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# Measurement of charge transfer in sprite-producing lightning using ELF radio atmospherics

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**Abstract.** Transient high altitude optical emissions referred to as “sprites” are believed to occur as a result of the transfer of large amounts of charge (∼100-300 C) from cloud altitudes of 5-10 km to the ground. Using a general subionospheric ELF propagation model, we quantitatively interpret magnetic field waveforms of ELF radio atmospherics originating in mid-western U.S. lightning discharges and observed at Stanford (∼1800 km range) to determine the temporal variation of the lightning current and thereby measure the charge transfer during the stroke. For 6 sprite-producing lightning current waveforms observed on July 24, 1996, we find that 25 to 325 coulombs of charge was transferred during the first 5 ms of the discharges, assuming a 10 km altitude for the initial charge.

## Introduction

The electromagnetic radiation from sprite-associated cloud-to-ground lightning exhibits large variations on time scales of 1-10 ms [*Reising et al.*, 1996]. This enhanced extremely low frequency (ELF, defined here as <2 kHz) component suggests that sprites are associated with lightning discharges that contain significant current lasting 1-10 ms, potentially moving a large amount of charge from cloud to ground and creating large quasi-electrostatic fields in the ionosphere which can heat the ambient electrons to levels exceeding the threshold for the generation of optical emissions via electron impact on atmospheric constituents [*Pasko et al.*, 1996]. Optical emissions may also be produced by runaway electrons driven upward by the same quasi-electrostatic fields [*Bell et al.*, 1995; *Taranenko and Roussel-Dupre*, 1996].

Previous measurements of charge transfer in lightning return strokes have been made by directly measuring current when lightning strikes an instrument tower [*Berger*, 1967] or an electrically-grounded rocket [*Hubert et al.*, 1984], and from multi-site electrostatic field measurements [*Krehbiel et al.*, 1979]. The difficulty in these measurements is a matter of practical placement of the sensors: direct rocket or tower observations must be made at the location of the lightning, and electric field observations must be made at most a few tens of kilometers from the charge center due to the rapid decay of the static component of the dipole electric field.

The omnipresent electromagnetic radiation produced by a lightning discharge (termed a radio atmospheric, or sferic) is easily measurable and can be used to deduce the lightning current waveform at large distances from the discharge, provided that the propagation effects are known or can be suitably modeled. In this study, we infer the total amount of charge transfer in sprite-associated cloud-to-ground lightning discharges from observations of the <2 kHz components of the sferic at ∼1800 km from the source.

## Observations

Continuous broadband (5 Hz-22 kHz) ELF/VLF magnetic field measurements were made at Stanford University during July 1996 with a single loop antenna. The waveforms studied herein were all digitally low-pass filtered at 1.5 kHz (-3 dB point) to limit the sferics to frequencies where only the quasi-transverse-electromagnetic (QTEM) mode of Earth-ionosphere waveguide propagation is present [*Wait*, 1957]. This filtering simplifies modeling of the propagation effects, but also eliminates any information about the lightning current on time scales shorter than ∼0.5 ms. Since sprites are usually observed at least 1 ms after the source lightning stroke [*Winckler et al.*, 1996; *Fukunishi et al.*, 1996], this shorter time scale information is relatively unimportant for our purposes.

Low-light level video observations were made at Yucca Ridge, Colorado during the same period in order to determine the times of sprite occurrence and associate particular sferics with the observed sprites. National Lightning Detection Network (NLDN) data were used to determine the precise location of the sprite-producing lightning strokes, thereby providing the distance and bearing from the source to Stanford, which are needed to accurately model the propagation effects.

## ELF Propagation Theory

We use the well-validated MODEFNDR program [*Shellman*, 1986] to calculate the attenuation and phase velocity of the QTEM mode as a function of frequency for arbitrary altitude profiles of the ambient electron and ion densities and collision frequencies, using appropriate values for ground conductivity and permittivity and ambient magnetic field. We assume that the ionosphere does not vary significantly along the ∼1800 km path. Assuming an impulsive-current vertical electric dipole source, we calculate the received field amplitude and phase as a function of frequency using the formulation of *Budden* [1962, eq. 42]. The time domain impulse response is calculated via the inverse Fourier transform, and the magnetic field variation observed at the receiver for an arbitrary input source current can be obtained from a simple convolution operation. For the analysis presented herein, we assume the initial altitude of the charge to be 10 km. The radiated field depends on charge moment (charge times altitude), so that if the charge were instead at 5 km altitude, the inferred current and charge magnitude would be doubled.

