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Simultaneous radio and satellite optical measurements of high-altitude sprite current and lightning continuing current

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[1] We report coordinated measurements of lightning and resulting sprites using ground-level magnetic field sensors (<0.1 Hz to 30 kHz bandwidth) and the ISUAL instrument on the FORMOSAT-2 satellite. These measurements demonstrate two distinct elements of the connection between the radio and optical emissions. First, the quasi-static magnetic field signature is tightly correlated with the low-altitude optical emissions from the lightning flash, indicating that this radio signature is produced by continuing lightning current. Second, in two events with strong postreturn stroke extremely low frequency (ELF) magnetic pulses, the optical emissions demonstrate that there are no observable intensifications of low-altitude optical emissions associated with those pulses. If they were produced by a lightning process, such as an M-component, the connection between optical emissions and current seen in the return stroke and the continuing current suggests they should be visible. However, as has been observed previously, the bright, high-altitude optical emissions associated with the sprite are simultaneous with the ELF pulse. This is strong evidence that these ELF pulses originate in high-altitude electric current in the sprite itself and are not produced by a low-altitude lightning process.

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1. Introduction

[2] Lightning remote sensing by low-frequency radio emissions is an effective technique for detecting and quantifying the large and sometimes unusual lightning discharges linked to above-thunderstorm processes. Applications of this general technique include the confirmation of the connection between sprites and large positive discharges [*Boccippio et al.*, 1995], the global detection of probable sprite-producing discharges [*Füllekrug and Constable*, 2000; *Sato and Fukunishi*, 2003], and the measurement of lightning charge moment changes thresholds for sprite generation [*Hu et al.*, 2002; *Cummer and Lyons*, 2005].

[3] The link between two specific low-frequency-radiating processes and lightning-driven high-altitude phenomena has been established thus far primarily through radio measurements. The first of these processes is sprite current, which is not surprisingly defined as significant electric current flowing in sprites. On the basis of unusual extremely low frequency (ELF) radio pulses sometimes seen in association with sprite-producing lightning, it was suggested (P. Krehbiel, personal communication, 1996) that these pulses originate in the sprite itself, rather than in a low-altitude lightning process. It was subsequently shown that the current responsible for these pulses followed the rise and fall of the sprite luminosity with submillisecond correlation [*Cummer et al.*, 1998] and that these pulses originate in current that is horizontally displaced by as much as 60 km from the lightning return stroke [*Füllekrug et al.*, 2001]. In light of this tight time correlation, the absence of these pulses except at sprite times, and the theoretical analysis showing that such pulses are expected if sprites modify the local electric conductivity of the atmosphere [*Pasko et al.*, 1998], it is generally thought that such pulses are evidence of sprite current flowing in a small subset (around 10%) of sprites [*Cummer*, 2003]. Balloon measurements of the occurrence of this class of pulse are consistent with ground measurements [*Thomas et al.*, 2005]. This evidence, however, is still circumstantial, and there is a well-known lightning process, the M-component [*Rakov and Uman*, 2003, p. 176], that radiates in a similar manner. Ruling out cloud-level lightning processes as a source of the radiated sprite current pulse would be important additional evidence that these ELF pulses originate in the sprite itself.

[4] The second process is lightning continuing current. It is well that a slowly-varying, long-lasting continuing current follows some lightning return strokes [*Rakov and Uman*, 2003, p. 173]. *Cummer and Füllekrug* [2001]

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showed that the long, quasi-static tails (hundreds of milliseconds in some cases) in the distant magnetic field produced by sprite-associated lightning strokes could be explained by unusually strong (up to 5–10 kA) continuing currents. The continuing current amplitudes were measured through the distant magnetic fields and it was shown that these continuing currents could explain why some sprites were delayed many tens of milliseconds from a lightning return stroke. *Ohkubo et al.* [2005] have reported similar signatures and interpreted them in the same way. Simultaneous measurements of magnetic fields and lightning flash luminosity would provide direct evidence that these quasi-static magnetic field signatures are produced by lightning continuing currents.

