

Lightning sferics and stroke-delayed pulses measured in the stratosphere: Implications for mesospheric currents

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[1] During the Brazil Sprite Balloon Campaign 2002–03, the vector ELF to VLF (25 Hz–8 kHz) electric and magnetic fields driven by cloud-to-ground (CG) lightning strokes at horizontal distances of 75–600 km were measured at altitudes of 30–35 km. Electric field changes were measured for each of the 2467 CG strokes detected by the Brazilian Integrated Lightning Network. ELF pulses that occur 4–12 ms after the retarded time of the lightning sferic, which have been previously attributed to sprites, were found for 1.4% of 934 strokes examined. Thus, lightning-driven electric and magnetic field changes were common and stroke-delayed ELF pulses were rare, which disagrees with results from the Sprites99 Balloon Campaign. **Citation:** Thomas, J. N., R. H. Holzworth, M. P. McCarthy, and O. Pinto Jr. (2005), Lightning sferics and stroke-delayed pulses measured in the stratosphere: Implications for mesospheric currents, *Geophys. Res. Lett.*, *32*, L22807, doi:10.1029/2005GL024629.

1. Introduction

[2] Ground-based and aloft (balloon-, aircraft- and rocket-borne) measurements of electric and magnetic field changes (dc to VLF) driven by lightning strokes have been conducted by numerous researchers [e.g., Holzworth *et al.*, 1985; Blakeslee *et al.*, 1989; Cummer *et al.*, 1998]. Since the first imaging of electrical discharges in the mesosphere above thunderstorms in 1989 [Franz *et al.*, 1990], many ground-based studies have focused on measuring the ULF to VLF waveforms of sprite-parent lightning and sprites themselves [Cummer *et al.*, 1998; Sato *et al.*, 2003]. A well accepted model for sprite production involves a quasi-electrostatic field (QSF) that forms after a large charge moment change, positive cloud-to-ground (+CG) stroke [Pasko *et al.*, 1997; Thomas *et al.*, 2005; Thomas, 2005], which if large enough, can cause electrical breakdown in the mesosphere. Electric and magnetic fields, driven by lightning strokes and measured at horizontal distances greater than about 75 km, are dominated by the induced fields due to the current flowing in the lightning stroke and radiated fields due to the time derivative of this current. Although these induced and radiated fields, which only exist for a few ms, are presumably not capable of generating sprites that often occur many ms after the parent stroke [São Sabbas *et al.*, 2003], they can be used as remote

sensors of the lightning current and sometimes the subsequent sprite current. Cummer *et al.* [1998] was the first to report ELF pulses correlated in time with images of sprites, which occurred a few ms after large charge moment change +CG lightning-driven sferics. This correlation suggests that these stroke-delayed pulses are evidence of mesospheric currents. Pasko *et al.* [1998] numerically modeled the ELF electric and magnetic fields driven by large charge moment change lightning strokes, which further supports that mesospheric currents drive these stroke-delayed pulses.

[3] The Sprites99 Campaign [Bering *et al.*, 2002, 2004a, 2004b; Bhusal *et al.*, 2004] was the first stratospheric balloon experiment that included ground-based sprite imaging with balloon-borne electric and magnetic field measurements. During Sprites99, the ELF lightning sferics were rarely measured, but stroke-delayed pulses were measured for 90% of the CG strokes detected by the National Lightning Detection Network (NLDN) [Bering *et al.*, 2004a, 2004b; Bhusal *et al.*, 2004]. These Sprites99 results, which suggest that mesospheric breakdown is a fundamental response to nearly all CG lightning, disagree with the ground-based measurements [Cummer *et al.*, 1998] and models [Pasko *et al.*, 1998] that indicate that all CG lightning drive ELF to VLF sferics and that only lightning with large charge moment changes should drive mesospheric currents. This letter presents results from the Brazil Sprite Balloon Campaign 2002–03, including vector ELF to VLF (25 Hz–8 kHz) stratospheric electric and magnetic fields driven by CG lightning, that disagree with Sprites99 observations.

