] From all 96 events in the CAL list we identified and selected 36 events which were sufficiently "clean" and "isolated," yielding a subset referred to below as S-plus events (S stands for sprite and "plus" as a quality stick) in contrast to all sprite events in the CAL list later referred to as S-events. We will make use of both sets. Note that the CAL list has been updated several times and its latest version includes some 140 sprites. The increase in number of events is to be understood that multiple +CG flashes were now counted separately. In our selection of isolated events, multiple flashes are in any case kicked out if they can be distinguished in the ULF data, so we stick to the first list issued.

3. Basic Types of ULF Response to Sprite-Associated Lightning

[15] A survey on the existing data reveals two basic types of ULF response; one (type I) is a single, unipolar deflection from the background level, a simple peak, so to speak, and the other (type II) is again a simple peak, however, with a subsequent asymptotic decay from the peak level over timescales of several peak widths. As a frequent variation of these basic types the unipolar peaks are followed by an enhanced oscillation. Below, first an example of each type is shown and then a superposed epoch analysis is made to have more ground for differentiating between the two "basic types," type I and II.

3.1. Individual Events

[16] An unstructured, simple, unipolar peak in the magnetic field registration at NUR was found in response to a +CG detected by Météorage, and 99 ms later followed by a sprite observation. Figure 3 shows the time series of the two magnetic field components around this time. The data has been corrected for the frequency and time response of the instruments and the coordinate system rotated such that the response maximizes (in absolute terms) in one component (H-component). This is achieved by rotating the horizontal H-D plane of the cartesian coordinate system (H, D, Z) around its vertical Z-axis by a suitable amount. In doing so the anticlockwise rotated, negative abscissa of the coordinate system (D-component) points into the direction of the source (+CG), as should be the case for a TM-mode. The oscillations, mainly in the D-component, are primarily Schumann resonances with some contributions possibly from the ionospheric Alfvén resonator (harmonic structure in the spectrum; not shown) overhead the station. The peak width of 100 to 200 ms is of the order of the impulse response length of the magnetometer. Note that the sprite time given in the title of the figure is only known within one video frame of the camera (40 ms), in fact for 21 July the frame integration time was 40 ms, while for all the other days it was 20 ms.

[17] A simple, unipolar peak in the magnetic field registration at NUR was also found in response to a +CG followed by the sprite S22plus but this time there was a

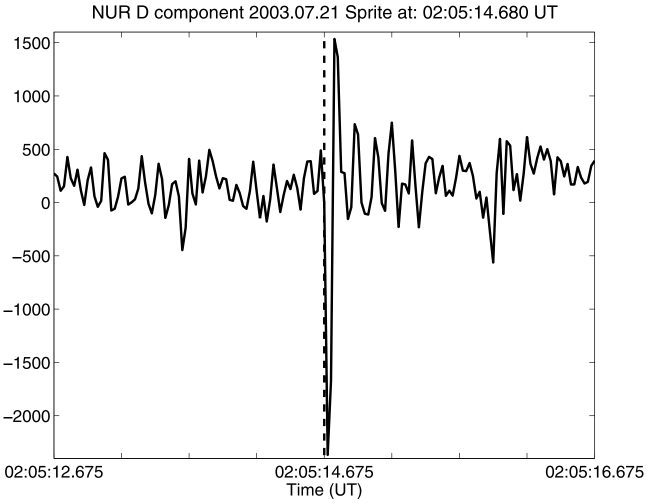

Figure 1. Time series of 4 s of registrations made at NUR around the time of the 1st sprite event detected during the EuroSprite 2003 campaign. The dashed vertical line indicates the time of the +CG lightning causing the sprite. The time difference between flash and sprite was 12 ms and is hardly discernable on this timescale.

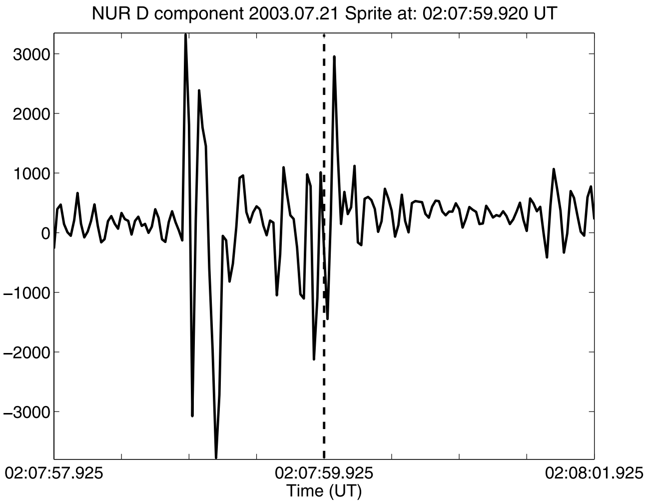

Figure 2. The same type of display as in Figure 1 but for the second event in the CAL list (cf. Table 1) of sprite-associated positive cloud-to-ground lightning flashes.