[5] We use simultaneous optical measurements from the ISUAL instrument on the FORMOSAT-2 satellite and ground-based magnetic field measurements covering a wide frequency range from <0.1 Hz to 30 kHz to investigate both of these issues. *Frey et al.* [2005] used a similar combination of optical and radio data to investigate the prestroke leader processes in high peak current, elve-producing lightning strokes. We show below that there are no detectable low-altitude optical emissions during the ELF sprite current pulse, but that there are clear low-altitude optical emissions that are tightly correlated with quasi-static magnetic field signatures of continuing current. This provides direct evidence that the sprite current pulses are not associated with a low-altitude lightning process, such as M-components, and thus originate in current inside the sprite itself.

2. Instrumentation

[6] During most of 2004 and 2005 the vector horizontal magnetic field was measured continuously at Duke University (35.975°N, −79.100°E) with two pairs of magnetic induction coils that cover 50 Hz to 30 kHz and <0.1 Hz to 400 Hz. The dominant signal in these fields are the short (typically a few ms) discrete impulses called sferics that are radiated by lightning strokes. These sensors record the azimuthal and radial components of the radiated magnetic field, from which a variety of parameters can be determined, including the time of and direction to the originating stroke [*Orville*, 1991], the polarity of the stroke, and the current and charge transfer characteristics of the stroke [*Cummer and Inan*, 2000]. From a comparison with U.S. National Lightning Detection Network (NLDN) data, these data have absolute timing accuracy and precision of ~20 μs, ensuring that individual events detected by other instruments with high time precision can be reliably identified in the magnetic field data. Data recorded by both coil pairs are used in this work as the >5 kHz signal from the higher-frequency coils is needed to discriminate between sprite currents and lightning return strokes, and the sensitivity of the low-frequency coils below a few tens of Hz is needed to detect the quasi-static magnetic field signature of continuing current.

[7] The Imager for Sprites and Upper Atmospheric Lightning (ISUAL) [*Chern et al.*, 2003; *Mende et al.*, 2005] operates on the Taiwanese FORMOSAT-2 satellite and is dedicated to observing transient luminous events (TLE) from space in a global and long-term sense. The satellite flies in a Sun-synchronous, repeating orbit at 890 km altitude and performs 14 orbits per day, traveling over the same geographic region once a day near 2130 local time with a side-looking limb view near local midnight. ISUAL consists of an image intensified CCD camera with a six-position filter wheel, a six-channel spectrophotometer (SP), and a two-wavelength array photometer (AP). All three subinstruments cover approximately the same 20° × 5° field of view. The photometers of the SP integrate over the whole field of view, while the AP contains 16 vertically stacked anodes over 3.6° that integrate horizontally, but distinguish the altitude profile in about 10 km steps at 2500 km distance. The primary SP channels used in this work are the 150–280 nm (N_2 LBH) band that is strongly absorbed by O_2 and O_3 below 40 km altitude, and the 774–785 nm band, which includes the 777.4 nm atomic oxygen emission. The red filtered (N_2-1P) AP channels pointed at the high altitude optical emissions are also used here. Below 100 km where ambient atomic O is minimal this emission is only emitted by higher energy discharges such as lightning and therefore it is primarily seen only at low altitudes (<40 km).

3. Radio and ISUAL Data

[8] On the basis of observations of their ELF radiation, sprite currents are defined empirically as ~1–2 ms pulses of ELF radiation that contain no VLF energy (distinguishing it from a return stroke) and that follow a lightning return stroke by a few milliseconds to a few hundred milliseconds (see *Cummer* [2003] for an example). We note that slower postdischarge current intensifications contained in the lightning channel also occur in association with sprites [*Cummer and Füllekrug*, 2001; *Ohkubo et al.*, 2005]. This definition places limits on the sensors required to unambiguously identify sprite currents: they must be sensitive between approximately 100 Hz and 1 kHz to detect the bulk of the energy in the sprite current pulses, and they must be sensitive above at least a few kHz in order to detect the VLF radiation that discriminates CGs from sprite currents. From a practical standpoint, it is more difficult to identify sprite current pulses the greater the distance from the stroke because the VLF energy becomes relatively weaker and temporally separated from the ELF pulse. On the basis of experience, detection is relatively straightforward for propagation distances less than a few thousand kilometers.

[9] In light of these constraints, we carefully examined for sprite current signatures the 14 ELF/VLF signals recorded that were associated with sprites detected by ISUAL in the American and Caribbean regions (defined roughly as −60° to −110°E longitude) in August through October 2004 and June through July 2005. Two of these contained sprite current signatures, which is consistent with the ~10% fraction reported by *Cummer* [2003] from an analysis of hundreds of sprites and ELF/VLF signatures during the summer of 2000.

