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Intense continuing currents following positive cloud-to-ground lightning associated with red sprites

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Abstract. In July-August, 1996, Stanford University carried out broadband ELF/VLF measurements of the magnetic field radiated by positive cloud-to-ground (CG) discharges associated with Red Sprites. We report these measurements for 17 Sprite associated discharges that occurred during a 15 minute period on August 1, 1996. The current and charge moments for each of the events are deduced, and it is found that, in every case, intense continuing currents of ~1 ms duration are responsible for most of the positive charge transfer to ground that precedes the appearance of the Sprite. The time delay between the causative positive discharge and the video field in which the Sprite first appeared varied from 0 to 15 ms for the larger events to as much as 100 ms for the smaller events. We suggest that in the smaller events the removal of significant positive charge during this delay interval is accomplished through a horizontal intracloud discharge.

Introduction

Red Sprites consist of large scale, transient, luminous (predominantly red color) structures in the mesosphere, which appear above thunderclouds following positive cloud-to-ground (CG) lightning discharges [*Sentman et al.*, 1995]. Sprites generally extend vertically from ~40-90 km, possess a transverse scale of ~10-50 km, and according to photometer observations typically endure for 1-10 ms [*Takahashi et al.,* 1996; *Cummer et al.,* 1998]. A number of models proposed for explaining Sprite production hypothesize that large amounts of thundercloud charge are lowered to ground during the positive CG discharge which precedes the Sprite. The remaining negative cloud charge, plus polarization charge above the cloud tops, then produces an intense electric field above the clouds which exceeds over a large altitude range the threshold field for either ordinary air breakdown or runaway electron avalanche ionization [*Pasko et al.*, 1995, 1996; *Bell et al.*, 1995; *Roussel-Dupré and Gurevich*, 1996; *Rowland et al.*, 1996]. In either case, the resulting heated electrons impact the neutral air molecules, producing ionization and optical emissions, constituting the visible Sprite.

The amount of positive charge which must be lowered to ground in order to produce this effect is determined by the dipole moment of the charge. The magnitude of the post-discharge electric field E above the clouds which drives the Sprite is proportional to the original dipole moment of the positive charge Q which was removed; i.e., $E \sim Ql$, where l is the mean altitude of the charge. For $l \sim 10$ km, the necessary value of Q in models of Sprite production ranges from ~100-300 C. Since it is unlikely that 100 - 300 C could be lowered to ground in the duration of a return stroke, it has been proposed that these charge transfers result from intense continuing currents which flow during a period of approximately 1 to 20 ms following the first return stroke [*Pasko et al.*, 1995, 1996; *Reising et al.*, 1996].

If these intense continuing currents exist at the levels proposed, they should radiate intense ELF waves into the Earth-ionosphere waveguide. To observe these ELF waves at close range, a campaign was carried out by the Stanford University STAR Laboratory at the Yucca Ridge Sprite Observatory in Colorado (40°40′06″N, 104°56′24″W) during July, 1996. During this campaign, two orthogonal components of the horizontal magnetic field B_h of both positive and negative discharges were measured with an ELF/VLF receiving system.

The present paper shows how the ELF portion of the B_h waveforms can be used to determine the magnitude of the continuing currents that follow the first return strokes for each positive discharge. This task is accomplished using a well established model of ELF wave propagation in the Earth-ionosphere waveguide.

Recent work on this same topic shows how continuing currents can be deduced from measurements of B_h at distant points (> 1800 km) using a generalized numerical model of Earth-ionosphere waveguide propagation [*Cummer* and *Inan*, 1997]. The accuracy of this method depends upon how well the D-region is modeled along the propagation path. Comparison of the *Cummer and Inan* model predictions with those of our own model for a number of test cases indicates that the predicted currents generally differ by less than 25%. However since the *Cummer and Inan* model uses only the radiated fields from the source, significant errors can arise whenever the observation point is in the near field of the source. The method we use accounts for all field components generated by the source and is not significantly subject to the uncertainty of the ionosphere because of the proximity of the receiver to the sources. In addition to charge transfer results, we also present data concerning the time delay between the positive CG discharge and the first appearance of the Sprites in video.

Observations

We report data acquired on 01 August 96 during the period 0817-0832 UT when a mesoscale convective system produced a large number of positive discharges in southwestern Kansas, approximately 600 km southeast of the Yucca Ridge Observatory. Figure 1 shows the location, according to the National Lightning Detection Network (NLDN), of all the discharges which occurred during the 15 minute observation period. In total there were 940 flashes, of which 84 were positive. Of the positive discharges, 17 were found to be associated with Sprites, and each of these Sprites was uniquely associated with one of the 17 positive discharges. According to the NLDN, the 17 discharges had peak currents ranging from 27 to 160 kA, with an average value of 52 kA. Thus the Sprites were associated with discharge currents with a wide range of intensity.