gradual decay from the peak value back to the background lasting almost one second as shown in Figure 4. Data handling and presentation follow the same procedures as for Figure 3. As stated above, the rotation angle is determined as the angle for which the ULF response in the rotated D-component is smallest (deepest minimum in the H-component). In the following the decay from the peak value back to the background will be referred to as the "fast tail" of the response. With the decay time of 0.3 to 1.0 s it is "fast" in comparison to the "ultra slow tail" with a timescale of 3 to 6 s addressed later. The fact that there is still a small impulsive deflection left in the D-component (cf. Figure 4) tells that the response is not entirely linearly polarized (as in the case of a pure TM mode). It indicates a coupling between TM and TE modes as is expected in the Earth-ionosphere wave guide with horizontal conductivity gradients at its boundaries (Earth's crust and/or ionosphere; cf. *Füllekrug and Sukhorukov* [1999]).

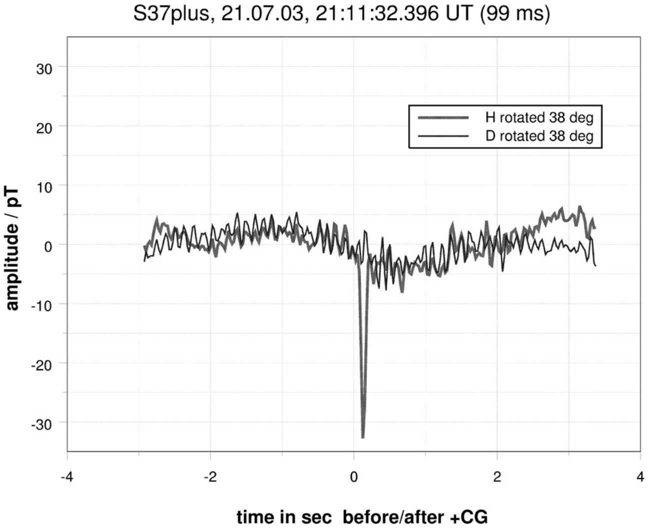

Figure 3. Perturbations of the magnetic field at the station NUR (60.5° north and 24.7° east) around the time of a +CG lightning flash in southern France (44.5982° north and 3.8661° east) with a primary discharge current of 60.4 kA. The headline gives the running number of the sprite (S37), qualifies it as a "clean" and "isolated" event (plus), gives the time of the sprite (2111:32.396 UT) and how much the sprite was delayed with respect to the +CG (99 ms). Owing to the discreteness of the data the zero time in the plot corresponds to 22 ms before the actual +CG time, thus the sprite occurred 99 + 22 ms after the zero on the time axis of the plot. For details see text.

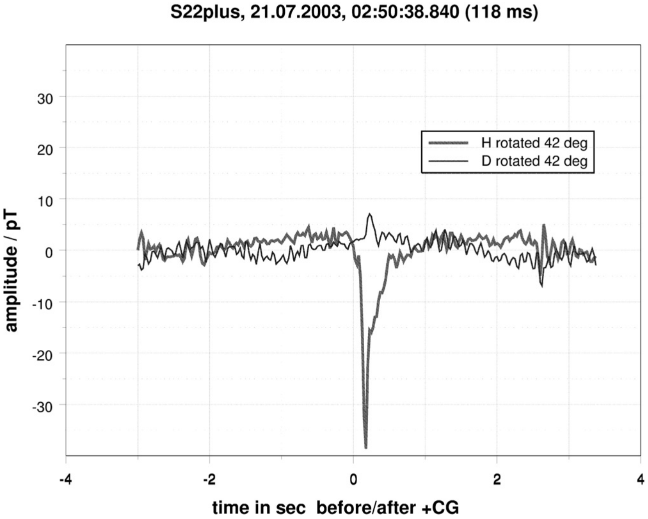

Figure 4. The same as Figure 3 but for sprite S22plus on 21 July 2003. The corresponding parameters are NUR, +CG (45.6041°N, 3.3416°E), current 25.9 kA, delay 118 ms, sprite occurred 118 + 22 ms after the zero on the time axis of the plot. For details see text.