[10] The first of these sprites was detected by ISUAL on 3 October 2004 at 0426:55.610 UT (~±5 ms due to documented timing uncertainties) with an estimated location of 12.1°N–87.5°E. The top panel of Figure 1 shows the azimuthal component (B_ϕ) of the ELF/VLF magnetic field recorded at Duke (2780 km from the approximate lightning location) at this time. The large sferic detected at

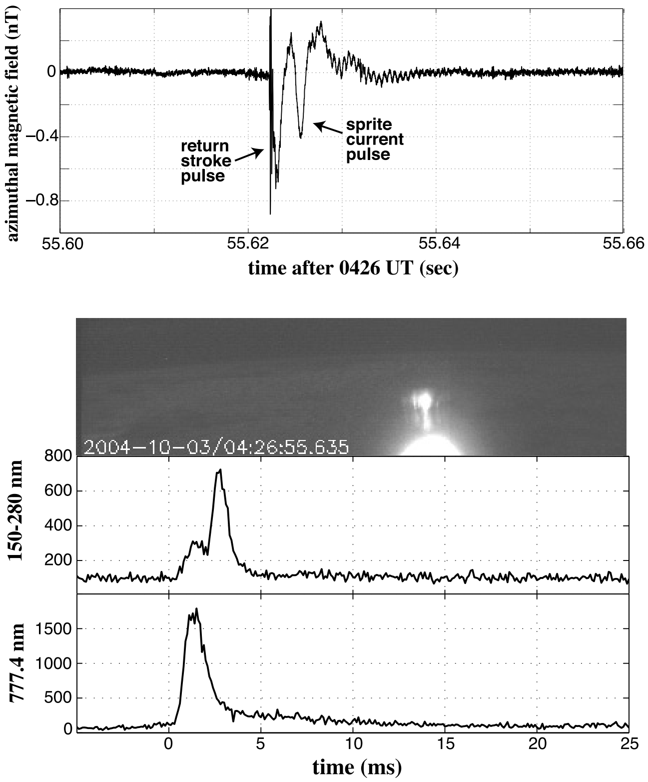

Figure 1. (top) VLF/ELF sferic containing a sprite current pulse recorded on 3 October 2004 at 0426:55.6 UT. (bottom) ISUAL data from the same sprite.

0426:55.622 UT is within the ∼±5 ms ISUAL timing uncertainty after subtraction of the 9.2 ms speed of light propagation from the lightning location to the sensor and is almost certainly radiated by the lightning stroke that produced the sprite. The predominantly negative polarity of the return stroke ELF (<1 kHz) B_ϕ pulse indicates net downward charge motion and a positive lightning stroke. The remotely measured impulse lightning charge moment change in this stroke is 390 C km. This includes the charge motion in the first 2 ms of the stroke and thus includes only the lightning return stroke, not continuing current or sprite current. The sprite current pulse, per the above definition, begins 2.5 ms after the return stroke onset defined by the sferic leading edge. Note the lack of VLF energy associated with this second pulse, which bounds the rise time of the source current moment at greater than 1 ms and shows that it is not produced by a lightning return stroke. The event timing indicates that the lightning charge moment change at sprite initiation is close to the 390 C km impulse charge moment change, which in turn is comparable to the 350–600 C km charge moment change threshold for short-delayed sprites measured by *Cummer and Lyons* [2005].

[11] The bottom three panels of Figure 1 show the relevant ISUAL data for this event. Some of the individual SP channels were saturated for this event and are not shown. The top panel shows a 29 ms integrated sprite image. The overall morphology is typical of large and bright sprites [*Sentman et al.*, 1995], containing multiple sprite elements with bright tops above roughly 60 km and dimmer emissions extending down to roughly 40 km. The middle panel shows the luminosity detected by the 150–280 nm photometer channel. These wavelengths are strongly absorbed by O_2 and O_3 in the lower atmosphere and this signal is primarily emissions only from above 40 km (i.e., the sprite). The stronger peak at 2.5 ms is from the main brightening of the sprite; the weaker peak at 1 ms could be a weak halo not visible in the image or could be strongly attenuated low-altitude emissions. The bottom panel of the figure shows the narrowband 777.4 nm photometer channel. As noted previously, 777.4 nm originates in the dissocation of O_2 in lightning and is thus a low altitude emission that is essentially confined to the lightning itself.

