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An improved ELF/VLF method for globally geolocating sprite-producing lightning

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[1] The majority of sprites, the most common of transient luminous events (TLEs) in the upper atmosphere, are associated with a sub-class of positive cloud-to-ground lightning flashes (+CGs) whose characteristics are slowly being revealed. These +CGs produce extremely low frequency (ELF) and very low frequency (VLF) radiation detectable at great distances from the parent thunderstorm. During the STEPS field program in the United States, ELF/VLF transients associated with sprites were detected in the Negev Desert, Israel, some 11,000 km away. Within a two-hour period on 4 July 2000, all of the sprites detected optically in the United States produced detectable ELF/VLF transients in Israel. All of these transients were of positive polarity (representing positive lightning). Using the VLF data to obtain the azimuth of the transients, and the ELF data to calculate the distance between the source and receiver, we remotely determined the position of the sprite-forming lightning with an average locational error of 184 km (error of 1.6%). *INDEX TERMS:* 3324 Meteorology and Atmospheric Dynamics: Lightning; 3329 Meteorology and Atmospheric Dynamics: Mesoscale meteorology; 6904 Radio Science: Atmospheric propagation; 3304 Meteorology and Atmospheric Dynamics: Atmospheric electricity

1. Introduction

[2] The discovery of sprites above thunderstorms more than a decade ago [*Franz et al.*, 1990] led to a completely new field of research in the atmospheric electricity and meteorology community. In the last decade we have made great progress in the understanding of sprites and other TLEs such as elves, blue jets, halos and trolls. However, some of the basic questions related to the global distribution of sprites are still unanswered. The reason for this is the difficulty in observing sprites on a global basis. Their maximum optical brightness is a few MR [*Stenbaek-Nielsen et al.*, 2000], making them difficult to see. Sprites are very short-lived events, lasting tens of milliseconds or less [*Lyons*, 1996]. They normally occur just several ms after the brightest portion of a lightning flash within the parent thunderstorm. Thus they can only rarely be seen without the aid of special low-light camera systems (LLTVs). In addition, while regular lightning occurs at a rate of 50–100 flashes per second around the globe, sprites are estimated to occur at a rate of only a few per minute.

[3] For the above reasons, the detection of radio waves from sprite-producing lightning has been investigated as a means for globally geolocating transients associated with sprites [*Boccippio et al.*, 1995; *Fullekrug et al.*, 1996; *Cummer et al.*, 1998; *Huang et al.*, 1999]. Some methods have used VLF antennas to determine the azimuth of the transients from a number of stations, with the resulting triangulation giving the location [*Reising et al.*, 1996]. A similar method has been used for detection in the ELF range, using three widely spaced stations [*Fullekrug and Constable*, 2000]. The VLF measurements are more accurate in calculating the azimuth due to their better temporal resolution of the lightning waveform. However, more stations are needed than for ELF methods to get global coverage. Besides azimuth, it is also possible to use the ELF measurements to calculate the distance to the TLE from the observing station [*Burke and Jones*, 1995].

[4] In this paper we suggest a combination of two methods, using a sensitive VLF antenna for direction finding, and an ELF antenna for distance estimation. This allows one to use only a few stations for accurately locating global sprite-producing lightning activity.

2. Data

[5] The data used in this study were obtained during the Severe Storm Electrification and Precipitation Study (STEPS) [*Capella*, 2000] from two observatories approximately 11,000 km apart. The Yucca Ridge Field Station (YRFS), located near Fort Collins, Colorado, has been used since 1993 for optical measurements of sprites, elves and other TLEs [*Lyons*, 1996]. The Negev Desert field sites are located in the south of Israel and were used to collect ELF/VLF transient data produced by lightning over the High Plains of the United States.

[6] The sprite component of STEPS covered the period 22 May–14 August, 2000. At YRFS investigators characterized the sprites and their parent lightning discharges using LLTVs, photometric sensors, radio frequency (RF) sensors and the U.S. National Lightning Detection Network (NLDN). The video fields were all GPS time stamped, allowing for comparison with the ELF/VLF data collected in the Negev Desert, Israel. During STEPS more than 1200 TLEs were imaged at YRFS. In this study we focus on a thunderstorm complex that occurred on 4 July 2000.

