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ELF sferic energy as a proxy indicator for sprite occurrence

Steven C. Reising

Microwave Remote Sensing Laboratory, University of Massachusetts, Amherst, Massachusetts

Umran S. Inan and Timothy F. Bell

Space, Telecommunications and Radioscience Laboratory, Stanford University, Stanford, California

Abstract. Broadband ELF/VLF measurements of sferics near Ft. Collins, Colorado, demonstrate that ELF sferic energy is a proxy for sprite occurrence which can be used to estimate the number of sprites produced by a thunderstorm. Ultra-long range (~12,000 km) measurements at Palmer Station, Antarctica, confirm the application of this proxy to storms where no video observations of sprites are available. Comparison with high-resolution photometer measurements demonstrate the simultaneity of sprite luminosity and an ELF "second pulse" believed to be radiated by electrical currents within the sprite body [*Cummer et al.*, 1998]. Measurements of the second ELF pulse are used to identify a quantitative relationship between the current in sprites and total sprite luminosity.

Introduction

Sprites are transient luminous glows in the mesosphere and lower ionosphere above thunderstorms, extending from ~40-90 km in altitude and having transverse extents of ~10-50 km [*Sentman et al.*, 1995; *Lyons*, 1996]. They develop to full brightness in 1-3 ms [*Cummer et al.*, 1998], but their luminosity may last for 10-100 ms [*Winckler et al.*, 1996]. Sprite occurrence is nearly always associated with a positive cloud-to-ground (+CG) flash. However, during the sprite producing phase of mesoscale convective systems (MCS), on average only ~15-20% of +CGs are associated with sprite occurrence [*Reising et al.*, 1996; *Lyons*, 1996]. The NLDN-measured peak currents of sprite-producing +CGs range from ~20-160 kA, giving little indication of sprite-producing capacity [*Reising et al.*, 1996].

In order to determine the total rate of sprite occurrence on continental and global scales, as well as the characteristics of sprite-producing storms, one needs a proxy for sprite occurrence based on remote measurements and independent of video observations. In this paper, we use broadband ELF/VLF measurements of radio atmospherics ("sferics") to examine the characteristics of *those* CG flashes which lead to sprite production. We then describe a proxy indicator for sprite occurrence based on the ELF sferic energy, which is enhanced by continuing currents flowing from cloud to ground *after* the +CG return stroke. This is consistent with the necessity of lowering large amounts of charge from the cloud to ground in order to produce a sprite (e.g., [*Pasko et al.*, 1997]). Without continuing currents, the maximum charge transfer in a +CG return stroke of ~0.5 ms duration is ~120 C [*Brook et al.*, 1982]. Measurements of sferics at Palmer Station, Antarctica, show that sferics launched by sprite-producing CG flashes exhibit enhanced ELF "slow tails" compared to non sprite-producing sferics, indicating that significant continuing currents on the time scale of ~1-5 ms are necessary for sprite production [*Reising et al.*, 1996].

Other techniques have been explored as possible indicators of sprite occurrence, including excitation of the resonances of the Earth-ionosphere cavity (also known as "Schumann resonances") [*Boccippio et al.*, 1995; *Füllekrug and Reising*, 1998]. Even though *Boccippio et al.* [1995] detected an ELF transient associated with nearly every sprite, many more transient excitations were detected which were not clearly associated with sprite-producing storms.

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Description of the Experimental Data

During late July and early August, 1996, a new wideband (15 Hz – 22 kHz) ELF/VLF sferics receiver was operated by Stanford University at Yucca Ridge Field Station (40°40′06″N, 104°56′24″W), in NE Colorado. The signals from two orthogonal magnetic loop antennas (geographic N/S and E/W) were recorded digitally on a continuous basis for six hours per night. The onset times of sferic waveforms are known to <1 ms from the recorded GPS time code, corrected for speed-of-light propagation and correlated with specific source lightning strokes. The locations of causative lightning strokes are determined to ±0.5 km by the National Lightning Detection Network (NLDN) [*Idone et al.*, 1998].