[12] The second of these sprites was observed on 30 July 2005 at 0439:42.717 UT with an estimated location of 30.6°N–84.6°E, only 785 km from the sensors. The top panel of Figure 2 shows the recorded ELF/VLF B_ϕ from this stroke. As in the other case, the negative ELF polarity indicates a positive stroke, and a sprite current pulse begins 3.0 ms after the return stroke. The remotely measured impulse lightning charge moment change in this stroke is 186 C km. Note that this value is somewhat lower than expected for a short-delayed sprite based on past measurements [*Cummer and Lyons*, 2005] and theory [*Pasko et al.*, 1997]. However, this return stroke was preceded by another positive CG 120 ms earlier, in apparently the same location and which was followed by a strong continuing current. Thus the electric field responsible for producing this sprite was almost certainly produced partly by this preceding continuing current, a possibility enabled by the slow

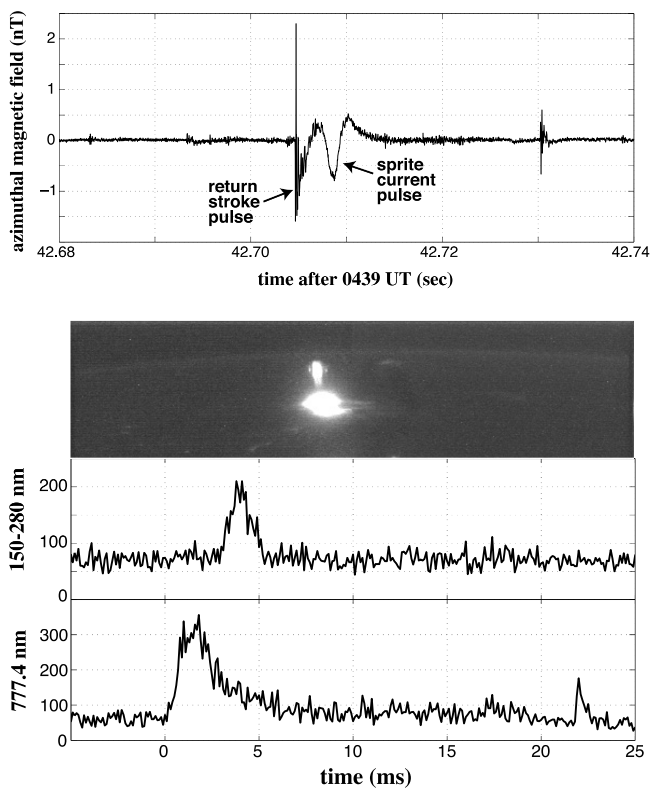

Figure 2. (top) VLF/ELF sferic containing a sprite current pulse recorded on 30 July 2005 at 0439:42.7 UT. (bottom) ISUAL data from the same sprite.

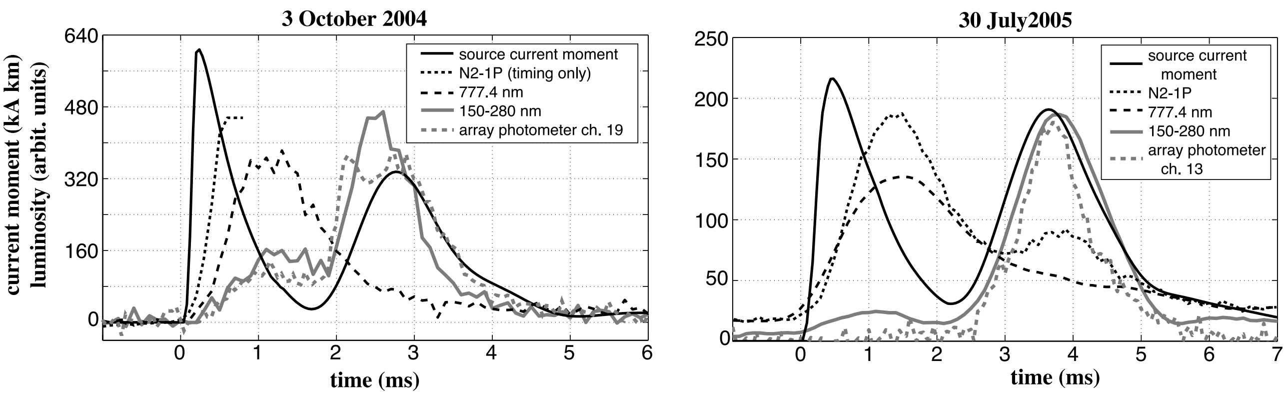

Figure 3. Time-aligned source current and optical emission waveforms for the 3 October 2004 and 30 July 2005 events.