The B_h component of the electromagnetic waves radiated in the Earth-ionosphere waveguide by each of the discharges was measured at Yucca Ridge by a broadband (15 Hz - 24 kHz) two-channel ELF/VLF receiver fed by vertically oriented crossed-loop antennas. A typical time series waveform of the B field produced by a positive discharge associated with a Sprite is shown in Figure 2. The single ELF pulse associated with the positive discharge is seen clearly in the lower panel and has a peak amplitude of ~14 nT and duration of ~1 ms. The ELF event shown in Figure 2 was associated with a Sprite of relatively large spatial scale as recorded

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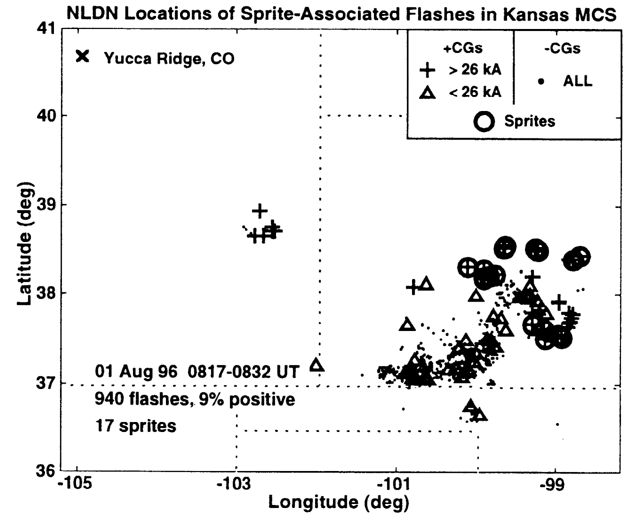

Figure 1. Geometrical symbols show the location of both positive and negative CG discharges in southwestern Kansas during the period 0817-0832 UT, 01 August, 1996. The locations of positive discharges associated with Sprites are shown by heavy circles encompassing "+" signs. The position of the Yucca Ridge Field Station is also shown.

on the Lockheed/Stanford low light level TV system which operated continuously during the events. A smaller sprite was associated with the positive discharge which produced the B field waveform shown in Figure 3. The ELF pulse, as shown in the lower panel of Figure 3, was of much lower amplitude ($\sim$3 nT) than the ELF pulse shown in Figure 2. but of similar shape and duration.

The ELF pulses shown in Figures 2 and 3 were typical of those observed and are evidence that continuing positive currents flow from the thundercloud to ground during a period of $\sim$1 ms following the first positive return stroke [c.f. *Reising et al.*, 1996]. The small negative excursion of the ELF amplitude extending from 2 to $\sim$7 ms is due to near field effects and not continuing current. In order to relate the characteristics of the ELF pulses to the characteristics of the continuing currents, a theoretical model is required. This model is described below.

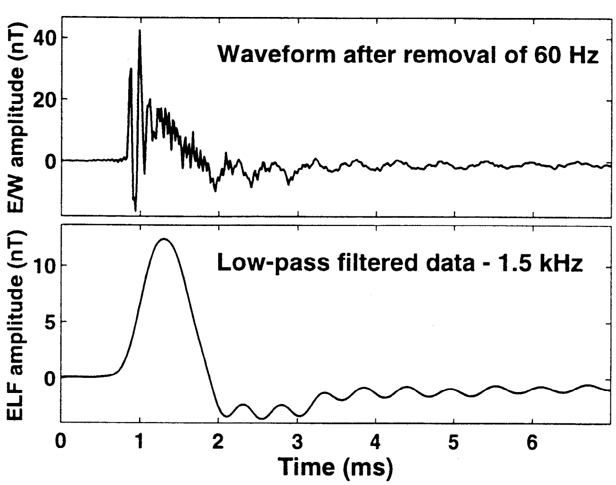

Figure 2. Time series waveform of the B field radiated by a large (163 kA, according to NLDN) positive CG discharge at 0826:09 UT and measured at Yucca Ridge on the E/W loop antenna. The upper panel shows the complete wideband waveform after removal of local 60 Hz interference. The lower panel shows the ELF waveform resulting from low-pass filtering of the broadband waveform.