2. Data Set

[4] The data used in this study are balloon-borne measurements in the stratosphere at altitudes of 30–35 km of vector electric (25 Hz–8 kHz) and magnetic fields (300 Hz–8 kHz) from the Brazil Sprite Campaign 2002–03 [Thomas *et al.*, 2004; Holzworth *et al.*, 2005; Thomas *et al.*, 2005; Thomas, 2005], along with CG lightning locations and peak currents given by the ground-based Brazilian Integrated Lightning Network (BIN) [Holzworth *et al.*, 2005, Figure 1]. The electric fields were obtained using the double Langmuir probe technique, which measured the voltage difference between pairs of conductors isolated via high input impedance operational amplifiers [Thomas *et al.*, 2004]. Separate low voltage (LV) and high voltage (HV) electric field sensors allowed for fields as small as 5 mV/m and as large as 195 V/m to be accurately measured. The

magnetic fields were measured using search coils with a full scale range of ± 15 nT. Two balloon payloads each equipped with these double Langmuir probe electric field sensors and magnetic search coils flew over or near intense thunderstorm activity in the southeast of Brazil on Dec. 6–7, 2002 (Flight 1) and March 6–7, 2003 (Flight 2). However, due to a ground station noise problem during Flight 2, only the data acquired during Flight 1 are used in this study. The view of the aircraft-based imaging cameras was blocked by clouds, so sprites could not be observed during the balloon flights. Moreover, the uplooking optical power sensor (a photo-diode) malfunctioned during Flight 1, preventing any detection of light sources located above the payload altitude. Sprites were imaged at other times during the campaign when there were no balloon flights [Pinto *et al.*, 2004]. The quasi-dc electric fields and conductivity measured during the Brazil Sprite Campaign have been discussed in previous publications [Thomas *et al.*, 2004; Holzworth *et al.*, 2005; Thomas *et al.*, 2005; Thomas, 2005].

3. Data Selection

[5] The vector electric fields driven by 2467 lightning strokes at horizontal distances of 75–600 km from the balloon payload (float altitude of 30–35 km) were measured including 429 +CG strokes. These strokes were all of the strokes detected by BIN at distances of 75–600 km during times when the balloon sensors and telemetry system were working properly, thus every stroke produced ELF to VLF electric field signals. An automated routine plotted the electric and magnetic field data at the times indicated by BIN. There were other lightning transients measured at the balloon not detected by BIN that are not part of this study. The electric field measurements for each of these 2467 strokes were examined individually to verify that the field change indeed occurred at the retarded time (speed of light delay time) of the lightning sferic. For 858 of these 2467 strokes, both the vector electric and magnetic fields were measured. Presumably, all of the strokes drove magnetic field changes, but only 35% of them produced signals above the noise level of 0.3 nT for B_z and 0.9 nT for B_ϕ and B_r (peak-to-peak noise magnitudes). The ratios of the magnitudes of the electric field and magnetic changes (E/B , using the peak-to-peak amplitudes of the initial lightning-driven sferics) for these ELF to VLF measurements had mean values of $(4.3 \pm 2.2) \times 10^8$ m/s for the +CG strokes and $(3.8 \pm 1.5) \times 10^8$ m/s for the –CG strokes. For the +CG strokes and –CG strokes, the speed of light ($c = 2.99 \times 10^8$ m/s) falls within the error bars of these mean E/B , which suggests that our field measurements were calibrated properly. The large errors in E/B are due to the high background noise level in the magnetic field data generated by electronics elsewhere on the payload.

[6] Electric and magnetic field data from Flight 1 of 934 CG strokes that occurred between 02:47:00 and 10:30:00 Dec. 7, 2002 at distances of 150–600 km were examined for evidence of delayed pulses that occurred 4–12 ms after the arrival of the lightning stroke-driven sferic. To prevent detection of false stroke-delayed pulses that were actually part of the slow tail of the lightning-driven sferic, delayed pulses that occurred within 4 ms were not included. Data obtained before 02:47:00, during a