dielectric relaxation time between 60 and 70 km altitude [*Holzworth et al.*, 2005]. This resulted in an anomalously low return stroke charge moment change for a sprite producing stroke.

[13] As before, the 150–280 nm channel shows the delayed, high-altitude sprite emissions, while the 777.4 nm SP channel shows the low altitude lightning emission. This event is approximately 2 times dimmer than the other, and the noise in the two channels is consequently higher. Overall, these two events are quite similar in both the ELF/VLF and ISUAL data.

4. Sprite Current Analysis

[14] To examine the specific relationship between the optical emissions, lightning currents, and possible sprite currents, we applied the approach described by [*Cummer and Inan*, 2000] to extract the source current moment waveform that produced the observed ELF/VLF magnetic fields in each of these two cases. The stories told by each of these examples are essentially identical.

[15] The left panel of Figure 3 shows, for the 3 October 2004 event, the extracted source current moment waveform, luminosity at high (150–280 nm) and low (777.4 nm) altitudes and N_2-1P luminosity in a narrow altitude range near the middle of the sprite (array photometer channel 19) after precise time alignment relative to the lightning onset. The saturated wide field N_2-1P SP channel (609–753 nm, including N_2-1P and N_2^+ Meinel) is shown because it contains a clearer event onset than the other channels and was used to align the optical data and inferred current moment waveform. The second current pulse and high altitude sprite luminosity are in submillisecond time correlation as has been found in all other cases analyzed in this way [e.g., *Cummer et al.*, 1998]. The double-peaked array photometer data give a particularly insightful view into this correlation. The first, sharp peak at t = 2.1 ms corresponds to the downward propagating streamers that closely follow sprite initiation [*Stanley et al.*, 1999; *Cummer et al.*, 2006]. This can be seen from the other array photometer channels (not shown) that show a clear downward motion in time of this narrow pulse [e.g., *McHarg et al.*, 2002]. The second, broader peak, centered around t = 2.7 ms, corresponds to the subsequent brightening of the upper portion of the sprite. This close alignment between the sprite current and the postinitiation sprite brightening has been found before [*Cummer and Stanley*, 1999] and suggests that sprite currents flow most strongly during this subsequent brightening, not during the initial downward streamer motion.

[16] The right panel of Figure 3 shows the same information in the same format for the 30 July 2005 event. The high-altitude optical emissions from the 150–280 nm channel and channel 13 of the array photometer clearly show the sprite luminosity with little or no lightning luminosity. The low-altitude optical emission from the 777.4 nm channel shows prompt return stroke luminosity with no increase in optical emissions at the time of the sprite. The N_2-1P SP channel reflects both lightning and sprite emissions and shows both peaks. The source current moment waveform shows the expected two peaks, with the second, sprite current peak in approximately 100 μs time alignment with the high-altitude optical emissions. The small timing discrepancy is easily attributed to uncertainties in the absolute time alignment of the optical and radio data.

[17] These two cases of close time alignment are still only indirect evidence that the second current moment pulse originates in the sprite, not the lightning. This type of subsequent current pulse is similar to a lightning M-component, which is a surge of current and luminosity in a postreturn stroke continuing current [see, e.g., *Rakov and Uman*, 2003, Figure 4.55]. Figure 3 confirms, however, that in both cases there is no intensification of low-altitude luminosity (777.4 nm) during the second pulse. Given the strong and comparable ELF intensities of the return stroke and sprite current pulses and that the channel current and luminosity of M-components are strongly correlated [*Fisher et al.*, 1993], it seems likely that some low altitude luminosity should be seen if the current that radiates the latter pulse flows in the lightning channel. This we address further the next section.