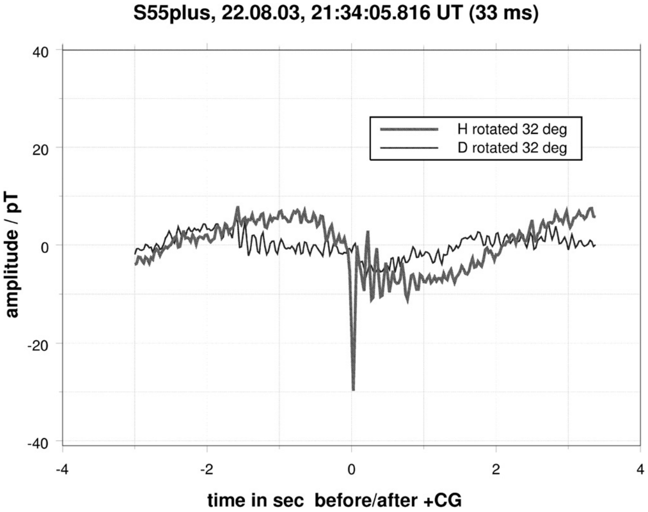

Figure 5. The same as Figure 3 but for sprite S55plus on 22 August 2003. The corresponding parameters are NUR, +CG (39.6649°N, −0.7869°E), current 56.6 kA, delay 33 ms, sprite occurred 33 + 8 ms after the zero on the time axis of the plot. For details see text.

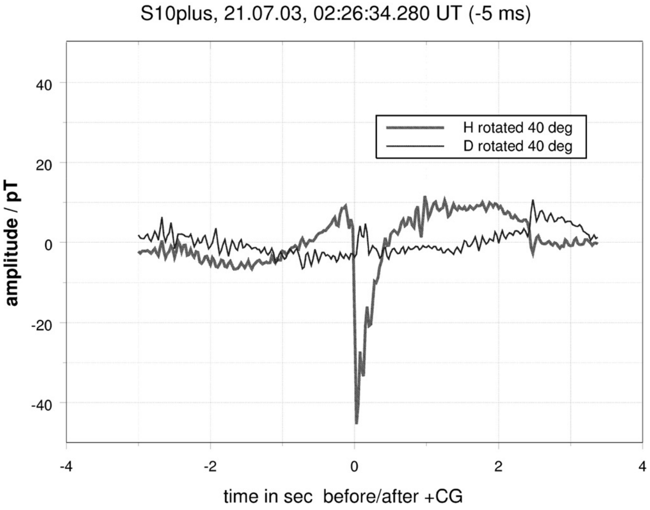

Figure 6. The same as Figure 5 but for sprite S10plus on 21 July 2003. The corresponding parameters are NUR, +CG (46.1675°N, 3.6957°E), 51.9 kA, delay −5 ms, sprite occurred −5 + 10 ms after the zero on the time axis of the plot. For details see text.

[18] In the statistical analysis of the next chapter it will be shown that the oscillations on top of the primary ULF response peak and thereafter (and in the background) will more or less average out. However, in order not to give an impression that the +CG could not trigger subsequent large oscillations, in the next two figures an example of this phenomenon is shown for ULF response types I and II.

[19] Let us turn to Figure 5. The subsequent oscillation after the primary pulse is a Schumann resonance transient. It is interesting that it is so strong although the fundamental Schumann resonance should have a zero (node) in the magnetic field close to the source. The answer most likely can be found in the position of the terminator with respect to the observation point (NUR) since the electromagnetic wave transmitted by the lightning experiences in the Earth ionospheric wave guide a partial reflection at the terminator. Note that the observation of Figure 3 was in late July (solar zenith angle ~97.5°), whereas the observation of Figure 5 was in late August (solar zenith angle ~111°). The transient Schumann resonance occurs after the primary pulse, since it takes some time before a standing wave pattern in the Earth ionosphere wave guide builds up. Note that Figure 5 does not show a fast tail, so the ULF response is of type I.

[20] The following Figure 6 shows a ULF response to a +CG of type II. Now the mentioned oscillation is superposed on the fast tail. Spectral analysis (not shown) confirms that the oscillations are basically Schumann resonances. Note that a delay of −5 ms means that the sprite was actually observed before the +CG. This has to be tolerated in view of the uncertainty of the exact sprite time due to a finite number of video frames per second (see above).

3.2. Average Properties

[21] The whole body of available data from the EuroSprite 2003 campaign has been subdivided in hourly intervals because the pulsation data is stored in hourly files. There are all together 15 hours of pulsation data to be correlated with sprite observations. By accident, the first hour in this data collection contains most of the sprite events. This is also true for our subset of Splus events. There are eight Splus events within the first hour. Scanning through each hour of campaign data revealed an astonishing fact: There seems to be a preference in the ULF response for type I at the beginning and for type II at the end of the campaign. In the following superposed epoch analysis therefore, first the result is shown using all Splus events and then separately for the first and last hours of the campaign.

