Sprites in low-frequency radio noise

Martin Füllekrug,[1] Andrew Mezentsev,[1] Serge Soula,[2] Oscar van der Velde,[3] and Thomas Farges[4]

Received 18 February 2013; revised 22 March 2013; accepted 22 March 2013; published 30 May 2013.

[1] Low-frequency radio noise is the electromagnetic background radiation which is compared here to the luminosity of 39 sprites recorded with a low-light video camera. It is found that the sprite luminosities coincide with ~10–30 ms long sudden enhancements of the electromagnetic background radiation ~6–8 μV m^{-1} Hz$^{-1/2}$ (~6–9 dB) with a relative maximum near ~125 kHz as measured with a wideband (~1–400 kHz) digital radio receiver. The sprites cluster in 10 groups of 2–5 consecutive sprites which are paralleled by up to ~1 s long slowly varying enhancements of the electromagnetic background radiation ~4–5 μV m^{-1} Hz$^{-1/2}$ (~2–4 dB). The observed electric field strengths place an upper bound on the low-frequency radiation from the electron multiplication associated with the exponential growth and branching sprite streamers predicted by *Qin et al*. [2012a]. This upper bound corresponds to a maximum of ~300–5000 sprite streamers at ~40 km height above thunderclouds. Some part of the observed electromagnetic background radiation might result from the superposition of low-frequency radiation emanating from the quick succession of numerous horizontal lightning strokes and/or stepped leaders inside thunderclouds which would constitute a fundamentally novel quasi-static discharge process inside thunderclouds radiating slowly varying low frequency radio noise.
Citation: Füllekrug, M., A. Mezentsev, S. Soula, O. van der Velde, and T. Farges (2013), Sprites in low-frequency radio noise, *Geophys. Res. Lett.*, *40*, 2395–2399, doi:10.1002/grl.50408.

1. Introduction

[2] Sprites are composed of individual streamer discharges [e.g., *Pasko*, 2010] which split into streamer tips [*McHarg et al.*, 2010] with diameters ~50–100 m at ~60–80 km height [*Kanmae et al.*, 2012]. The sprite luminosity coincides in time and space with extremely low frequency (ELF) electromagnetic radiation ≲3 kHz in excellent agreement with theory [*Cummer and Füllekrug*, 2001]. This theory is based on current flowing in the body of sprites at ~70–80 km height associated with large streamer densities [*Pasko et al.*, 1998]. A more detailed study shows specifically that it is the electron multiplication associated with the exponential growth and splitting of sprite streamers at ~70–80 km height which produces the observed radiation [*Qin et al.*, 2012a]. It is suggested that this physical process might also result in low-frequency (~30–300 kHz) electromagnetic radiation emanating from sprite streamers at ~40 km height, albeit with very small magnetic fields ~10^{-17}–10^{-12} T from a single streamer. Brief very low frequency (VLF) clusters are attributed to lightning discharges inside thunderclouds [*Ohkubo et al.*, 2005; *Johnson and Inan*, 2000]. Longer-lasting low-amplitude signals were detected in association with sprites and particularly long-delayed carrot sprites [*van der Velde et al.*, 2006], but may also occur without sprites [*Marshall et al.*, 2007]. The aim of this letter is therefore to test the challenging theory put forward by *Qin et al.* [2012a] by use of more detailed experimental measurements and analyses of low-frequency radio noise [*Füllekrug and Fraser-Smith*, 2011].

2. Observations

[3] The predicted low frequency electromagnetic radiation from sprite streamers scales with the total number of streamers such that it is suggested to investigate particularly bright sprite occurrences [*Qin et al.*, 2012a]. An exceptional sequence of 10 spectacular clusters of sprites is used for analysis which occurred above a mesoscale convective system in the Mediterranean during the early morning hours from 00:55 to 02:17 UTC on 31 August 2012. The parallel stratiform mesoscale convective system [*Parker and Johnson*, 2000] was initiated by unstable air masses off the south-eastern Spanish coast over the Mediterranean and it propagated south-eastward toward northern Africa until it reached a horizontal extent ~330 × 140 km^2 shortly after midnight. Numerous lightning discharges occured in the convective core of the mesoscale convective system (Figure 1, left) and some particularly intense positive lightning discharges in the stratiform region caused the 10 spectacular clusters of sprites which included 39 individual sprites, i.e., ~32% of all the 122 sprites observed during that night. Each sprite cluster comprises 2–5 consecutive sprites which occur within ~120–960 ms, with time differences between consecutive sprites of ~80–620 ms. These sprites comprise numerous luminous sprite elements, some of which exhibit significant deviations from the vertical direction (Figure 1, right) which is indicative of a superposition of the forcing electric field with the preceding electric field decay [*Neubert et al.*, 2011]. Several of these sprites show trolls, palm trees, or secondary jets; all of which are very rare phenomena named secondary transient luminous events (TLEs) [*Lee et al.*, 2012; *Marshall and Inan*, 2007].