[7] The ELF instruments are located at Tel Aviv University's astronomical observatory near the town of Mitzpe Ramon. The station has two horizontal magnetic induction coils, and one vertical electrical ball-antenna [*Price et al.*, 1999]. The three components of the electromagnetic field are sampled in the 1–50 Hz range, using a notch filter at 50 Hz. The magnetic induction coils can detect field variations at the pico-Tesla (10^{-12} T) level. During the STEPS campaign a sampling frequency of 1kHz was used. The raw data were continuously collected during a 6-hour period from 0200–0800 UT each day. The VLF antenna is very similar in size and sensitivity to the Palmer Station, Antarctica, antenna operated by Stanford University [*Reising et al.*, 1996]. It has two orthogonal triangular loop-antenna 9 meters high, with a baseline of 18 meters. The sensitivity of the system in the broadband range (0.1–50 kHz) is 6 μV/meter. The dynamic range of the antenna/preamp is approximately 100 dB, implying that the signal would clip if greater than 6 V/m. The broadband VLF data were recorded during the same 6-hour period on digital audiotapes

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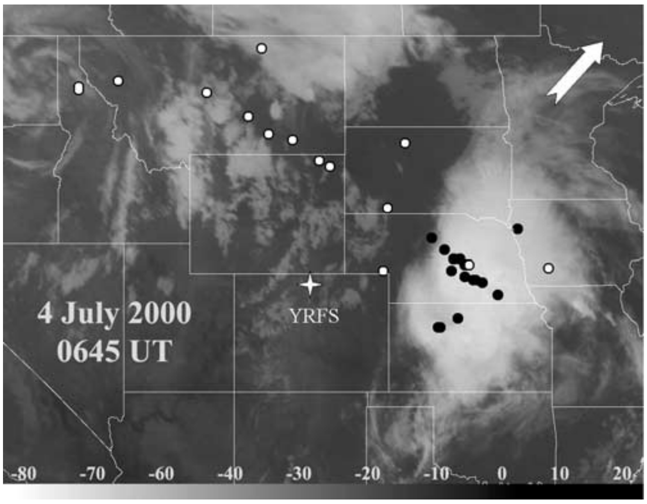

Figure 1. NOAA GOES-8 infrared satellite image obtained at 06:45 UTC showing the storms with the coldest cloud tops below −80°C. The geolocation using only ELF (white dots), and the geolocation using both ELF and VLF (black dots) are shown. The arrow shows the great circle direction to Israel. Image courtesy of Pat King, Environment Canada.

(DAT) and later digitized at 100 kHz to analyze the signals. Both ELF and VLF antenna have GPS clocks for temporally correlating with the sprites observed at YFRS. The VLF antenna is located at the Ben Gurion University Desert Research Institute at Sde Boker.

3. Methodology

[8] Sprite observing techniques at YRFS have been described in previous papers [*Lyons*, 1996; *Lyons et al.*, 2000]. The list of universal times of all STEPS sprite observations can be found at www.FMA-Research.com. For this study we analyzed the events within a two-hour period from 05:35–07:35 UT on 4 July 2000. During this period 31 sprites were observed from YFRS.

[9] The timing of the sprite events detected in the Negev Desert is independently calculated using the ELF vertical electric field changes. We look at the derivative of the electric field time series (dE/dt) and register all occurrences where the derivative (slope) of the E-field is greater than a specifiable number of standard deviations (SD) from the mean. This threshold method supplies a list of times where this threshold is first exceeded, the polarity of the impulses, and their amplitudes.

[10] Of the 31 sprites imaged from YRFS (see Figure 1) during this time interval, ELF transients were automatically detected for all events. The times registered for the ELF transients detected in Israel appear with a mean delay of 0.6 seconds after the videotape time (Table 1). This delay can be explained by the propagation time from the United States to Israel; the inaccuracies in the timing of the sprite (16.7 ms per video field); the inaccuracies in the timing of the ELF computer system; and the inaccuracies in the timing of the ELF peak based on our threshold algorithm.

[11] Using the VLF data for direction finding has a much greater accuracy since the temporal resolution (sampling freq. = 100 kHz) of the original lightning waveform is much better preserved [*Fullekrug et al.*, 1996]. On the other hand the waveform is not well resolved in the ELF data (sampling freq. = 1 kHz), and can result in significant bearing errors, translating into large absolute errors in location when 11,000 km from the lightning source. Hence, the ratio of the VLF horizontal magnetic components was used to obtain the azimuth of the incoming sferics.