[22] The superposed epochs (events) are synchronized in such a way that the H-component minima (cf., e.g., Figure 3) are put on top of each other. This required a slight adjustment in the time axis for each event since the +CG times from Météorage (given with ms accuracy) fall in between the discrete data points (25 ms apart) and the observed peak times therefore jump around the given +CG time. Moreover, physical processes (in which also the sprite may be involved), which are not accounted for in this procedure, may produce some sort of varying delays. Also the Météorage times may not always be correct. In any case it is absolutely essential that the peaks are exactly on top of each other due to the steep flanks on either or both sides of the peaks (cf., e.g., Figure 3). After the time adjustment each event is normalized in order to give it the same statistical weight. After normalization the peak value throughout gets minus unity and if the synchronization is done correctly also the superposed epoch carries the same peak value. For the D-component we used the same normalization factor as for the H-component since the D-component does not carry an expressive minimum or maximum thanks to rotation. Since the rotation angle has also some spread and is determined by individual inspection, we used an hourly average rotation angle for the superposed epoch analyses. The rational behind is an

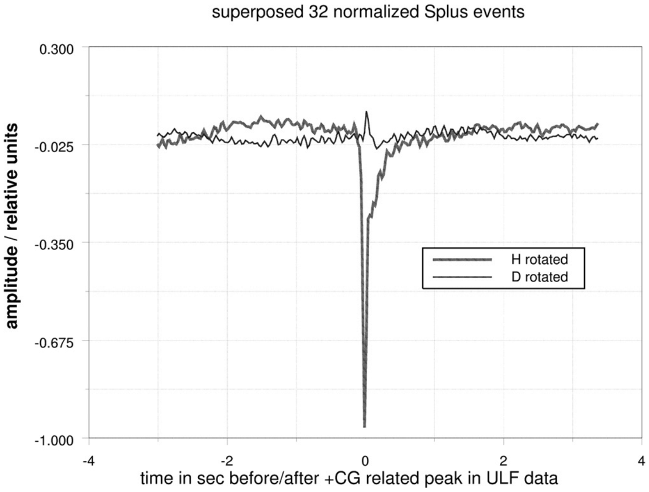

Figure 7. The ULF response to 32 "clean" and "isolated" +CG events which were associated with sprites. The zero time mark represents the data point with the minimum value (peak) in the rotated H-component. The individual time series in the superposition were normalized to this minimum. For details see text.

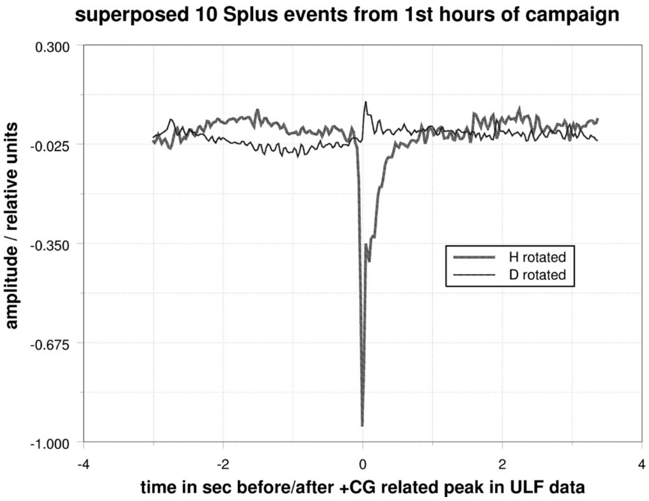

Figure 8. The same as Figure 7 but for the first 2 hours of the campaign, that is for 21 July 2003 from 0200 to 0400 UT. For details see text.

average lifetime of about an hour for individual thunderstorm centers. It has also been convenient in the sense that our magnetic data is stored in hourly files.

[23] Figure 7 shows the result of superposing all 32 Splus events of the campaign. As can be seen, the average property resembles very much the property of an individual event as shown, for example, in Figure 4: there is a unipolar excursion in the magnetic field of the width of roughly the impulse response length of the instrument (~100 ms) with a subsequent slower decay in some sort of exponential fashion to the background level, lasting some 500 to 1000 ms.

[24] The following figures, Figure 8 and Figure 9, show the same as Figure 7 but for the beginning of the campaign and for the end of it. As already mentioned, the productivity in producing sprite-associated +CG lightning flashes was largest during those periods and the first 2 hours of data exhibit a definite preference for type II and the last 2 hours a preference for type I in the ULF response. In other words, at the end of the campaign the fast tail was much less expressed. This difference seems to be of little significance, especially in the light of poor statistics; however, we will see that the control group behaves just in the same way and for the control group the statistics is much better.

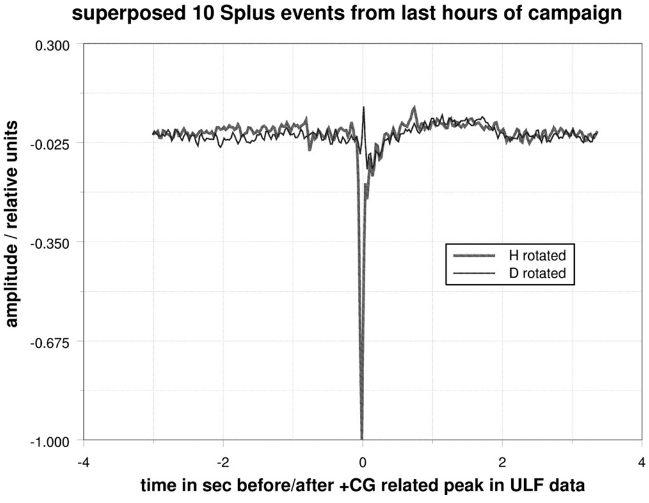

Figure 9. The same as Figure 7 but for the last 2 hours of the campaign, that is for 25 August 2003 from 2000 to 2200 UT. For details see text.