period of nearby storm activity (75–150 km), were excluded to eliminate lightning-driven quasi-electrostatic fields (which last for 10 s–100 s of ms) that could produce false delayed pulses. An automated search routine identified 240 candidate strokes (of the 934 studied) for which the vertical electric field was greater than two standard deviations above the background value during the 4–12 ms time window after the retarded time of the lightning sferic. The electric field measurements for these 240 strokes were then examined individually. Only unipolar pulses that had frequencies less than 1 kHz (to eliminate pulses driven by tropospheric discharges that tend to produce higher frequency radiation) and were consistent with mesospheric current flow (positive polarity for +CG strokes, negative for –CG strokes) were considered. It was determined that only 0.5% (4/750) of the –CG strokes and 4.9% (9/184) of the +CG strokes were followed by ELF pulses that fit these criteria. These stroke-delayed pulses were only evident in the vertical electric field data. Charge moment changes for these lightning events are not known. Future studies may involve estimating charge moment changes from these stratospheric data or from distant ELF sensors in Japan and Antarctica [Sato *et al.*, 2003].

4. Case Studies

[7] Figure 1 is the ELF to VLF electric and magnetic field data for a 111 kA +CG stroke that occurred at 03:01:50 UT Dec. 7, 2002 about 328 km from the payload measured at an altitude of 32.7 km. Figure 2 is data for a 101 kA +CG stroke which occurred at 08:22:39 UT (after sunrise) about 409.9 km from the payload measured at an altitude of 35.1 km. A stroke-centered cylindrical coordinate system is used, and the dashed vertical lines are the retarded times at the payload of the CG lightning strokes. The vertical electric field (Figures 1a and 2a) and azimuthal magnetic field (Figures 1e and 2e) components were dominant with polarity of the transients consistent with a vertical flow of current downward, as in a +CG stroke, with ELF frequencies of a few hundred Hz dominant in both the electric and magnetic field data. The mechanism that drives the relatively large, damped oscillations present in the azimuthal and radial components of the electric field in Figure 1, but only weakly in Figure 2, is not understood. These damped oscillations were found in the azimuthal and radial components of the electric field changes driven by some of the other distant lightning strokes as well. One possible explanation is that these oscillations are reflections of the lightning-driven VLF radiation in the earth-ionosphere waveguide. To further support this explanation, the 0.5 ms oscillation period in Figure 1 is approximately the speed of light travel time for a lightning-driven sferic generated near the ground to propagate to the lower ionospheric boundary at 90 km and reflect back down to the balloon payload at 33 km.

[8] For each event, the vertical electric field saturates the LV field sensor, so the peak value of this component cannot be determined from these data. By examining data from the HV electric field sensor (not shown) for these events, the peak values were determined to be 1.6 ± 0.2 V/m (+111 kA +CG) and 0.9 ± 0.2 V/m (+101 kA +CG) with the large uncertainty due to the poor sensitivity of the HV field sensor for small field changes. The electric to magnetic field ratio

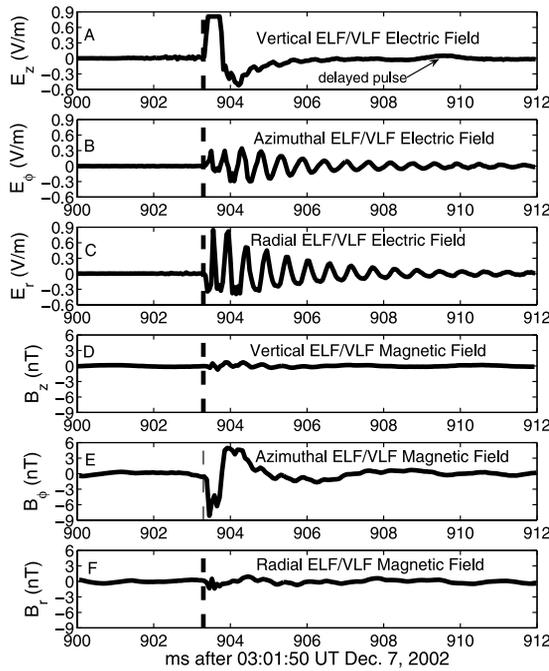


Figure 1. The ELF/VLF electric and magnetic field transient from a 111 kA +CG lightning stroke located 328 km horizontal distance from the payload measured at an altitude of 32.7 km.

for these events are $E/B \approx 2.86 \times 10^8$ and 2.37×10^8 or about 96% and 79% of the speed of light in vacuum c . While 96% of c is a reasonable value for electromagnetic radiation in the earth-ionosphere waveguide at these ELF frequencies, 79% of c is lower than expected and is likely due to the HV sensor not measuring this small field change properly.