[12] The final step was to calculate the distance between the source lightning and the observing station. This is done using the impedence method developed by *Burke and Jones* [1995]. The ELF transients produced by lightning discharges travel in the earth-ionosphere waveguide producing standing waves, at the characteristic Schumann resonances of 8, 14, 20, . . .Hz [*Schumann*, 1952]. The different modes of these standing waves have different amplitudes in the magnetic and electric components, depending only on the distance between the source and receiver. Therefore, looking at the ratio between the electric and magnetic spectra of the Schumann resonances allows one to calculate the distance of the observing station from the source [*Kemp and Jones*, 1971]. The spatial resolution (D) achieved using this method depends on the length of the ELF pulse used for calculating the spectrum ($D \sim f/N$). Using a time interval of 1.5 seconds ($N = 1500$, $f = 1$ kHz) results in a distance resolution of 1000 km. A 1 second interval ($N = 1000$) results in 500 km resolution, while a 0.5 second pulse ($N = 500$) gives a location resolution of 250 km. For our analysis we use $t = 0.5$ seconds. It should be noted that any increase of sampling frequency above 100 Hz does not add any more information to the ELF spectrum.

[13] The combination of the VLF azimuth and the ELF distance estimation allow the location of the source to be determined.

4. Results

[14] The results presented here are only for 4 July 2000. Several nocturnal mesoscale convective systems (MCSs) formed as predicted in western Kansas and central Nebraska. At sunset the tops of the developing storms (which reached to almost 20 km) could be seen from YRFS at a range of 350 km. The two MCS were maintained by very high convective available potential energies

Table 1. A list of 15 sprite events that were recorded at YRFS and the Negev site during from 05:35–07:35 UT

Time (YRFS)	Time (Negev)	Polarity (Negev)	Ipeak (kA)	Azimuth (°)	Distance (km)	Lon. MR	Lat. MR	Long. NLDN	Lat. NLDN	Error (km)	Error (%)
5:36:28.2	5:36:29.0	+	61.1	−33.4	10711	−99.1	41.5	−98.6	39.6	215	1.9
5:38:51.9	5:38:52.2	+	116.5	−33.3	10460	−99.1	41.1	−99.3	38.7	267	2.4
5:45:32.1	5:45:32.4	+	86.3	−32.8	10711	−99.5	41.8	−99.0	38.8	280	2.5
5:47:04.2	5:47:04.9	+	15.1	−34.6	10962	−99.7	39.2	−97.6	40.8	252	2.3
5:47:43.5	5:47:44.1	+	24.8	−32.4	10711	−100.1	42.1	−97.9	40.9	226	2.0
5:52:05.1	5:52:05.8	+	20.0	−34.6	10711	−97.8	40.7	−98.1	39.8	103	0.8
6:10:28.5	6:10:29.2	+	57.5	−34.5	10962	−99.8	39.1	−97.9	41.1	274	2.5
6:40:36.1	6:40:37.3	+	56.1	−34.4	10711	−98.1	40.9	−97.6	41.6	88	0.8
6:58:20.6	6:58:21.4	+	65.5	−35.4	10962	−98.9	39.5	−97.6	41.8	278	2.5
7:06:01.1	7:06:02.1	+	120.3	−33.5	10460	−97.1	40.3	−97.9	39.1	149	1.3
7:08:35.4	7:08:35.6	+	148.5	−33.8	10711	−98.6	41.3	−98.3	40.7	71	0.6
7:11:00.7	7:11:01.1	+	29.0	−34.4	10711	−98.1	40.9	−97.9	41.3	47	0.4
7:21:38.5	7:21:39.3	+	121.0	−34.3	10460	−96.2	42.5	−96.5	41.4	124	1.1
7:25:13.0	7:25:13.2	+	80.8	−34.4	10711	−98.0	40.8	−98.1	39.0	200	1.8
7:33:11.3	7:33:11.8	+	65.7	−34.5	10711	−98.9	41.5	−96.7	41.5	183	1.6

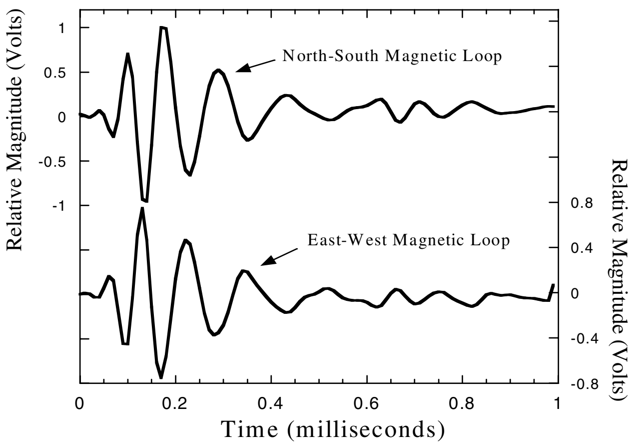

Figure 2. The NS and EW components of the broadband VLF magnetic field observed in Israel, associated with the sprite that occurred above the storm in Figure 1, at 05:52:05 UT.