5. Continuing Current Analysis

[18] To show that ISUAL is capable of detecting optical emissions from post-return-stroke processes such as M-components, we analyze here whether optical emissions associated with continuing current are detected by ISUAL. If both the return stroke and continuing current are visible, it becomes difficult to imagine a process in which tens of coulombs of charge flow from cloud to ground in a few

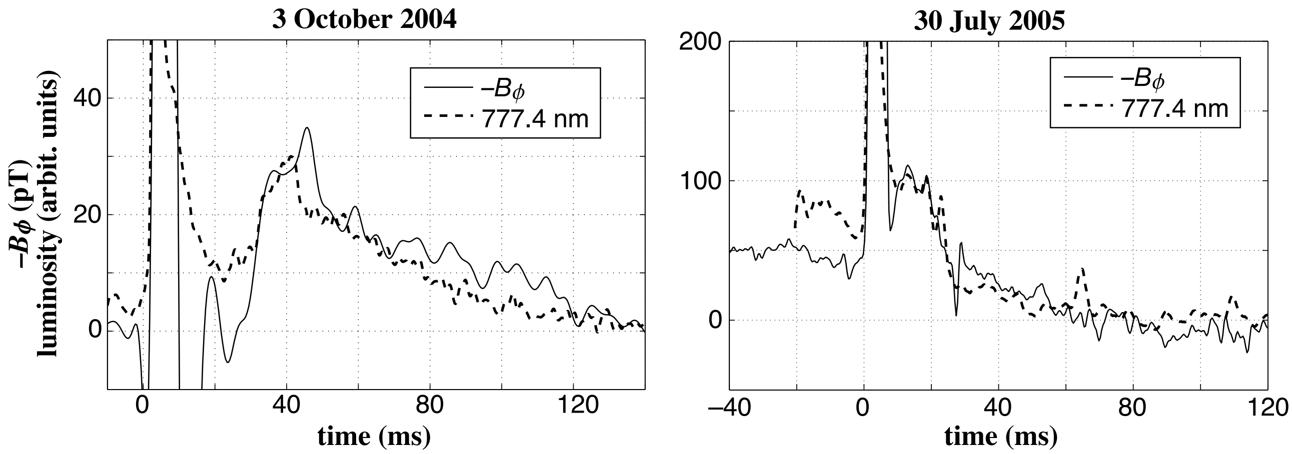

Figure 4. Correlation between low altitude lightning luminosity and the distant quasi-static magnetic field signature for both events. The almost linear connection indicates that the observed luminosity is proportional to the vertical, cloud-to-ground continuing current.

milliseconds that would not be visible in the low-altitude optical emissions. This analysis has the secondary result of providing further evidence that distant quasi-magnetostatic fields attributed by [*Cummer and Füllekrug*, 2001] to unusually large continuing currents are produced by lightning continuing currents.

[19] Figure 4 shows for both events, on a longer timescale than above, the ISUAL 777.4 nm channel aligned with the <0.1–400 Hz inverted B_ϕ signal ($-B_\phi$ is shown so that both curves are positive) measured by the lower frequency coils described in section 2. For the more distant, 3 October 2004 event, the left panel the low-altitude luminosity drops steadily for 20 ms after the return stroke but increases again at t = 30 ms and then falls steadily to zero at t = 140 ms. This luminosity is also seen in the images that are collected for 120 ms after the return stroke. After the initial transients decay at about t = 20 ms, the low-frequency magnetic field rises and falls almost in lockstep with the 777.4 nm luminosity.

[20] For the closer, 30 July 2005 event, the same connection is evident. The two signals become linearly proportional after only 10 ms because the shorter distance to the stroke puts the sensors in the quasi-static near field for higher frequencies. Both signals are approximately constant until t = 20 ms, at which point both drop sharply by almost a factor of 4. They then both decay approximately linearly to zero at t = 80 ms. In this case, interestingly, neither B_ϕ nor the 777.4 luminosity are zero before the return stroke. This is because a return stroke 120 ms earlier was followed by strong continuing current which persisted through the second, sprite-associated return stroke shown here. This earlier continuing current produced easily detectable 777.4 luminosity and quasi-static magnetic fields. ISUAL did not trigger on the earlier return stroke and thus no photometer data are available.