[9] The best examples of stroke-delayed ELF pulses in the data set are the 111 kA and 101 kA +CG strokes examined above with ELF/VLF data shown in Figures 1 and 2, although the stroke-delayed pulses are difficult to resolve due to the axis scaling used to capture the complete lightning transient. In Figure 3, the vertical electric field data for each of these +CG strokes are shown with the electric field axis adjusted to resolve the stroke-delayed pulses. For the 111 kA +CG stroke (Figure 3a), the stroke-delayed pulse can be seen with an amplitude of about 80 mV/m at 909–910 ms, which is about 5.5 ms after the retarded time of the lightning sferic. A pulse of about 95 mV/m at 837–839 ms or about 5 ms after the lightning sferic can be seen in Figure 3b for the 101 kA +CG. These pulses have similar delay times and magnitudes compared to those measured during the Sprites99 Campaign [Bering *et al.*, 2004b; Bhusal *et al.*, 2004], although the Brazil payloads detected the lightning sferics too, not just the delayed pulses. Bering *et al.* [2004b] and Bhusal *et al.* [2004] attributed these delayed pulses to mesospheric current moments, which were substantiated by optical data of sprites or halos that occur simultaneously with a small percentage of these pulses. Cummer *et al.* [1998] has measured similar delayed ELF pulses with ground-based magnetic field sensors that were directly correlated with video images of sprites. Note that the ground-based data of Cummer *et al.* [1998] always included the lightning sferic

first then the delayed pulse, like the measurements from the Brazil Sprite Campaign.

5. Discussion and Conclusions

[10] During the Brazil Sprite Balloon Campaign 2002–03, electric field changes (25 Hz–8 kHz) were measured at altitudes of 30–35 km for each of the 2467 CG strokes detected by the Brazilian Integrated Lightning Network (BIN), and magnetic field changes (300 Hz–8 kHz) above the background noise were measured for about 35% (858) of these strokes. The Brazil balloon payloads measured stroke delayed pulses for 1.4% of the 934 CG strokes examined with a bias towards +CGs (4.9% of all +CGs) compared to –CGs (0.5% of all –CGs). To verify that these delayed pulses were not an artifact of the response of the electric field sensor to a lightning sferic, the recovered sensor from Flight 1 was driven by simulated lightning sferics (1–10 V/m square waves at 100 Hz–2 kHz) in the laboratory and no delayed pulses were observed. If the stroke delayed pulses were due to vertical current flowing in the mesosphere, an azimuthal magnetic field component should also be measured at the payload. However, since these pulses are small in amplitude (less than 100 mV/m), the azimuthal magnetic field component (less than 0.33 nT assuming $B = E/c$) likely was not resolved above the background noise of the search coils.

[11] These distant (75–600 km) lightning events drove ELF to VLF electric and magnetic fields, with large vertical electric field and azimuthal magnetic field components, that are generally consistent with ground-based measurements [Cummer *et al.*, 1998] and models [Pasko *et al.*, 1998]. However, the results of the Brazil campaign are in disagreement with the previous balloon campaign, Sprites99, con-