[1]Department of Electronic and Electrical Engineering, Centre for Space and Atmospheric Science, University of Bath, Bath, UK.
[2]Laboratoire d'Aérologie, CNRS, Université de Toulouse, Toulouse, France.
[3]Department of Electrical Engineering, Technical University of Catalonia, Terrassa, Spain.
[4]Commissariat à l'Energie Atomique et aux Energies Alternatives, DAM-DIF, Bruyères le Châtel, France.

Corresponding author: M. Füllekrug, Department of Electronic and Electrical Engineering, Centre for Space and Atmospheric Science, University of Bath, Bath, UK. (M.Fullekrug@bath.ac.uk)

0094-8276/13/10.1002/grl.50408

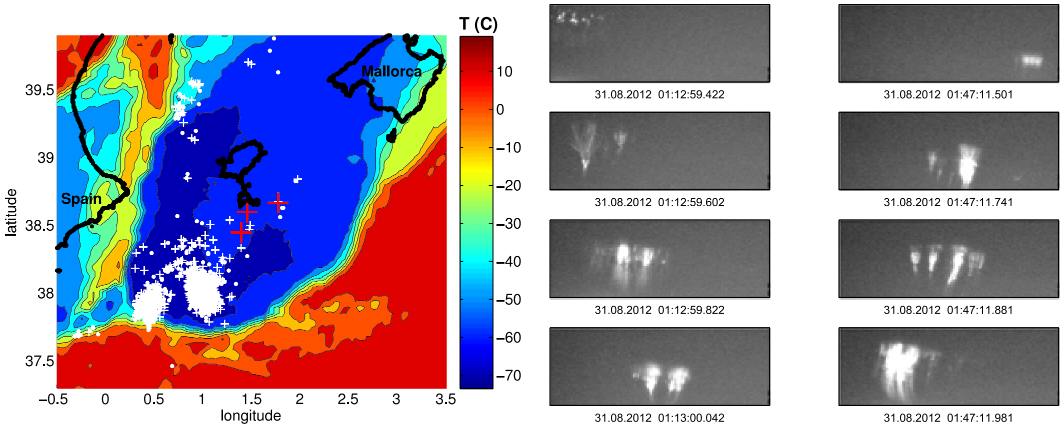

Figure 1. A mesoscale convective system in the Mediterranean produces numerous sprite clusters. (left) The mesoscale convective system in the Mediterranean reaches a horizontal extent ~330 × 140 km^2 during the early morning hours from 00:15 to 00:35 UTC on 31 August 2012. The negative lightning discharges mainly occur in the center of the convective core (circles) while positive lightning discharges also occur in the parallel stratiform region (white crosses) as reported by the Météorage lightning detection network. Three positive lightning discharges initiate sprites during this time interval (red crosses). (right) Two examples of the 10 sprite clusters which are observed with a video camera on Pic du Midi in southern France (42.9°N, 0.1°E, 2877 m). Both sprite clusters illuminate a substantial volume of the atmosphere. Note the deviations of the sprite luminosity from the vertical direction which indicates an influence of the electric fields associated with preceding sprites.