(CAPEs) in excess of 4000 J/kg. Severe weather (hail, damaging winds and tornadic circulations) was widespread. The percentage of CGs with positive polarity reported by the NLDN remained uncharacteristically low, less than 10%, during the sprite-production period (0329–0737 UT). The northern, stronger system built southwest and gradually merged with the southern system (Figure 1). The MCS tops were very cold, with large areas under −75°C. Initially, the Nebraska storm produced sprites for a while, with nothing from the Kansas system. Then the Kansas storm took over, ending in random sprites from both after they began merging around local midnight (06 UT). A few sprites were bright enough to be visible to the naked eye at a range >500 km.

[15] The analysis of a single ELF/VLF transient associated with one of these sprites is given below. Figure 2 shows the two components of the VLF horizontal magnetic field recorded at the time of a sprite observed at 05:52:05 UT from YRFS (see Table 1). The x-axis represents only 1 millisecond of data showing the sferic that arrived at the Negev site. Using standard geometry to calculated the azimuth, the direction of this pulse is calculated to originate from −34.6 degrees from geographic North.

[16] The ELF transient in the vertical electric field is shown in Figure 3. The initial rapid rise of the field (dE/dt) is used to automatically determine the timing of the event in Israel. Note that the x-axis now represents 2 seconds. The time of the sprite is at t = 0 sec, with the initial deviation of the electric field defined such that a positive deviation represents a positive parent lightning. This is true for all events in agreement with previous studies [*Boccippio et al.*, 1995]. Furthermore, eight maxima can clearly be seen during the first second after the arrival of the transient, representing the first mode of the SR (~8 Hz).

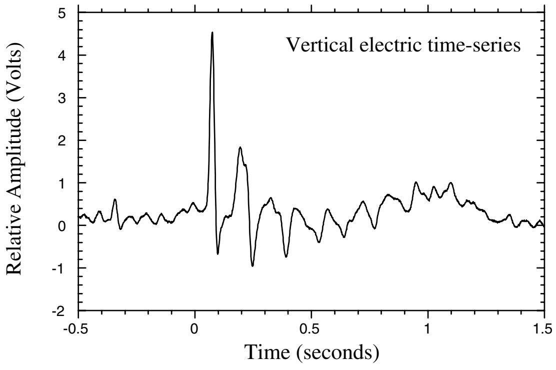

Figure 3. The vertical electric ELF signal associated with the sprite observed at 05:52:05 UT.

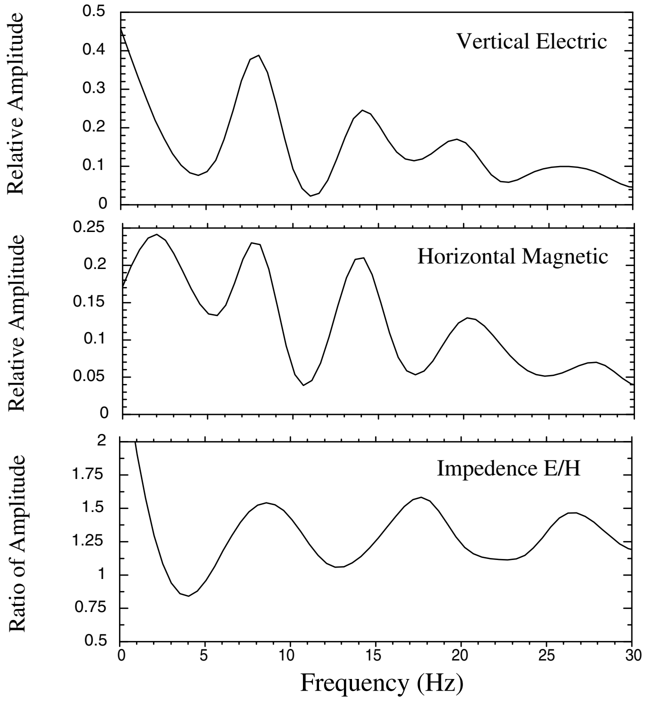

Figure 4. The spectrum of a) the vertical electric field, and b) the combined horizontal magnetic field associated with this event, clearly showing the Schumann Resonances; c) the impendence spectrum E/H used to calculate the distance between sprite and the observing station.