Continuous video observations of sprites were also conducted at Yucca Ridge (YR) as part of the Stanford/Lockheed Fly's Eye experiment [*Inan et al.*, 1997]. Sprites and elves were observed above an MCS in western Kansas, ~550 km from YR (Figure 1) on August 1, 1996. A total of 98 sprites were recorded during this period (0644-0907 UT), except for a three-minute gap (~0815-0818 UT), giving an average rate of one sprite every ~90 seconds. The occurrence of elves is not considered in this study. During the observations, the intensified CCD camera was pointed southeast, with a field of view (FOV) as shown in Figure 1, along with the NLDN-recorded flash locations. Red circles indicate those +CGs which are associated with sprites. In this analysis the NLDN data were filtered to include only those +CGs which, if they had produced sprites, those sprites would have occurred in the camera FOV.

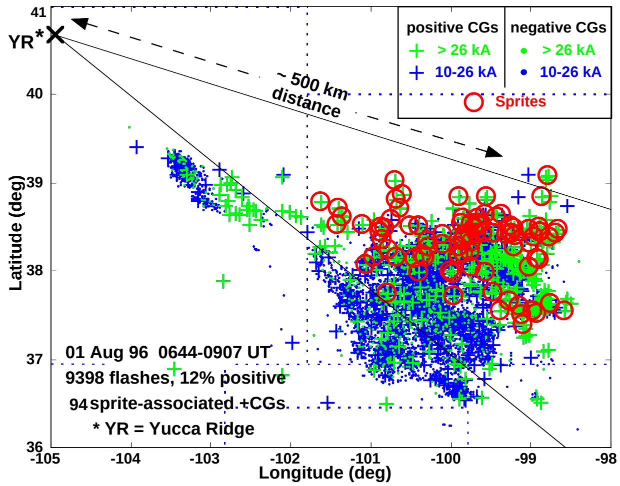

Figure 1. NLDN lightning locations and camera FOV from Yucca Ridge, Colorado, on August 1, 1996. Negative CG flashes are denoted by dots, and +CGs by pluses. Red circles denote sprite-associated +CGs.

Sferics Data Analysis

Sferics propagating in the Earth-ionosphere waveguide consist of many modes; all modes except one have cutoff frequencies of ~1.8 kHz or higher. We extract the single mode with no cutoff (QTEM mode, hereafter the "ELF sferic") from the sferics data by digital lowpass filtering with a cutoff of 1.5 kHz, as in *Bell et al.* [1998]. For unbiased comparisons among sferics arriving from different directions, we compute the magnitude, the vector sum of wave magnetic field components.

A measure related to total charge transfer is the time-average of the squared magnitude of the ELF wave magnetic field. The ELF sferic energy is defined as the time-average between $t = -2$ ms and $t = 20$ ms, where $t = 0$ is the sferic onset, for all sferics measured at YR. The ELF "slow-tail magnitude" defined by *Reising et al.* [1996] for Palmer measurements is the square root of the ELF sferic energy, between $t = -2$ ms and $t = 10$ ms.

ELF Proxy from Yucca Ridge Measurements

The onset times of all 98 sprites during the August 1 observation period were compared to occurrence times of sferics and of NLDN-recorded CG flashes. In 94 (96%) of the cases, the sprite was associated with a +CG, as detected by the ELF/VLF sferics data. These 94 sprite-associated +CGs had NLDN-measured peak currents from 19 to 164 kA. We chose a threshold of 26 kA to limit the total number of +CGs in the analysis. In addition, we selected only those sprites which followed +CGs within 200 ms. Of the 94 sprite-producing +CGs, 81 met both criteria. The NLDN peak-current distribution of these 81 sprite-producing +CGs is shown in the shaded bars of Figure 2a. The unshaded portions of the bars show the NLDN peak-current distribution of all other +CGs which are >26 kA and in the camera FOV (see Figure 1).