[4] Whilst the sprites are observed with a video camera on the Pic du Midi in southern France (42.9°N, 0.1°E, 2877 m) [*Soula et al.*, 2012] ~470 km away from the mesoscale convective system, low-frequency radio waves are measured simultaneously with a wideband digital radio receiver [*Füllekrug*, 2010] at a sampling frequency of 1 MHz near Bath in south-west England (51.4°N, 0.3°E) ~1400 km away from the sprites. The recordings are used to calculate consecutive spectra with a temporal resolution of 1 ms. The decadic logarithms of the spectral amplitudes are subsequently averaged from ~1–400 kHz to characterize the 1 ms long modulation of the entire spectrum. Note that the derived 1 ms logarithmic mean in insensitive to constant longwave radio transmitters and lightning continuing current at frequencies $\lesssim$3 kHz which contributes only a minor fraction 3 kHz/400 kHz ≈ 0.8% to the modulation of the spectrum. But the 1 ms modulation is sensitive to impulsive lightning strokes which typically last for ~0.1–1 ms. Consecutive lightning strokes are known as sferic clusters which can cause sprites [*van der Velde et al.*, 2006; *Ohkubo et al.*, 2005]. Yet, after the impulse from a lightning stroke, the intensity of the electromagnetic background radiation observed here falls back to the level of the background radiation before the lightning stroke, similar to sferic bursts in the frequency range ~3–30 kHz [*Marshall et al.*, 2007]. This background radiation varies only slowly on time scales $\gtrsim$10 ms when compared to the impulsive lightning strokes (Figure 2, top image of left panel). The influence of lightning strokes is therefore removed by only using the smallest 1 ms value within each 10 ms long time interval. This minimum value is finally used to characterize the electromagnetic background radiation with a temporal resolution of 10 ms. This background radiation exhibits a sudden enhancement at the onset of the sprite cluster which was initiated by a positive lightning discharge with a peak current +117 kA at 01:12:59.420 UTC (Figure 2, top image of left panel). A more detailed analysis of this sudden enhancement of the background radiation shows that all spectral amplitudes from 1–400 kHz exhibit a relative enhancement by a factor of ~2–4 after the onset of the sprite cluster (Figure 2, right). The largest relative enhancement is found to be ~1 order of magnitude near ~125 kHz. On the other hand, the background radiation does not show any enhancement at the onset of a halo [*Qin et al.*, 2012b] which was initiated by a negative lightning discharge with a peak current of –160 kA at 22:50:21.313 UTC (Figure 2, bottom image of left panel). It is interesting to note that this negative lightning discharge is accompanied by many more and stronger impulsive lightning strokes than the positive lightning discharge. Yet, all these impulsive lightning strokes have virtually no effect on the electromagnetic background radiation.

[5] The sprite luminosity is inferred from the images recorded with the low-light video camera at a temporal resolution of 20 ms for comparison with the electromagnetic background radiation. The sprite luminosity typically lasts for ~1–2 images. This luminosity is quantified by counting the number of pixels above a threshold near the higher end of the distribution function of the observed luminosities present in a normal video image without any sprites. This threshold is roughly half the maximum luminosity in one pixel (140 out of 256 possible values). The sprites observed here are easily detected with this method because the sprites are so bright that they often saturate the chip of the camera. The sprites also appear to be relatively large in the recorded images (typically ~0.1–1% of 288 × 720 pixels) such that the logarithm of the number of pixels above the chosen threshold describes the sprite luminosity very well (Figure 3). The sprite luminosity coincides with the ~10–30 ms long sudden enhancements of the electromagnetic background radiation ~6–8 μV m^{-1} Hz$^{-1/2}$ (~6–9 dB). One sudden enhancement of the background radiation at