Theoretical Model

For wave frequencies below $\sim$1.8 kHz, it is well known that only a single quasi-TEM waveguide mode can propagate within the Earth-ionosphere waveguide [*Greifinger and Greifinger*, 1986; *Sukhorukov*, 1992]. According to the waveguide model of *Greifinger and Greifinger* [1986], the horizontal magnetic field B_h produced by a vertical current element $I(t)$ of length l is related to the current through the Fourier transform relationship:

$$\begin{aligned} B_h(\omega) &= -i\frac{\mu_o}{4c}\frac{S_o^3(\omega)\omega}{\bar{h}_o(\omega)}H_1^{(1)}\left[\frac{\omega r}{c}S_o(\omega)\right]lI(\omega) \\ &\equiv F(\omega)lI(\omega) \end{aligned} \tag{1}$$

where $B_h(\omega)$ and $I(\omega)$ are the temporal Fourier transforms of $B_h(t)$ and $I(t)$, respectively; $S_o(\omega)$ is the complex effective refractive index of the single propagating ELF waveguide mode as defined in *Sukhorukov* [1992, equation 6] for highly conducting ground; r is the radial distance between the source $I(t)$ and the observer; $\bar{h}_o(\omega)$ is the equivalent complex height of the bottom of the ionosphere [Booker, 1980], ω is the angular frequency of the waveguide mode, and $H_1^{(1)}[\cdot]$ is the Hankel function of the first kind of order one.

We assume that the nighttime ionosphere is described by the exponential conductivity profile of *Greifinger and Greifinger* [1978] with scale height $\zeta_o = 2.8$ km. and with electron density of 300 electrons/cm^3 at the base of the E region at 90 km altitude.

The ELF frequency response of the receiver used is flat down to $\sim$ 100 Hz , but falls off slowly for $f < 100$ Hz. The overall response is nearly identical to that of a single-pole high pass filter with a -3 dB point of $f_o = 15$ Hz. Thus the Fourier transforms of the measured and actual fields are related through the expression:

$$B_{hm}(\omega) = \left(\frac{\omega}{\omega + i\omega_0}\right) B_h(\omega), \tag{2}$$

where $B_{hm}(\omega)$ is the Fourier transform of the total B field waveform measured on the N/S and E/W loop antennas and $\omega_o = 2\pi f_o$.

From (1) and (2), an inverse Fourier transform yields an expression relating the CG current $I(t)$ to $B_{hm}(\omega)$:

$$lI(t) = g(t) + \omega_0 \int_o^t g(t)\ dt \tag{3}$$

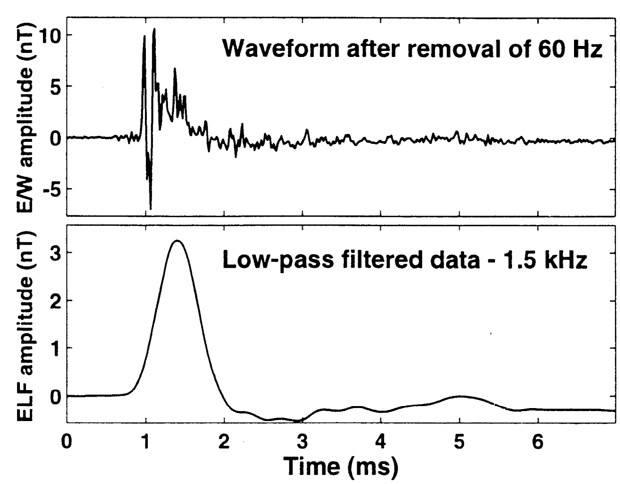

Figure 3. Time series waveform of the B field radiated by a smaller (52 kA) positive CG discharge. The ELF pulse shape is similar to that shown in Figure 2.

where $g(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} B_{hm}(\omega)F^{-1}(\omega)e^{-i\omega t}d\omega$. Thus once $B_{hm}(t)$ is found, the causative positive current moment can also be found. Clearly, if the current channel length l is known, then $I(t)$ can be found directly. Estimates of typical values of l range from 4-10 km [*Pasko et al.*, 1995, 1996; *Marshall et al.*, 1996].

Finally, the total charge removed from the cloud to the ground by the positive discharge is given by the expression:

$$Q_T = \int_{o}^{t_o} I(t)dt \tag{4}$$

where the discharge begins at $t = 0$ and t_o represents the time at which $|B_{hm}(t)|$ falls below the RMS noise level.