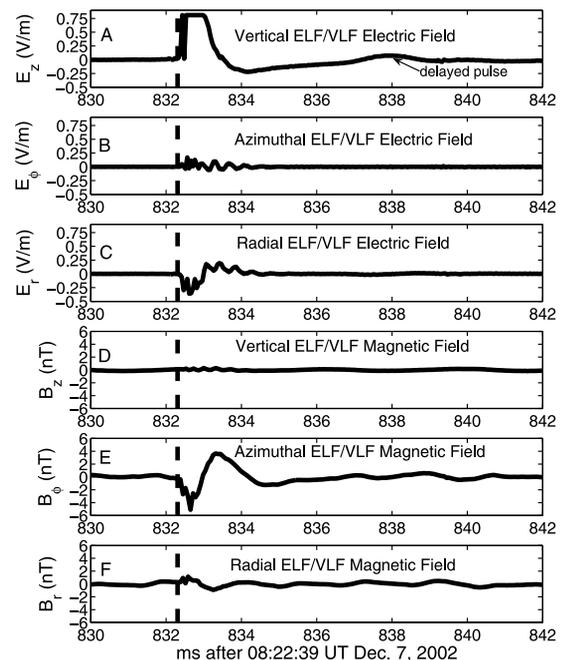


Figure 2. The ELF/VLF electric and magnetic field transient from a 101 kA +CG lightning stroke located 409.9 km horizontal distance from the payload measured at an altitude of 35.1 km.

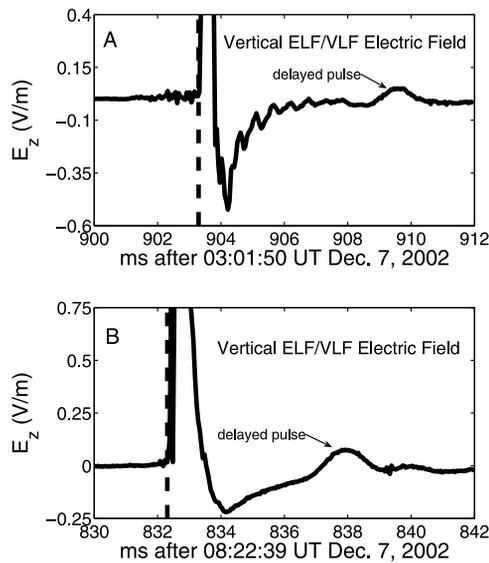


Figure 3. The ELF/VLF vertical electric field with the different axis scaling for the 111 kA (a) and 101 kA (b) +CG strokes shown in Figures 1 and 2. The delayed pulse can be seen in Figure 3a at about 909–910 ms and in Figure 3b at 837–839 ms.

ducted over the U. S. High Plains [Bering *et al.*, 2002, 2004a, 2004b; Bhusal *et al.*, 2004], which rarely measured the lightning sferics, but measured stroke-delayed pulses for 90% of CGs detected by NLDN that were attributed to mesospheric current. Although the Sprites99 payloads had a 1 kHz low pass filter [Bering *et al.*, 2004b], well below the 8 kHz filter employed on the Brazil payloads, the Brazil measurements, along with the ground-based measurements [Cummer *et al.*, 1998] and models [Pasko *et al.*, 1998], suggest that the Sprites99 payloads should have measured the ELF transient of the distant lightning. To test this quantitatively, the Brazil data were run through a 1 kHz low pass Fourier filter, and the lightning sferics remained evident for all 2467 strokes. Since stroke-delayed pulses were measured for almost every CG stroke during Sprites99, Bering *et al.* [2004b] and Bhusal *et al.* [2004] concluded that mesospheric breakdown and currents are a fundamental response to nearly all lightning strokes. This disagrees with the quasi-electrostatic field (QSF) model [see Pasko *et al.*, 1997; Thomas *et al.*, 2005] that suggests that only very large charge moment change lightning (greater than about 300–1000 C-km) are capable of producing mesospheric breakdown. For some of these stroke-delayed pulses measured during Sprites99, correlated sprites and halos were imaged, which indicates that at least some of these delayed pulses are indeed driven by mesospheric currents. Yet, the Brazil payloads rarely measured CG delayed pulses. The ionospheric conditions were presumably different during the Brazil flights at 22°–23°S latitude compared to mid-latitude Sprites99 flights, but this cannot explain the drastic disagreement between data sets. Hence, according to the Brazil data, mesospheric breakdown and currents are not a fundamental response to most CG lightning strokes, which is consistent with previous ground-based measurements [Cummer *et al.*, 1998] and a fully electromagnetic model of lightning-driven fields

[Pasko *et al.*, 1998]. Thus, the Brazil results suggest that there is no significant flaw in our understanding of the physics of the upward propagation of a sferic through the conducting atmosphere as suggested from the Sprites99 observations [Bering *et al.*, 2002]. Moreover, the Brazil results are not inconsistent with the QSF model of mesospheric current production.

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