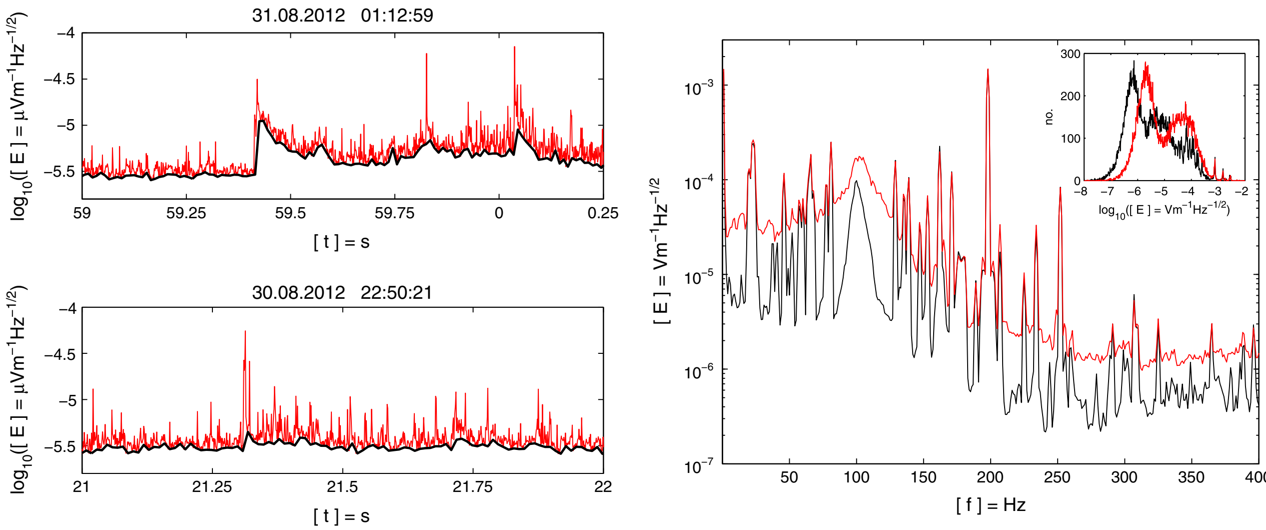

Figure 2. Modulation of the low frequency electromagnetic background radiation. (left) Impulsive lightning strokes on the 1 ms time scale (red lines) are superimposed on the electromagnetic background radiation which varies more slowly on the time scale $\gtrsim$10 ms (black lines). (top) The background radiation exhibits a sudden enhancement during the onset of a sprite cluster associated with a positive lightning discharge peak current +117 kA at 01:12:59.420 UTC. (bottom) The background radiation remains unaffected during the onset of a halo associated with a negative lightning discharge peak current –160 kA at 22:50:21.313 UTC, even though it is associated with many more and stronger impulsive lightning strokes. (right) The spectral amplitudes are averaged for 100 ms before (black line) and after (red line) the onset of the sprite cluster, including the first sprite. An enhancement of the electromagnetic background radiation by a factor of $\sim$2–4 over the entire frequency range from $\sim$1–400 kHz is evident. The largest relative enhancement is found near $\sim$125 kHz where it exceeds 1 order of magnitude. Note that the transmitters (spikes) are practically not affected by the background radiation. The distribution of the background logarithmic spectral amplitudes (inset, black line) is shifted toward larger values after the onset of the sprite cluster (inset, red line). This shift can be characterized by the mean of the distribution function.

$\sim$ 01:47:12.401 is not paralleled by any sprite luminosity (Figure 3, bottom panel). A closer inspection of the original video images revealed a very weak and small sprite near the left edge of the image. This sprite was missed by the optical detection method because either the sprite did not exceed the threshold luminosity of the video images significantly or the background radiation indicates the presence of a sprite outside the field of view of the video camera because the sprites appear to progress from the right to the left (compare to Figure 1, right). Nevertheless, all the 39 sprite occurrences within the 10 sprite clusters exhibit similar sudden enhancements of the electromagnetic background radiation with minor ambiguities. But all the 10 sprite clusters are unambiguously paralleled by a smaller enhancement of the background radiation $\sim$4–5 μV m^{-1} Hz$^{-1/2}$ ($\sim$2–4 dB) lasting up to $\sim$1 s without any exception. Note that this slowly varying radiation reflects the modulation of the entire frequency spectrum from $\sim$1–400 kHz, where lightning continuing current does not contribute significantly.

3. Discussion

[6] The observed sprite luminosities coincide with sudden enhancements of the electromagnetic background radiation $\sim$6–8 μV m^{-1} Hz$^{-1/2}$ ($\sim$6–9 dB) with the largest enhancement occurring near $\sim$125 kHz. Sprite streamers at $\sim$70–75 km height have a median width of $\sim$300–500 m before splitting [*McHarg et al.*, 2010, Figure 5] which reduces to $\sim$3–5 m at $\sim$40 km height by using a scaling of $\sim$1/100 derived from the similarity laws for sprites associated with the varying neutral density. The $\sim$3–5 m long line current element develops over a time scale of $\sim$5–10 μs [*Qin et al.*, 2012a, Figure 3, lower panel]. Similarly, the growth rate of sprite streamers $\sim 10^3$ s^{-1} at $\sim$70–75 km height increases to $\sim 10^5$ s^{-1} at $\sim$40 km which corresponds to frequencies of $\sim$100 kHz. This growth rate and the time scale of the sprite streamer development $\sim$5–10 μs imply a radiated magnetic field of $\sim 10^{-17}$–10^{-16} T at a distance of $\sim$600 km [*Qin et al.*, 2012a, Figure 4]. The corresponding electric field strength E of the radiation from one sprite streamer is $E = Z_0 H \approx$ 3–30 nV m^{-1}, where $Z_0 = (\mu_0/\varepsilon_0)^{1/2} \approx 120\pi\ \Omega$ is the free space wave impedance. The electric field strength is further reduced to $\sim$1.6–16 nV m^{-1} by an attenuation of $\sim$5.3 dB/Mm [*Füllekrug et al.*, 2009] during the subionospheric propagation to the radio receiver $\sim$1400 km away. The number of sprite streamers is then calculated to be $\sim$300–5000 by using the ratio of the observed electric field strengths $\sim$5–8 μV m^{-1} to the theoretically predicted value $\sim$1.6–16 nV m^{-1} for one streamer. The more continuous smaller enhancement of the background radiation $\sim$4–5 μV m^{-1} Hz$^{-1/2}$ ($\sim$2–4 dB) suggests an $\sim$1 s long persistence of weaker background radiation, possibly from sprite streamers at lower heights above the thundercloud. The optical detection of these streamers remains a substantial challenge as a result of the strong absorption of optical wavelengths in the atmosphere.