Figure 2b shows the distribution of ELF sferic energy with 0 dB mean for the same 334 +CGs in Figure 2a. From Figure 2b it is evident that the mean ELF energy of *sprite-associated* sferics (shaded bars) exceeds the mean ELF energy of the entire storm by $\sim\sigma$.

To use the ELF sferic energy as a proxy indicator for sprite production, we use $\sigma(= 7$ dB$)$ above the mean as an absolute threshold for sprite prediction. With this assumption, we are 83% correct and the number of sferics above the threshold is 49 / 0.83 = 59% of the total sprites produced. So we predict the total number of sprites during this period by multiplying the number of sferics exceeding the threshold by 1 / 0.59 = 1.7. This technique allows prediction of the number of sprites produced by a mid-latitude MCS; however, further measurements of storm-to-storm variability of ELF sferic energy distributions are needed to determine the precision of this proxy indicator.

Application of Proxy to Multiple Storms

We studied sferic measurements at Palmer Station from multiple thunderstorms in order to demonstrate the usefulness of ELF sferic energy as a proxy indicator for sprite occurrence above thunderstorms for which optical recordings of sprites are not available. The +CG flashes from 0644–0800 UT on August 1, 1996, with NLDN peak current >23 kA are shown in the left panel of Figure 3. Storm A is the Kansas MCS (Figure 1); Storm B is in Sonora, Mexico; and Storm C is a thunderstorm in South Dakota.

Using time of arrival and azimuth measurements [*Reising et al.*, 1996], we identified sferics radiated by many of the NLDN +CGs shown in the map of Figure 3. The distributions of ELF sferic energy for sferics measured from 0644–0745 UT in each of the three storms are shown in the right panel of Figure 3. For Storm A (top), the shaded bars show the ELF energy of sferics generated by sprite-associated +CGs, as determined from optical sprite measurements. The ELF proxy predicted that Storm B produced at least 10 sprites during the period studied (middle right panel). Storm C was a smaller storm with a lower rate of +CGs, and our measurements indicate that it did not produce sprites.

ELF Radiation from Currents in Sprites

In this section we analyze 1996 sferic measurements at YR, ~500-600 km from the sprite-producing lightning. At this range, a typical sprite-associated ELF sferic consists of

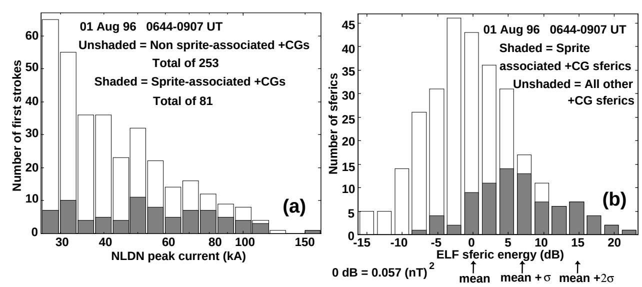

Figure 2. (a) Peak current histogram of first strokes of NLDN-recorded +CG flashes with peak current >26 kA. Sprite-associated CGs are shown as shaded bars. (b) ELF sferic energy histogram of the same flashes as (a). Sprite-associated sferics are shown as shaded bars.

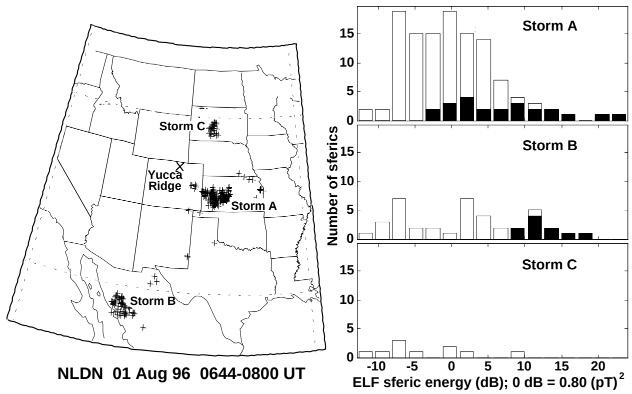

Figure 3. (Left) Locations of NLDN +CGs with peak current >23 kA from 0644-0800 UT on August 1, 1996. (Right) ELF energy distributions of sferics recorded at Palmer from Storms A, B and C from 0644-0745 UT. For Storm A, shaded bars indicate sferics associated with sprites observed at Yucca Ridge. For Storm B, shaded bars indicate predicted sprites.