## Model Ionospheric Parameters

Previous theoretical analyses of ELF sferic waveforms [e.g., *Sukhorukov*, 1992] were based on relatively simple representations of the ionosphere and do not reproduce some of detailed

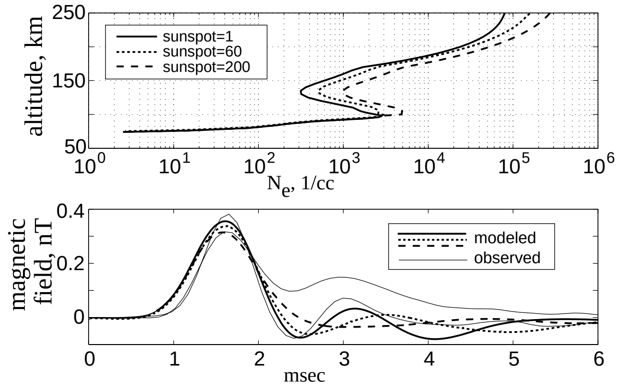


**Figure 1.** Three input nighttime electron density profiles and the modeled impulse responses for propagation from the sprite region to Stanford. Shown for comparison are two observed sferics launched from the same region and received at Stanford.

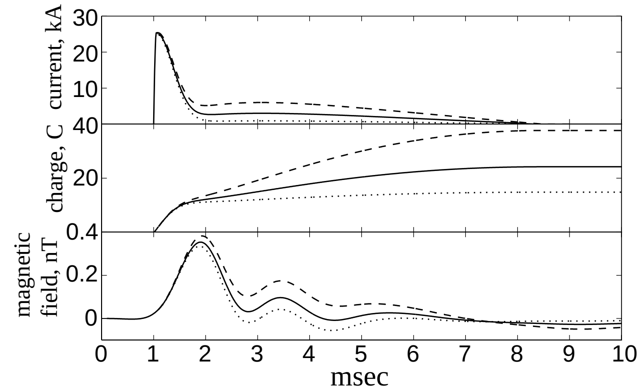


**Figure 2.** Three input current waveforms, charge transfer variations, and associated modeled sferics.

features of the sferics recorded in our observations. The more general MODEFNDR program provides enough flexibility in defining the ionosphere to reproduce these fine features, but the sensitivity of the modeled sferics to the ionospheric parameters must be investigated so that the appropriate ionosphere to use with a particular set of observations can be selected and the current variations can be accurately extracted.

Figure 1 shows the theoretical magnetic field impulse responses as would be observed at Stanford under three different ionospheric *E* and *F* region electron density ($N_e$) profiles for discharges which move 10 C of charge. The profiles for altitudes above 95 km were obtained from the 1986 International Reference Ionosphere (IRI) [*Bilitza et al.*, 1993] with the following input parameters: 37°N 101°W location, midnight local time, and sunspot numbers of 1, 60, and 200. The *D* region (<95 km) electron density profile used is profile 2 from *Lev-Tov et al.* [1995], and electron and ion collision frequency profiles are from *Wait and Spies* [1964] (below 100 km) and *Rishbeth and Garriott*, [1969, p. 131] (above 100 km). The density of positive ions ($N_i^+$) is taken to be equal to $N_e$ for $N_e > 1000$ cc$^{-1}$ (which occurs at ∼92 km) and and equal to 1000 cc$^{-1}$ for $N_e < 1000$ cc$^{-1}$. This altitude dependence is an extrapolation of results reported in *Narcisi* [1971]. Negative ion density is defined as $N_i^- = N_i^+ - N_e$ to maintain charge neutrality. Positive and negative ion masses are set to 32 AMU.

The modeled impulsively-launched sferics shown in Figure 1 illustrate the sensitive dependence of the post-peak oscillations on the *E* and *F* region electron densities. This dependence allows us to choose the appropriate ionosphere to apply to this set of observed sferics. For comparison, two observed sferics originating from the sprite-producing region are also plotted in the figure. One observed sferic agrees well with the modeled bold solid line waveform, indicating that this sferic was launched by a nearly impulsive discharge, while the other has a much longer decay time, indicating significant continuing current in the source discharge. However, the amplitude and frequency of the post-peak oscillations in both of these observed sferics are similar, which indicates that they are a propagation effect rather than a source effect. The amplitude and frequency of these oscillations agree well with the modeled response for the ionospheric profile indicated by the bold solid line, and this ionospheric profile is used in the modeling results presented below.