[17] In Figures 4a and 4b are shown the Fourier Transform of the vertical electric and horizontal magnetic fields (sqrt[H_{ns}^2 + H_{ew}^2]) for the first 0.5 second of this ELF transient. The Schumann resonances (8, 14, 20, 26 Hz) clearly appear in the spectrum of both electric and magnetic component, although the relative amplitudes of the various maxima differ depending on the distance of the lightning from the field station. In Figure 4c the ratio E/H known as the impedence spectrum is presented. The periodicity of the impedence spectrum is uniquely related to the distance traveled by the ELF electromagnetic wave [*Kemp and Jones*, 1971]. Using the model of *Burke and Jones* [1995], the distance (in Megameters, Mm) to the source lightning D = −125.5 T + 20.5 where T is the period (1/Hz) in seconds of the impedence spectrum. This example gives a value of T = 0.078 seconds resulting in a distance D = 10.711 Mm (10,711 km).

[18] The combination of the direction finding from the VLF antenna, and the distance calculation from the ELF antenna allow us to determine the longitude and latitude of the EM wave arriving at the Negev station. For this event the location is determined to be at 40.7N, 97.8W. The National Lightning Detection Network (NLDN) detected location of this positive lightning flash (peak current of 20 kA) was 39.8N, 98.1W. This implies an error of 103 km or 0.8% in our location accuracy.

[19] Using the ELF electric field threshold of 3 SD resulted in 65 ELF transient events being registered, within 2 hours, from this storm (radius of 500 km from center of storm). Using a 3.5 SD threshold reduced the number of transients detected to 43. Reducing the spatial filter to 300 km around the storm further reduced the number of detected transients to 36. The False Alarm Rate (FAR) depends on the SD threshold, as well as the spatial filter. For the 3.5 SD temporal threshold, and the 500 km spatial filter we

overestimate the number of sprites by approximately 39%. Using the 300 km spatial filter we overestimate by 16%. If we further determine that only positive polarity transients are related to sprites, our FAR reduces to 14 and 9% respectively.

[20] In Table 1 we supply a list of 15 randomly picked events (out of 31 total) that occurred between 05:35–07:35 UT. As can be seen from the table, all 15 events show positive polarity, implying that the parent lightning was a positive cloud-to-ground discharge. The azimuth and distance are shown, together with the longitude and latitude of these events as determined from the Negev site (MR), together with the locations and peak currents of the NLDN parent lightnings. The location errors (absolute and percentage) are also presented in Table 1. The mean error is 183 km, or 1.6%.

[21] In Figure 1 the ELF/VLF locations of the parent lightning for the 15 events are indicated (black dots), together with the locations determined using the bearings only from the ELF horizontal magnetic components (white dots). The scatter of locations using only the ELF data is quite large. The alignment of data points is perpendicular to the great circle path from Colorado to Israel (large arrow). Using the new method all the locations of the parent lightning (block dots) fall within the area of the storm.

5. Conclusions and Discussion

[22] We have presented a new method of combining VLF and ELF measurements to better estimate the location of sprite-producing lightning from distances greater than 10,000 km. The errors could be reduced even further by improving the model used to calculate the distance of the source [*Burke and Jones*, 1995], while finding the optimum pulse time needed for calculating the impedence spectrum. Nevertheless, this simple model and methodology allows us to study the global distribution and variability of sprite-producing lightning with high spatial accuracy using only a few stations. Using the YRFS measurements to verify and calibrate the Negev detection algorithm, we are confident that soon we will be able to map the major source regions of sprite activity continuously from our single Negev station.

[23] This new technique may allow us to address several outstanding questions. What is the global frequency of these unusual lightning events? How frequently do we see negative polarity? Is there a difference between these transients from land and ocean thunderstorms? What is the diurnal, daily and seasonal variability of these transient events according to region? How are these events related spatially and temporally to their parent thunderstorms in different regions of the world?

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