[21] The continuing current generates the observed quasi-magnetostatic fields through the physical current and the associated infinite series of ground and ionospheric image currents [*Cummer and Füllekrug*, 2001]. At the 2780 km range from the source for the 3 October 2004 event, the 30 pT peak of the slowly varying component of the azimuthal magnetic field (approximately 40 ms after the return stroke) corresponds to a continuing current moment of 33 kA km (or 4.2 kA for an 8 km lightning channel) with an assumed nighttime effective ionospheric height of 80 km. The slowly varying signal from the 30 July 2005 event at 785 km range is 3.3 times bigger at its peak 15 ms after the return stroke, but it is also 3.5 times closer to the sensor. This results in an almost identical peak continuing current moment of 31 kA km.

[22] These two cases show that continuing current amplitude, which is linearly proportional to the quasi-static magnetic field [*Cummer and Füllekrug*, 2001], is itself close to linearly proportional to the 777.4 luminosity. This is not a surprise given the known link between channel current and luminosity [*Fisher et al.*, 1993]. From this, we can conclude that continuing currents bigger than approximately 1 kA are seen by ISUAL through the 777.4 nm channel. Consequently, M-components of comparable amplitude, when present, should also be visible. In both of these cases the current moment of the second peak is several hundred kA km. If it were an M-component, the second peak should thus be easily seen in the low altitude 777.4 nm photometer channel. The lack of any 777.4 nm emissions that follow the rise and fall of the second pulse of ELF radiation observed in these two events strongly suggests that the source current is not flowing in a lightning-related process at cloud and lower altitudes. It is possible that some unusual lightning process is radiating these strong ELF fields without any detectable optical emissions. However, the simpler explanation, and one that is expected theoretically if sprites modify the mesospheric electrical conductivity [*Pasko et al.*, 1998], is that these pulses originate in high-altitude currents in the sprite itself.

6. Conclusions

[23] Using simultaneous multispectral optical measurements from the ISUAL instrument on the FORMOSAT-2 satellite and ground-based magnetic field measurements spanning a frequency range from <0.1 Hz to 30 kHz, two elements of the connection between the radio and optical emissions were investigated. Two individual cases were analyzed in detail. From both events, it was shown the

quasi-static magnetic field amplitude closely follows the low-altitude 777.4 nm luminosity observable from orbit, confirming that this radio signature is produced by strong lightning continuing current that can be measured quantitatively through analysis of the magnetic field waveform. This also demonstrates the ability of ISUAL to see optical emissions associated with changes in cloud-to-ground continuing current, such as M-components, that are known to have an optical signature. Each of these two events contained a strong post-return-stroke ELF magnetic pulse that that occurred without any observable intensification of low-altitude optical emissions. Given that continuing currents on the order of 1 kA were associated with observable 777.4 emissions, the observed pulses of several hundred kA km vertical current moment almost certainly should have produced detectable optical emissions if they were associated with a low-altitude lightning process. We conclude that the vertical source current responsible for this class pulse does not flow in a low-altitude lightning process but instead flows at mesospheric altitudes in the sprite itself.

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References

Boccippio, D. J., E. R. Williams, S. J. Heckman, W. A. Lyons, I. T. Baker, and R. Boldi (1995), Sprites, ELF transients, and positive ground strokes, *Science*, *269*(5227), 1088–1091.

Chern, J. L., R. R. Hsu, H. T. Su, S. B. Mende, H. Fukunishi, Y. Takahashi, and L. C. Lee (2003), Global survey of upper atmospheric transient luminous events on the ROCSAT-2 satellite, *J. Atmos. Terr. Phys.*, *65*, 647–659.

Cummer, S. A. (2003), Current moment in sprite-producing lightning, *J. Atmos. Sol. Terr. Phys.*, *65*, 499–508.

Cummer, S. A., and M. Füllekrug (2001), Unusually intense continuing current in lightning causes delayed mesospheric breakdown, *Geophys. Res. Lett.*, *28*, 495–498.

Cummer, S. A., and U. S. Inan (2000), Modeling ELF radio atmospheric propagation and extracting lightning currents from ELF observations, *Radio Sci.*, *35*, 385–394.

Cummer, S. A., and W. A. Lyons (2005), Implications of lightning charge moment changes for sprite initiation, *J. Geophys. Res.*, *110*, A04304, doi:10.1029/2004JA010812.

Cummer, S. A., and M. Stanley (1999), Submillisecond resolution lightning currents and sprite development: Observations and implications, *Geophys. Res. Lett.*, *26*(20), 3205–3208.