## Model Lightning Current Waveforms

To accurately estimate the source current waveform, we must be able to discriminate between the output magnetic field waveforms produced by different input current waveforms. We consider an input current waveform which contains two components: a fast (<1 ms) component with a linear rise and gaussian decay, and a slower component defined by the difference of two decaying exponentials [e.g., *Jones*, 1970]. The slow component also can be delayed relative to the fast component, and a linear decay to zero can be superposed on the slow exponential decay. The resulting current waveforms are composed of two strictly positive pulses that have different amplitudes and that overlap to a varying degree, and they are found to provide a very good match to all of the observed sferic waveforms presented herein. Observations of lightning currents varying on two time scales are well-documented [*Uman*, 1987, p. 201], especially in positive cloud-to-ground lightning discharges. Using a gaussian decay for the fast current provides a reasonable approximation of measured positive lightning stroke current waveforms [*Uman*, 1987, p. 199].

The key parameter in determining the shape of the sferic waveform is the ratio of peak current in the fast component to peak current in the slow component. Figure 2 shows three input current waveforms with different ratios of fast to slow peak current amplitudes, the corresponding cumulative charge moved as a function of time (defined as $q(t) = \int_0^t i(\tau)d\tau$), and the three modeled sferic waveforms for these currents as would be observed at 1800 km range. The significant differences between the three modeled sferics indicates that one can distinguish between different current waveforms on the basis of the observed sferics and that an appropriate fast/slow current ratio can be extracted in order to accurately measure the charge transfer.

Figure 2 also demonstrates that the first 6 ms of the sferic waveform is sensitive to slowly varying, low amplitude current components. This implies that there is no current component that transfers significant charge in 5 ms or less that would not recognizably alter the first 5 ms of the sferic waveform, so the inferred source current waveforms shown below are accurate for

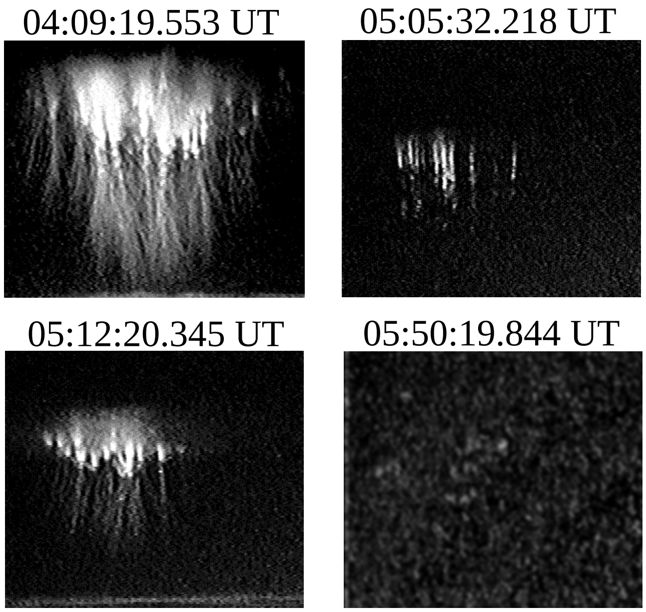


**Figure 3.** Four video images containing sprites. The lower right image was enhanced by subtracting the previous video frame. This sprite is very weak and is composed of a few small glowing regions, the brightest of which is near the center of the image.

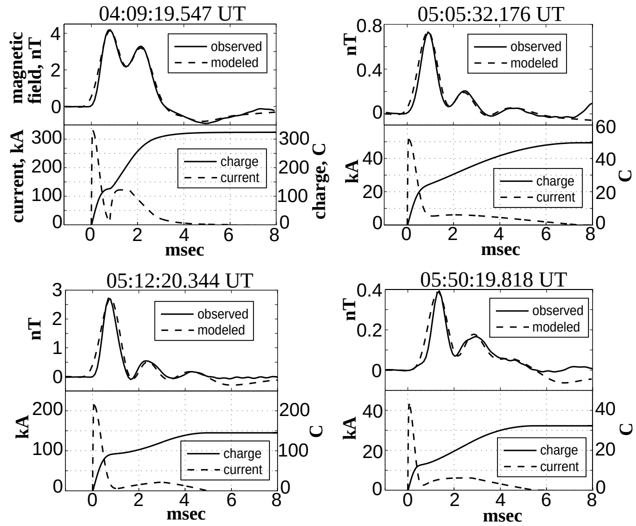


**Figure 4.** Observed and good-fit modeled ELF sferics with the inferred current and cumulative charge variations for each.