[7] Although the experimental results lend support to the theory of *Qin et al.* [2012a], it is intuitively tempting to

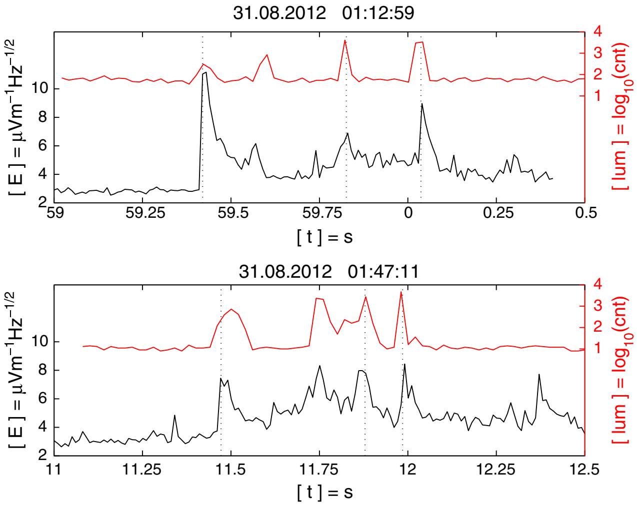

Figure 3. Comparison of the sprite luminosity inferred from the video images (red lines) with the electromagnetic background radiation inferred from the radio recordings (black lines) and positive lightning discharges (dotted lines). The sprite luminosity coincides with sudden enhancements of the electromagnetic background radiation. The enhancement of the background radiation at ~01:47:12.401 is associated with a very small sprite near the left edge of the image. This sprite does not exceed the threshold luminosity of the video images significantly, or the background radiation indicates the presence of a sprite outside the field of view because the sprites appear to progress from the right to the left (Figure 1, right).

associate the observed electromagnetic background radiation with ordinary lightning strokes inside thunderclouds, even though there is not much experimental evidence for it. For example, sprites are usually initiated by positive lightning discharges [*Boccippio et al.*, 1995] and this is confirmed here for 36 out of 39 sprites by broadband electric field measurements with a dipole antenna [*Farges and Blanc*, 2011] near Rustrel (43.9°N, 5.5°E) ~600 km away from the sprites. Yet, the sprites coinciding with the sudden enhancements of the electromagnetic background radiation at ~01:12:59.602, ~01:47:11.741, and ~01:47:12.401 are not initiated by intense positive lighting discharges as evidenced by the absence of corresponding vertical electric field signatures recorded with the dipole antenna near Rustrel and the absence of lightning strokes recorded by the Lightning Network (LINET) and the Météorage Lightning Detection Network. In addition, impulsive lightning strokes typically discharge the electric field inside thunderclouds on time scales ~0.1–1 ms [*Rakov and Uman*, 2003, p. 8 and 215] which have virtually no effect on the observed electromagnetic background radiation even if many more and stronger lightning strokes occur (Figure 2, bottom image of left panel). As a result, it is difficult, if not impossible, to understand the observed electromagnetic background radiation as the superposition of many individual lightning strokes with varying intensity inside the thundercloud. Finally, the absence of any luminosity in video observations does not necessarily imply the absence of streamers above thunderclouds as a result of the strong absorption of optical wavelengths in the atmosphere. In fact, the larger sensitivity of radio measurements to electric current in comparison to optical measurements might actually help to quantify the density of visual and subvisual streamers above thunderclouds which is an important parameter for sprite modeling [*Pasko*, 2010].