a positive-going pulse of half width 0.5-1 ms [*Bell et al.*, 1998]. However, a second positive-going ELF pulse follows ~20% of the sprite-associated sferics, as shown in Figure 4b. The lack of a VLF oscillation at the onset of the second ELF pulse (Figure 4a) indicates that this pulse is not generated by a lightning discharge. Figure 4c shows high time resolution (~30 μs) data from the Fly's Eye photometer, with a 6.6°× 3.3° FOV (Figure 4e). Consistent with *Cummer et al.* [1998], these observations verify that the sprite luminosity rises and falls nearly simultaneously (±0.2 ms) with the source current which radiated the second ELF pulse. If the second ELF pulse were generated solely by current in

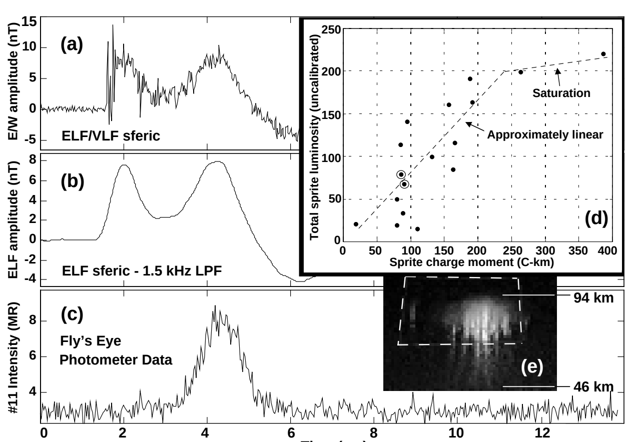

Figure 4. (a) ELF/VLF sferic waveform launched by a 67-kA +CG discharge and measured at Yucca Ridge at 08:24:00 UT on August 1, 1996. (b) The ELF sferic after lowpass filtering with a cutoff of 1.5 kHz. (c) Optical intensity data measured by the Fly's Eye photometer with a FOV shown in (e). (d) The relationship between total sprite luminosity and sprite charge moment for 17 sprites on July 24, 1996. (See text for details.)

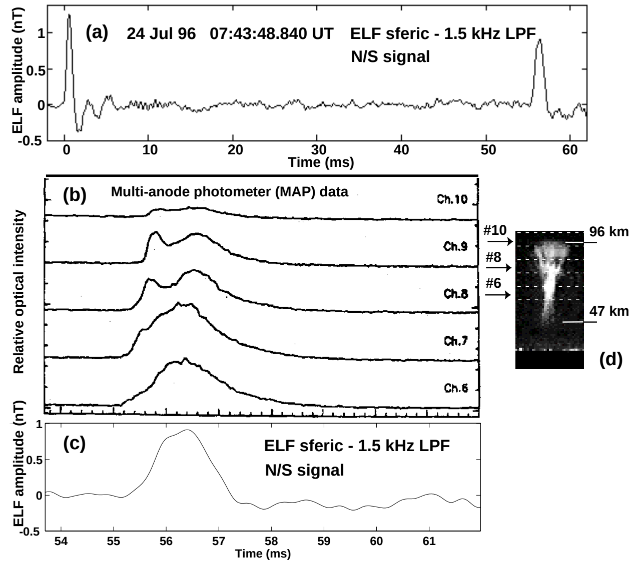

Figure 5. (a) The ELF sferic waveform launched by a 48-kA +CG discharge and measured at YR at 07:43:48 UT on July 24, 1996. (b) Sprite optical intensity, as recorded by the multi-anode photometer (MAP). (c) The second ELF pulse on the same time scale as (b). (d) The MAP FOVs are indicated by dotted lines.