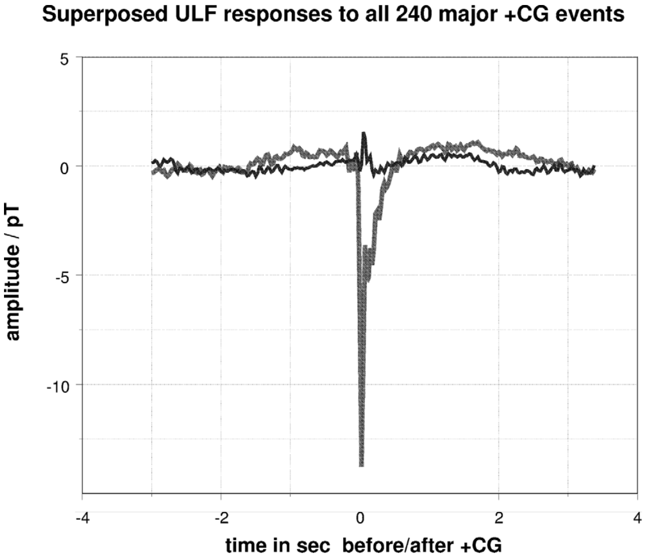

Figure 10. The result of superposing all major +CG events of the "Météorage" EuroSprite 2003 list. For the various time periods from mid-July to the end of August 2003, hourly average rotation angles were implied in the same way as above. The individual peak values were not normalized before superposing. Thus the outcome shows in absolute terms the average ULF response to major +CG events. The peak value amounts to ~15 pT. The distance to the thunderstorm centers is about 2000 km. For details see text.

4. Comparison With the Control Group

[25] The same requirement of "clean and isolated events" must be imposed on the control group, otherwise it is not strictly comparable. This means from all +CG events in the Météorage list we have to select those which exhibit "good timing" and can be regarded as sufficiently "isolated" (cf. section on event selection). Moreover, we have to discard those +CG events which are associated with sprites. Before going into this tedious inspection of individual events, we can make use of the fact that the majority of +CG events are in any case not associated with sprites. Therefore as a first trial we superposed all major (peak current larger than 40 kA) 240+CG events of the Météorage list regardless of their association or nonassociation with sprites and regardless of their quality. In our previous analysis of sprite-associated events we had only 32 clean and isolated events. Here we have now 240 events and it can be expected that this is a sufficiently large number to show the average ULF response to +CG which are not associated with sprites. The result is shown in Figure 10.

[26] As we can see, the signatures are very much like as in Figure 7, Figure 8, and Figure 9. There is a fast unipolar

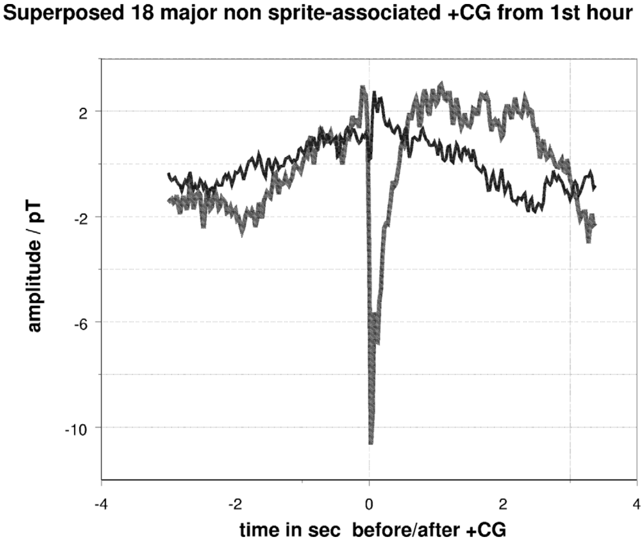

Figure 11. The result of superposing the ULF signature of 19 non-sprite-associated, major +CG events from the first hour of the campaign. The individual peak values were not normalized before superposing. This figure represents the result of the control group to Figure 8.

response to the +CG with a distinct peak followed by a slower decay with an average duration of ~500 ms. The decay exhibits indications of an oscillatory behavior. All these principal characteristics do not change any more after some 100 events are included in the epoch analysis. Thus our statistics based on 240 events is fully trustworthy.