[8] On the other hand, it is currently not possible to exclude beyond any doubt that the superposition of low-frequency radiation from numerous horizontal lightning pulses, e.g., stepped leaders inside thunderclouds, might produce the electromagnetic background radiation reported here. For example, sferic bursts are thought to result from numerous lightning pulses which coincide with bursts of stepped leaders inside thunderclouds and can last up to ~1 s [*Marshall et al.*, 2007; *Marshall and Inan*, 2007; *van der Velde et al.*, 2006; *Ohkubo et al.*, 2005]. In this picture, the quick succession of consecutive lightning pulses from radiating stepped leaders might blend into the slowly varying background radiation observed here, possibly assisted by wave propagation effects. However, to the best of our knowledge, there is currently no scientific rationale to describe the transition from Poisson-distributed lightning return stroke intensities [*Chrissan and Fraser-Smith*, 2003] or stepped leaders to smoothly varying low frequency background radiation. On the other hand, the mere absence of such kind of theory does not exclude the possibility of this blending process to occur. But this hypothetical theory would definitely describe a fundamentally novel quasi-static discharge process inside thunderclouds which radiates slowly varying low frequency radio noise.

[9] In summary, it is concluded that the observed electric field strengths from the slowly varying low frequency electromagnetic background radiation place an upper bound on the predicted low frequency radiation from sprite streamers with a potential contribution from horizontal lightning strokes and/or stepped leaders which remains to be quantified in future studies. From an experimental point of view, it seems therefore vital to investigate the relationship between low frequency radio noise, stepped leaders inside thunderclouds and sprite streamers above thunderclouds in much more detail than previously thought.

4. Summary

[10] Sprite luminosities coincide with ~10–30 ms long sudden enhancements of the electromagnetic background radiation ~6–8 μV m^{-1} Hz$^{-1/2}$ (~6–9 dB) in the frequency range ~1–400 kHz with a relative maximum near ~125 kHz. The sudden enhancements are superimposed on ~1 s long enhancements of the electromagnetic background radiation ~4–5 μV m^{-1} Hz$^{-1/2}$ (~2–4 dB). The observed electric field strengths place an upper bound on the predicted low frequency radiation from the electron multiplication associated with the exponential growth and branching of sprite streamers. This upper bound corresponds to a maximum of ~300–5000 sprite streamers at ~40 km height. Some part of the observed electromagnetic background radiation might result from the superposition of low-frequency radiation from numerous lightning strokes and/or stepped leaders inside thunderclouds which would constitute a fundamentally novel quasi-static discharge process inside thunderclouds radiating slowly varying low frequency radio noise.

[11] **Acknowledgments.** The work of MF and AM is sponsored by the Natural Environment Research Council (NERC) under grant NE/H024921/1. OV is supported by the Spanish Ministry of Science and Innovation under project AYA2011-29936-C05-04. The authors wish to thank the team of the Laboratoire Souterrain à Bas Bruit for hosting the dipole antenna. Special thanks to Julien Poupeney, Christophe Sudre, Alain Cavaillou, Daniel Boyer, and Stéphane Gaffet, whose assistance and hospitality were invaluable to conduct the experiments in south-eastern France. MF wishes to acknowledge stimulating discussions with Ondrej Santolik, Mike Kosch, and Adrian Evans. The authors wish to thank the reviewers for their help to improve the quality of the manuscript.

[12] The Editor thanks two anonymous reviewers for their assistance in evaluating this paper.

References

Boccippio, D., E. Williams, S. Heckman, W. Lyons, I. Baker, and R. Boldi (1995), Sprites, ELF transients, and positive ground strokes, *Science*, *269*, 1088–1091, doi:10.1126/science.269.5227.1088.

Chrissan, D., and A. Fraser-Smith (2003), A clustering Poisson model for characterizing the interarrival times of sferics, *Radio Sci.*, *38*(4), 1–14, doi:10.1029/2002RS002693.

Cummer, S., and M. Füllekrug (2001), Unusually intense continuing current in lightning produces delayed mesospheric breakdown, *Geophys. Res. Lett.*, *28*(3), 495–498, doi:10.1029/2000GL012214.

Farges, T., and E. Blanc (2011), Lightning and TLE electric fields and their impact on the ionosphere, *C. R. Phys.*, *12* (2), 171–179, doi:10.1016/j.crhy.2011.01.013.