Cummer, S. A., U. S. Inan, T. F. Bell, and C. P. Barrington-Leigh (1998), ELF radiation produced by electrical currents in sprites, *Geophys. Res. Lett.*, *25*(8), 1281–1284.

Cummer, S. A., N. Jaugey, J. Li, W. A. Lyons, T. E. Nelson, and E. A. Gerken (2006), Submillisecond imaging of sprite development and structure, *Geophys. Res. Lett.*, *33*, L04104, doi:10.1029/2005GL024969.

Fisher, R. J., G. H. Schnetzer, R. Thottappillil, V. A. Rakov, M. A. Uman, and J. D. Goldberg (1993), Parameters of triggered-lightning flashes in Florida and Alabama, *J. Geophys. Res.*, *98*, 22,887–22,902.

Frey, H. U., et al. (2005), Beta-type stepped leader of elve-producing lightning, *Geophys. Res. Lett.*, *32*, L13824, doi:10.1029/2005GL023080.

Füllekrug, M., and S. Constable (2000), Global triangulation of intense lightning discharges, *Geophys. Res. Lett.*, *27*(3), 333–336.

Füllekrug, M., D. R. Moudry, G. Dawes, and D. D. Sentman (2001), Mesospheric sprite current triangulation, *J. Geophys. Res.*, *106*(D17), 20,189–20,194.

Holzworth, R. H., M. P. McCarthy, J. N. Thomas, J. Chin, T. M. Chinowsky, M. J. Taylor, and O. Pinto (2005), Strong electric fields from positive lightning strokes in the stratosphere, *Geophys. Res. Lett.*, *32*, L04809, doi:10.1029/2004GL021554.

Hu, W., S. A. Cummer, W. A. Lyons, and T. E. Nelson (2002), Lightning charge moment changes for the initiation of sprites, *Geophys. Res. Lett.*, *29*(8), 1279, doi:10.1029/2001GL014593.

McHarg, M. G., R. K. Haaland, D. Moudry, and H. C. Stenbaek-Nielsen (2002), Altitude-time development of sprites, *J. Geophys. Res.*, *107*(A11), 1364, doi:10.1029/2001JA000283.

Mende, S. B., H. U. Frey, R. R. Hsu, H. T. Su, A. B. Chen, L. C. Lee, D. D. Sentman, Y. Takahashi, and H. Fukunishi (2005), D region ionization by lightning-induced electromagnetic pulses, *J. Geophys. Res.*, *110*, A11312, doi:10.1029/2005JA011064.

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, doi:10.1029/2004GL021943.

Orville, R. E. (1991), Calibration of a magnetic direction finding network using measured triggered lightning return stroke peak currents, *J. Geophys. Res.*, *96*(D9), 17,135–17,142.

Pasko, V. P., U. S. Inan, T. F. Bell, and Y. N. Taranenko (1997), Sprites produced by quasi-electrostatic heating and ionization in the lower ionosphere, *J. Geophys. Res.*, *102*(A3), 4529–4561.

Pasko, V. P., U. S. Inan, T. F. Bell, and S. C. Reising (1998), Mechanism of ELF radiation from sprites, *Geophys. Res. Lett.*, *25*(18), 3493–3496.

Rakov, V. A., and M. A. Uman (2003), *Lightning*, Cambridge Univ. Press, New York.

Sato, M., and H. Fukunishi (2003), Global sprite occurrence locations and rates derived from triangulation of transient Schumann resonance events, *Geophys. Res. Lett.*, *30*(16), 1859, doi:10.1029/2003GL017291.

Sentman, D. D., E. M. Wescott, D. L. Osborne, D. L. Hampton, and M. J. Heavner (1995), Preliminary results from the SPRITES94 aircraft campaign: 1. Red sprites, *Geophys. Res. Lett.*, *22*(10), 1205–1208.

Stanley, M., P. Krehbiel, M. Brook, C. Moore, W. Rison, and B. Abrahams (1999), High speed video of initial sprite development, *Geophys. Res. Lett.*, *26*(20), 3201–3204.

Thomas, J. N., R. H. Holzworth, M. P. McCarthy, and O. Pinto (2005), Lightning sferics and stroke-delayed pulses measured in the stratosphere: Implications for mesospheric currents, *Geophys. Res. Lett.*, *32*, L22807, doi:10.1029/2005GL024629.

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