[27] Still we go on with some differentiation in our analysis following the logic of section on "average properties," above. The following Figure 11 shows the result of superposing the ULF signature of 19 major +CG events from the first hour of the campaign. These events were not associated with sprites and were all "clean" and "isolated" (in the same sense as used before). Only 19 events out of 56 survived our strict selection. This figure represents the result of the control group to Figure 8. The number of events in this control group is about twice as much as the number of sprite-associated +CGs in Figure 8. This is simply because there are many more +CG events which are not accompanied with sprites. As can be seen, the control group does not behave differently: all basic signatures can be found, especially the decay time (the fast tail) is of the same order in both groups. It is worth noticing that also the differences to Figure 10 are not of principal nature. The background noise is much smaller in this figure because of the large amount of superposed events.

[28] Finally, we proceed to the control group representing the last 2 hours of the campaign (25 August 2003), which is shown in Figure 12. It was obtained by superposing the ULF signature of eight major +CG events. These events were not associated with sprites and were all "clean" and "isolated." Only eight out of 24 events survived our strict selection rule. This figure should be compared with Figure 9.

[29] As can be seen, the ULF response looks alike. The tail is relatively short as was already noticed with the sprite-associated +CG lightnings from the same time period. Actually, only two out of the eight events had a tail. The responsible thunderstorms produced more tailless responses than the thunderstorms at the beginning of the campaign, as was already mentioned before. The point to stress here is that this signature has no relation to sprites.

5. Observational Summary

[30] We examined the ULF response to +CG lightning discharges. The response was measured by a pulsation magnetometer located in southern Finland. All the +CG events occurred in thunderstorm centers over central France. The great circle path from the magnetometer to the lightning flashes formed in all cases approximately the same angle of 40 deg ± 5 deg with the magnetic meridian. Rotation by this angle of the geomagnetically aligned two horizontal components of the magnetic disturbance vector resulted in a magnetic deflection maximizing in one component and minimizing in the other. The latter was then practically unaffected by the lightning indicating a merely linearly polarized signal. The affected component was characterized by a sharp, fast unipolar pulse followed by a slower decay (a tail) lasting typically 0.5 to 1.0 s. There were observations, however, with only a sharp unipolar pulse without a gradual decay (without a tail). In both cases the pulse had a duration of typically 0.1 s. Rather frequently the pulse triggered some damped oscillations superimposed on the tail. These oscillations persisted sometimes still beyond it.

[31] We used superposed epoch analysis to look for possible differences in the ULF response to sprite-associated and non sprite-associated +CG lightning discharges. Out of a collection of some 100 sprite-associated +CGs (outcome of the EuroSprite 2003 campaign), we selected 32 "clean" and "isolated" ULF responses for the analysis. It turned out that the characteristics derived from inspection of

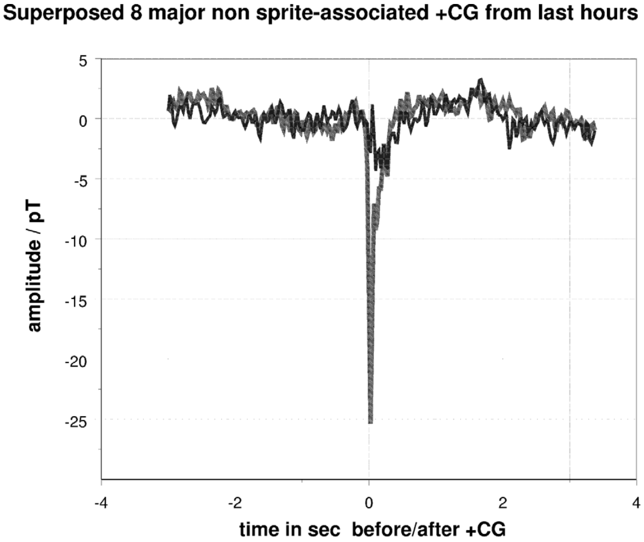

Figure 12. The result of superposing the ULF signature of 8 non-sprite-associated, major +CG events from the last 2 hours of the campaign. The individual peak values were not normalized before superposing. This figure represents the result of the control group to those results shown in Figure 9.

individual events prevailed also in this kind of statistics. It was interesting to note that the thunderstorms at the beginning of the campaign (21 July) had a preference of producing ULF pulses with a tail, whereas those at the end of the campaign (25 August) were rich in ULF pulses without a tail. However, both types were present in both scenarios.

[32] Special attention was paid to the formation of the control group, that is to say a collection of non sprite-associated +CG lightning discharges. For this purpose it was not enough to exclude the 32 "clean" and "isolated" events from the Météorage list but all documented sprite-associated discharges (if single or multiple) had to be removed. Thereafter the same principle of "clean" and "isolated" had to be applied to make the control group really comparable. This strict selection rule resulted in a final amount of non sprite-associated +CGs which was relatively small in spite of the fact that non sprite-associated +CGs are much more frequent than sprite-associated ones. The final output was rather disillusive. We could not find any clear signature which made the control group behave differently from its counterpart. This is also true for the peculiar observation that the thunderstorms at the beginning of the campaign (21 July) had a preference of producing ULF pulses with a tail, whereas those at the end of the campaign (25 August) were rich of ULF pulses without a tail. So the two groups had in terms of our investigation everything in common.