a pre-existing CG channel, there would be a ≥1 ms time lag between the initial current and the sprite onset, in order to lower enough charge to ground to produce a sprite (compare [*Bell et al.*, 1998]). Therefore, the simultaneity strongly suggests that the source of the second ELF pulse is current flowing in the body of the sprite itself [*Bell et al.*, 1997].

We calculated the dipole moment of charge transfer in the source region by a method previously applied to the first ELF pulse [*Bell et al.*, 1996; 1998]. To obtain a lower bound for the sprite charge moment, we reduced the calculated charge moment by 25% because, for short CG-to-sprite delays, weak CG continuing currents may augment the second ELF pulse [*Cummer et al.*, 1998]. Of the sprite-associated sferics produced by a Kansas MCS on July 24, 1996, at least 17 exhibited second ELF pulses. Using intensified CCD images, we measured the total sprite luminosity as the sum of each sprite-illuminated pixel scaled by the square of the range from the camera to the sprite-associated +CG. The sprite-to-CG horizontal distance is <40 km in most cases [*Winckler et al.*, 1996; *Lyons,* 1996]. For these 17 cases, Figure 4d shows an approximately linear relationship between sprite charge moment and total sprite luminosity. At the two largest values, the luminosity appears to saturate, but the CCD was not saturated, so further data are needed to understand this effect.

In two cases of the 17, the CG-to-sprite delay exceeded 50 ms. For these cases, we use high time resolution (~20 μs) multi-anode array photometer (MAP) measurements at YR [*Takahashi et al.*, 1997]. The MAP consists of a 16-element vertical column of photometers, each with a ~9°× 1° FOV (Figure 5d). Figure 5a shows the ELF sferic produced by a 48-kA +CG at 07:43:48 UT on July 24, 1996, and measured at YR. The first ELF pulse follows the return stroke (in <1 ms), and the second ELF pulse occurs ~56 ms later. Figure 5b shows data from MAP channels #6-10 on the same time scale as the second ELF pulse (Figure 5c), which occurs simultaneously with the sprite luminosity. Other events also exhibit simultaneous (<0.2 ms) second ELF pulse and sprite luminosity, and show CG-to-sprite delays of up to 70 ms.

Summary

Broadband ELF/VLF measurements of sferics near Ft. Collins, Colorado, demonstrate that ELF sferic energy is a proxy for sprite occurrence which can be used to estimate the number of sprites produced by a thunderstorm. Ultra-long range (∼12,000 km) measurements at Palmer Station, Antarctica, confirm the application of this proxy to storms where no video observations of sprites are available. Our results are in agreement with criteria for sprite-producing thunderstorms in the U.S. Great Plains [*Lyons*, 1996] and extend these predictions to other geographical regions. At ∼500 km from sprite-producing thunderstorms, an ELF "second pulse" is measured in association with ∼20% of sprites. Our results confirm the simultaneity of the second ELF pulse with sprite luminosity, indicating that it is produced by currents in the body of the sprite [*Bell et al.*, 1997; *Cummer et al.*, 1998]. Measurements of the second ELF pulse are used to identify a quantitative relationship between sprite current and total sprite luminosity. These measurements confirm that some sprites occur up to 50-70 ms after the associated +CG.

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S. C. Reising, 113B Knowles Engineering Bldg., University of Massachusetts, Amherst, MA 01003-4410. (e-mail: reising@ecs.umass.edu)

U. S. Inan and T. F. Bell, STAR Laboratory, 324 Durand Bldg., Stanford University, Stanford, CA 94305-9515. (e-mail: inan@nova.stanford.edu)

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