Lightning Currents

Figure 4 shows $lI(t)$ as calculated from (3) for the event shown in Figure 2. The current pulse has a form similar to that of the positive portion of the B field waveform shown in Figure 2. The current endures for $\sim$ 1 ms and peaks at a value of 180 kA, assuming that $l = 10$ km. Integrating the current over time, as in (4), it is found that $Q_T = 110\ C$. The ELF current pulse calculated for the event of Figure 3 is similar in form to that shown in Figure 4, but exhibits a peak current of only 52 kA and a total charge transfer of $Q_T = 32$ C (assuming $l = 10$ km).

In general in each case we determined $I(t)$ for the entire period during which $|B_h(t)|$ exceeded the RMS magnetic field noise level in the 15 Hz - 1.5 kHz pass band, which ranged from 0.01 to 0.02 nT during the observation interval. In all cases the major portion of the total CG current flowed within the first 1 to 3 ms following the beginning of the ELF current pulse and in 13 of the 17 cases no measurable B field from the discharge could be detected after 10 to 15 ms had passed.

In the other 4 events, small currents flowed for up to 50 ms following the initial large ELF current pulse. In these cases, discussed further below, Q_T was evaluated only over the 15 ms interval following the initial current pulse for consistency with the other events.

Performing a similar analysis of the remaining 15 events, we find that the average CG peak ELF current $\bar{I}_p$ and average total charge $\bar{Q}_T$ removed to ground have the values $\bar{I}_p \simeq 57$ kA and $\bar{Q}_T \simeq 55$ C, again assuming $l = 10$ km. In general for the 17 events, I_p varied from 6 to 180 kA and Q_T varied from 10 to 112 C.

Time Delays

The time delay between the causative positive discharge and the subsequent Sprite showed a wide range of values.

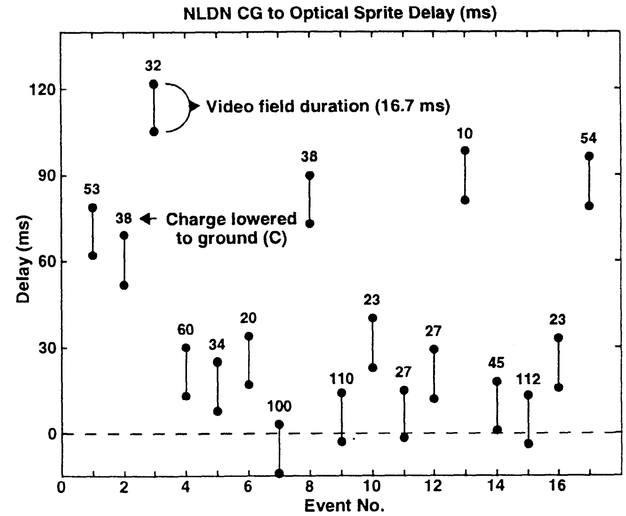

Figure 5. Time delay between the causative positive CG discharge ($t = 0$) and the video field in which the Sprite first appeared, for each of the 17 events. The time duration of the video field is indicated by two dark circles connected by a straight line. The number immediately above each video field marker represents the positive charge Q_T lowered to ground during the intense continuing currents that followed the first positive return stroke, assuming $l = 10$ km.

In all cases the Sprite was identified from low-light-level video images obtained with an intensified Xybion camera, and consequently the exact time of occurrence of the Sprite was known only to within $\sim$ 17 ms, the duration of the video field (VF). To identify the causative positive discharge, we assumed that it had to occur in each case before the end of the first VF showing the Sprite. We also assumed that the discharge would have to occur within 100 ms preceding the beginning of this VF, since after 100 ms the original electric field in the mesosphere relaxes for altitudes > 50 km. In all cases only one positive discharge was found to be recorded by NLDN within this interval, which was also the only VLF sferic with intensity > 3 nT detected by the Stanford receiver. The time delays between the positive discharges and the Sprites are shown in Figure 5. The horizontal axis shows the temporal sequence of the events but does not show the actual time delay between events. The vertical axis shows the delay between the time of the causative positive lightning discharge, as determined by the NLDN, and the VF in which the Sprite first appeared. The charge values given for each event were determined from the ELF waveform using (3) and (4), and assuming that $l \sim 10$ km.

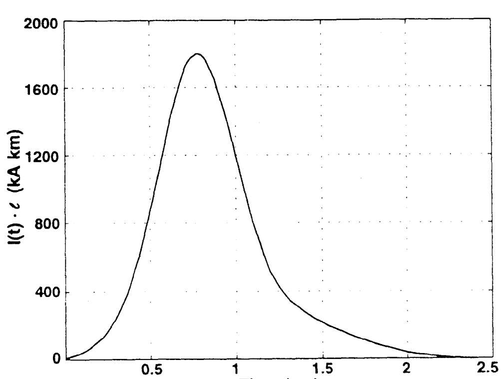

Figure 4. The predicted current moment of the discharge which produced the B field shown in Figure 2. The peak value of the current moment is $\sim$ 1800 kA-km, which represents a peak current of 180 kA, assuming $l = 10$ km.