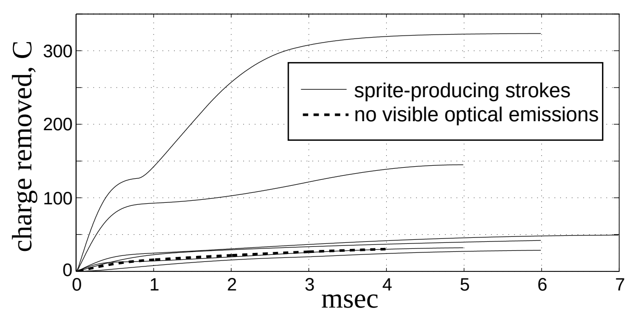


**Figure 5.** Cumulative charge transfer in six sprite-producing strokes and the largest sferic not associated with any optical emissions.

the duration of the good agreement of the observed and modeled sferics. There could be low amplitude, slowly varying currents that could contribute significantly to the total charge transfer over much longer time scales, but the relatively few published high time resolution sprite observations have shown that sprites occur within 5-10 ms of the source discharge [*Winckler et al.*, 1996; *Fukunishi et al.*, 1996], indicating that longer duration charge transfer is not important for sprite initiation.

## Extracted Lightning Current Waveforms

By varying the parameters of the lightning current waveform, we obtained very good agreement between modeled and observed sferic waveforms for a group of discharges between 0400 and 0600 UT on July 24, 1996. Figure 3 shows four video frame images, each containing a sprite. The integration time for each image begins at 33.3 ms before the GPS time stamp (shown above each image) and ends 16.7 ms after the time stamp. The sprite at 5:05:32.218 UT peaked in brightness in this frame, but it first appeared in the 5:05:32.185 UT frame.

Figure 4 shows the observed and modeled sferic total horizontal magnetic field waveforms (with the time that they were received at Stanford) and the inferred source current and cumulative charge transfer variations for the four sferics associated with the four sprites in Figure 3. The agreement between the observed and modeled sferics is excellent and all are produced with physically reasonable source currents, despite the variation in the sferic characteristics.

We estimate the uncertainty in the absolute calibration of the receiving system to be approximately ±5%. The observed attenuation rate for frequencies above ∼800 Hz appears to be lower than that predicted by the model, indicating that the modeled waveforms are slightly wider and have lower peaks than those observed. Since the best-fit current waveform was chosen to match the peak observed magnetic field, this modeling error could result in an overestimation of the total charge removal by as much as 15%.

Figure 5 shows the inferred cumulative charge transfer $q(t)$ for 6 sprite-associated discharges and 1 not associated with a sprite (this one is discussed below). Based on the polarity of the sferics and the NLDN data, all of these discharges were positive. The $q(t)$ are plotted only for the duration of the agreement between the modeled and observed sferics.

The three smallest sprite-producing discharges shown in Figure 5 produced very small and dim sprites, while the two largest produced quite large and spectacular sprites. The dashed $q(t)$ variation plotted in Figure 5 was extracted from the largest ELF sferic launched from an NLDN-recorded discharge during the $\sim 2$ hour study period that produced no visible mesospheric optical emissions, but which was recorded by the NLDN data to be within the field of view of the video camera. The fact that this discharge moved approximately the same amount of charge as some others producing very weak sprites suggests a charge threshold for the production of optical emissions visible with our video camera of roughly 25 coulombs in 5 ms.

## Conclusions

We have combined broadband ELF magnetic field recordings and a general ELF propagation model measure the charge transfer during the first 5-7 ms of sprite-producing lightning discharges. The ELF propagation characteristics are strongly dependent on the *E* and *F* regions of the ionosphere, and we found good agreement between observed sferics and those simulated using a reasonable IRI-based ionosphere. The demonstrated sensitivity of the model to lightning current characteristics allows the estimation of the total charge transfer with high accuracy.

For the 6 sprite-producing strokes examined, the total charge transfer during the first 5 ms of the stroke varied from 25 to 325 coulombs, assuming a 10 km altitude for the initial location of the removed charge. The two discharges in which 145 C and 325 C were removed and which led to large and bright sprites are large enough to produce optical emissions through both the quasi-electrostatic heating (QE) and runaway electron mechanisms. The fact that relatively weak but nevertheless detectable sprites were produced by the removal of $<$50 C of charge indicates that other factors not considered in the present QE and runaway electron models may also be involved in the generation of optical emissions at mesospheric altitudes.

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