[33] We made one more test: We superposed the ULF signatures form all 240 major (>40 kA) +CGs of the campaign. Having in mind that sprite-associated +CGs form a small minority of all +CGs, the superposed epoch should reflect the signatures of the majority. The result was as expected and fully in accord with the result from the control group.

6. Discussion

[34] For our strategy it is essential to have enough certainty on the selection of non-sprite-associated +CG forming the control group. Sprites can be missed because of various reasons such as clouds (cf. Table 1), light pollution, low emission intensities, or simply because the camera's field of view (FOV) does not cover the entire convection cell with lightning activity. With respect to this difficulty we are in a fortunate position. We are using the same data set as *Haldoupis et al.* [2004] and *Mika et al.* [2005]. The one-to-one association found by these authors implied already a pinpointing of every +CG within the camera's FOV. Moreover, their various VLF links crossing the inspected thunderstorm regions provided an additional monitoring capability to infer about sprite occurrence. A detailed description of their experiment set up and strategy is given in the two papers. The overview paper on the EuroSprite 2003 summer campaign by *Neubert et al.* [2005] gives additional technical information. For the sake of convenience we repeat here some essentials: All sprites were detected which were brighter than the threshold sensitivity of the camera [*Neubert et al.*, 2005]. The camera's FOV (22.5°) covered the entire thunderstorm areas under investigation (cf. Table 1 with respect to "distance") except for the thunderstorm on 28–29 August 2003. This storm was not included in this study. Moreover, the list of sprites indicates that the conditions for observations must have been good in almost all cases, since there were no suspicious interruptive gaps within intervals of sprite observations.

[35] Regarding magnetic observations the perfect correlation of Q-bursts with +CG localized by Météorage within 1 km and 1 ms did not leave any doubt as to where the signal came from. The rotation angle is not a very precise parameter for triangulation and should not be taken too literally. This is in the nature of the low-frequency signal and its getting affected by conductivity gradients [*Füllekrug and Sukhorukov*, 1999].

[36] There remains nevertheless some uncertainty with regard to non-sprite-associated +CGs for reasons what so ever. It belongs to the nature of excluding populations that they cannot be absolutely certain. However, our approach of incorporating individual as well statistical analyses did not run into any sort of controversial results.

[37] The result of the present investigation can be characterized as negative, that is, there is no unique signature of a ULF response to sprite-associated flashes of lightning. Almost all of the 240 major +CG lightnings from the Météorage list were accompanied by Q-bursts since the lightnings left clear signatures in the ULF data. Thanks to our investigation it is now obvious that a Q-burst is not a ULF sprite signature. It is true, however, that in accordance with *Boccippio et al.* [1995], large (major in our definition) +CG discharges which are sprite-causative do also produce Q-bursts. The important point here to make is that the Q-burst is not identifiable only to the sprite producing process, but it is an inherent property of the +CG discharge.

[38] Our collection of some 100 well-documented sprite events is quite exceptional. Our strategy of forming a control group allowed us to operate with at least a similar amount of non-sprite-associated +CG events. The final numbers in our statistics were small, since "clean" and isolated "events" are rare but the complexity of nature requires dealing with simple and well defined items. It should, however, be noticed that we presented also a superposed epoch analysis of all the documented 240 +CG events of the CAL campaign. Its outcome was just the same as that received for all other subclasses of +CG events, either sprite-associated or not. This leads us now to the properties as such: the unipolar pulse of typically 75 to 100 ms duration followed by a more gradual decay to ground level of up to 1 s length. The intriguing observation was that this gradual decay, referred to above as the tail, was not always observed. Especially the thunderstorms of August 2003 produced often single, unipolar pulses without a tail.

[39] The traditional interpretation of the tail is that it is the signature of continuing currents. As a matter of fact, the continuing current of a +CG is in most cases inferred from the magnetic signature. There are, however, other options. Processes in the *D* region [*Shalimov and Bösinger*, 2006], and in the *E* and *F* region [*Füllekrug et al.*, 1998] may cause damped oscillations in the ULF signature which follow the excitation by the unipolar pulse. The most straightforward answer to the tailless unipolar pulses is that there are obviously +CG lightning discharges which have only a very short lasting continuing current, only of some tenths