Discussion

We note that the positive discharges associated with the largest values of Q_T (i.e, # 4, 7, 9, and 15) all occur within 15 ms of the beginning of the VF in which the Sprite first appeared. In fact, the average value of Q_T for the eight

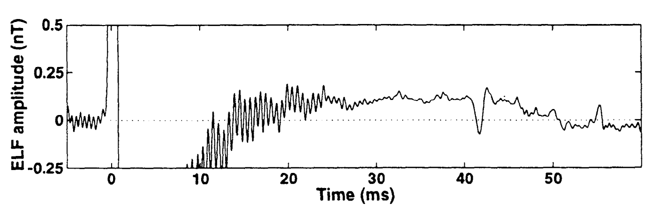

Figure 6. Same event as that shown in Figure 2, but with expanded B field axis and compressed time axis. Positive B field amplitude during the period $\sim$ 20 to 50 ms is evidence of small, but longer duration positive currents which carry significant charge to ground.

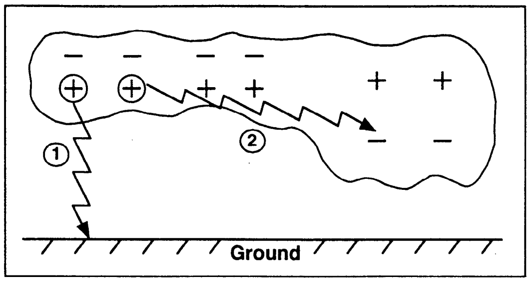

Figure 7. After intense continuing currents first remove significant positive charge from a particular location in a thundercloud, smaller positive currents may continue to flow from the same region for $\geq$ 40 ms. In the larger events, these longer duration currents flow vertically within the same C-G discharge channel (1). In the smaller events these currents apparently flow horizontally to another portion of the cloud (2).

discharges that occurred within 15 ms of the beginning of the VF is $\bar{Q}_T \sim 65$ C, while for the others, $\bar{Q}_T \sim 30$ C and the average waiting time until the beginning of the VF was $\sim$ 55 ms.

We also note that the 4 events (#7, 9, 14, 15) for which CG currents were detected at times > 15 ms after the initial ELF current pulse included the three events with the largest values of Q_T and shortest delay times (#7, 9, 15). For example, Figure 6 shows a positive B field of $\sim$ 0.1 nT (average) measured from $\sim$ 20 to 50 ms following the initial B field pulse shown in Figure 2 (event #9). Using this B field to find $I(t)$ through (3), it is found that $I(t) \sim 1$ kA during the 30 ms period when $B_{hm} \sim 0.1$ nT. Thus $\sim$ 30 C was transferred from the cloud to the ground during this period.

For the events with smaller Q_T, the maximum CG current that could have flowed without detection would produce a B field approximately equal to the noise level of $\sim$ 0.02 nT. In this case $I_{max} \sim 200$ A, and only 15 C additional charge would move to ground during the 73 ms average delay time between the CG discharge and the end of the VF in which the Sprite first appeared.

These results suggest that there may be at least two ways by which a Sprite is produced. The first mechanism involves quick removal of a large amount ($\sim$ 100 C) of positive charge from a thundercloud, in which case a Sprite may appear shortly thereafter (Figure 7). This mode applies to events 7, 9, and 15. Alternatively, initial removal of a smaller amount of charge ($\sim$10-50 C) from a particular location in the cloud may lead to a delayed Sprite, appearing > 40 ms later. This mode applies to events 1, 2, 3, 8, 13, and 17. As illustrated in Figure 7, during this delay period more charge may be removed from the same location by longer lasting, but less intense, continuing currents flowing entirely within the cloud (intracloud discharge). For example, after the first $\sim$30 C is brought to ground, a steady intracloud continuing current of 2 kA flowing for 40 ms could remove an additional 80 C from the original charge distribution, resulting in a total charge transfer of 110 C. A dramatic observation of a discharge combining both CG and intracloud elements is presented in *Marshall et al.*, [Figure 1, 1996].

In view of these considerations we believe that the values of charge shown in Figure 5 are actually lower bounds to the total charge removed from the cloud prior to the appearance of the Sprite.

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