Füllekrug, M. (2010), Wideband digital low-frequency radio receiver, *Meas. Sci. Technol.*, *21* (015901), 1–9, doi:10.1088/0957-0233/21/1/015901.

Füllekrug, M., and A. Fraser-Smith (2011), The Earth's electromagnetic environment, *Geophys. Res. Lett.*, *38*(L21807), 1–5, doi:10.1029/2011GL049572.

Füllekrug, M., M. Parrot, M. Ash, I. Astin, P. Williams, and R. Talhi (2009), Transionospheric attenuation of 100 kHz radio waves inferred from satellite and ground based observations, *Geophys. Res. Lett.*, *36* (L06104), 1–4, doi:10.1029/2008GL036988.

Johnson, M., and U. Inan (2000), Sferic clusters associated with early/fast VLF events, *Geophys. Res. Lett.*, *27* (9), 1–4, doi:10.1029/1999GL010757.

Kanmae, T., H. Stenbaek-Nielsen, M. McHarg, and R. Haaland (2012), Diameter-speed relation of sprite streamers, *J. Phys. D*, *45* (275203), 1–11, doi:10.1088/0022-3727/45/27/275203.

Lee, L., et al. (2012), Characteristics and generation of secondary jets and secondary gigantic jets, *J. Geophys. Res.*, *117* (A06317), 1–7, doi:10.1029/2011JA017443.

Marshall, R., and U. Inan (2007), Possible direct cloud-to-ionosphere current evidenced by sprite-initiated secondary TLEs, *Geophys. Res. Lett.*, *34*(5), 1–4, doi:10.1029/2006GL028511.

Marshall, R., U. Inan, and W. Lyons (2007), Very low frequency sferic bursts, sprites, and their association with lightning activity, *J. Geophys. Res.*, *112*(D22105), 1–9, doi:10.1029/2007JD008857.

McHarg, M., H. Stenbaek-Nielsen, T. Kanmae, and R. Haaland (2010), Streamer tip splitting in sprites, *J. Geophys. Res.*, *115*(A00E53), 1–7, doi:10.1029/2009JA014850.

Neubert, T., O. Chanrion, E. Arnone, F. Zanotti, S. Cummer, M. Fullekrug, S. Soula, and O. van der Velde (2011), The properties of a giant jet reflected in a simultaneous sprite, *J. Geophys. Res.*, *116*(A12329), 1–16, doi:10.1029/2011JA016928.

Ohkubo, A., H. Fukunishi, Y. Takahashi, and T. Adachi (2005), VLF/ELF sferic evidence for in-cloud discharge activity producing sprites, *Geophys. Res. Lett.*, *32* (L04812), 1–4, doi:10.1029/2004GL021943.

Parker, M., and R. H. Johnson (2000), Organizational modes of midlatitude mesoscale convective systems, *Mon. Weather Rev.*, *128*(10), 3413–3436, doi:10.1175/1520-0493(2001)129<3413:OMOMMC>2.0.CO;2.

Pasko, V. (2010), Recent advances in theory of transient luminous events, *J. Geophys. Res.*, *115* (A00E09), 1–24, doi:10.1029/2009JA014860.

Pasko, V., U. Inan, T. Bell, and S. Reising (1998), Mechanism of ELF radiation from sprites, *Geophys. Res. Lett.*, *25*(18), 3493–3496, doi:10.1029/98GL02631.

Qin, J., S. Celestin, and V. Pasko (2012a), Low frequency electromagnetic radiation from sprite streamers, *Geophys. Res. Lett.*, *39* (L22803), 1–5, doi:10.1029/2012GL053991.

Qin, J., S. Celestin, and V. Pasko (2012b), Formation of single and double-headed streamers in sprite-halo events, *Geophys. Res. Lett.*, *39*(L05810), 1–5, doi:10.1029/2012GL051088.

Rakov, V., and M. Uman (2003), *Lightning, Physics and Effects*, pp. 687, Cambridge University Press , Cambridge.

Soula, S., et al. (2012), Multi-instrumental analysis of large sprite events and their producing storm in southern France, *Atmos. Res.*, 1–14, doi:10.1016/j.atmosres.2012.10.004.

van der Velde, O., A. Mika, S. Soula, C. Haldoupis, T. Neubert, and U. Inan (2006), Observations of the relationship between sprite morphology and in-cloud lightning processes, *J. Geophys. Res.*, *111* (D15203), 1–8, doi:10.1029/2005JD006879.