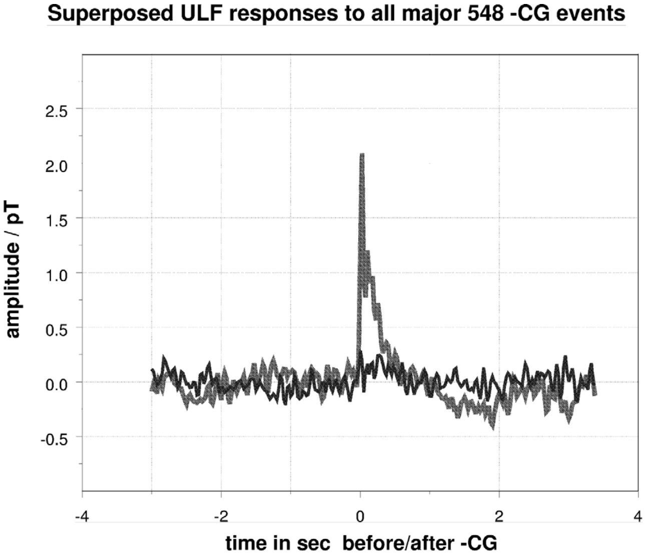

Figure 13. The result of superposing all major −CG events of the "Météorage" EuroSprite 2003 list. For the various time periods from mid-July to end of August 2003, hourly average rotation angles were implied in the same way as in Figure 10. The individual peak values were not normalized before superposing. Thus the outcome shows in absolute terms the average ULF response to major −CG events. The peak value amounts ~2 pT. The distance to the thunderstorm centers is about 2000 km. For details see text.

of milliseconds. In this respect these +CGs would behave like the −CGs.

[40] It may be argued that the tail is caused by a successive series of +CGs. It is more typical of −CG that they cluster but also in our collection examples exist where three to four +CGs follow each other in fast succession. It should be recalled that we paid great attention to selecting isolated events. These kinds of double, triple, multiple +CG events were avoided. Also visual inspection of the tail allows in many cases to discern successive pulses or a kind of a continuous process such as the continuing current.

[41] At this point we go a little bit beyond the scope of our paper and present in the last figure, Figure 13, the result of superposing the ULF responses to all 548 major (peak current larger than |−40| kA) −CG events of the "Météorage" list. It is known that −CGs are much more frequent but after having selected only major events it turned out that their number was only about twice the number of major +CG events from the same period. In producing Figure 13 the same rotation angles were applied as for Figure 10. Besides a change in polarity, two important findings can be made: First, the average amplitude of the unipolar pulse is only about one tenth of the corresponding amplitude associated with +CGs (cf. Figure 10), and second, also −CGs produce a ULF tail. Its time scale is very similar to the one of +CG (cf. Figure 10). The first finding is compatible with a theoretical estimate by *Surkov et al.* [2005]: since the peak currents in both CG categories were the same, the small amplitude can tell that the discharge processes of −CGs are much faster (i.e., continuing current shorter) and consequently produce a much weaker response in the ULF bandwidth (10 Hz). The second finding is disturbing. It emphasizes the fact that we do not have a clue yet about the physical nature of the tail. The similarity of the ULF tail between −CGs and +CGs suggests a *D* region effect of the type conjectured by *Shalimov and Bösinger* [2006] rather than an atmospheric electricity effect in terms of continuing currents.

[42] Finally, a word about the Schumann resonance: with an average distance from the observation site to the thunderstorm centers of ~2000 km, the magnetic signatures of the Schumann resonance stay very weak. At the northernmost observation point of Finland, in KILpisjärvi (69.0°N, 20.7°E) (http://spaceweb.oulu.fi/projects/pulsations/), the ULF response to the +CG events of the EuroSprite campaign included more of Schumann resonance oscillatory behavior. This became obvious from comparing time series but could also be confirmed by spectral analysis. KIL is some 1500 km north of NUR. Thus for our analysis the observation site at NUR was ideally located with respect to the thunderstorm centers over southern France. It was enough screened from the rigorous local effects but not too far to catch the outgoing primary electromagnetic field with sufficient intensity. It takes time to invoke the global modes such as Schumann and they would in any case be small at NUR because of a magnetic null of the fundamental mode close to the source.

[43] In summary, the evidence presented here shows no unique and identifiable ULF signatures relating to sprites. Therefore Q-bursts cannot be indicative of sprite occurrence.

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T. Bösinger, Department of Physical Sciences, University of Oulu, P. O. Box 3000, FIN-90014 Oulu, Finland. (tilmann.bosinger@oulu.fi)

C. Haldoupis and Á. Mika, Department of Physics, University of Crete, Iraklion, Crete, Greece GR-71003. (chald@physics.uoc.gr; agnes@ianos.physics.uoc.gr)

T. Neubert, Danish National Space Center, Juliane Maries Vej 30, DK-2100 Copenhagen O, Denmark. (neubert@spacecenter.dk)

S. L. Shalimov, Institute of Physics of the Earth, B. Gruzinskaya 10, 123810 Moscow, Russia. (shalimov@ifz.ru)