AN IMPROVED ELF/VLF METHOD FOR GLOBALLY GEOLOCATING SPRITE-PRODUCING LIGHTNING

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ABSTRACT

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 11000 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%).

INTRODUCTION

The discovery of sprites above thunderstorms more than a decade ago [1] led to a completely new field of research in the atmospheric electricity and meteorology community. The detection of radio waves from sprite-producing lightning has now been investigated as a means for globally geolocating transients associated with sprites [2, 3, 4, and 5]. 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 [6].

The data used in this study were obtained during the Severe Storm Electrification and Precipitation Study (STEPS) [7] from two observatories approximately 11000 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 [8]. 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.

At YRFS 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. For further background details see [6].

METHODOLOGY

Sprite observing techniques at YRFS have been described in previous papers [8, 9]. 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. 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 threshold. This method supplies a list of times where this threshold is first exceeded, the polarity of the impulses, and their amplitudes.

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. 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.

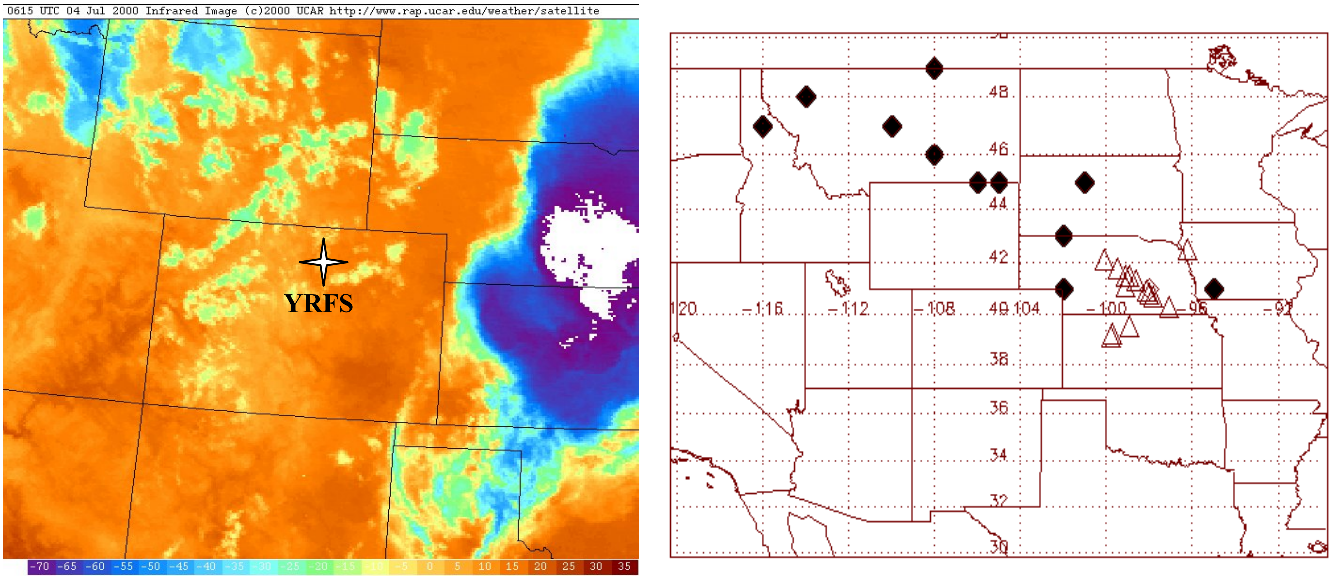

Fig. 1. a. NOAA GOES-8 IR satellite image obtained at 06:15 UTC showing the storms with the coldest cloud tops below –75°C.
b. Geolocation of lightning-producing sprites using ELF only (black diamonds) and ELF/VLF combination (triangles).

Using the VLF data for direction finding has a much greater accuracy since the temporal resolution (sampling frequency=100 kHz) of the original lightning waveform is much better preserved [3]. On the other hand the waveform is not well resolved in the ELF data (sampling frequency=1kHz), and can result in significant bearing errors, translating into large absolute errors in location when observing 11000 km from the lightning source (Fig. 2). Hence, the ratio of the VLF horizontal magnetic components was used to obtain the azimuth of the incoming sferics.

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 [10]. The ELF transients produced by lightning discharges travel in the earth-ionosphere waveguide exhibiting the characteristic Schumann resonances of 8, 14, 20, …Hz. The different modes of these resonant 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 [11]. 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. Unfortunately, continuously reducing N reduces the data points needed for analysis, and therefore there is an optimal value of N which allows good spatial resolution while not compromising spectral information of the ELF transient. It should be noted that any increase of sampling frequency above 100Hz does not add any more information to the ELF spectrum. The combination of the VLF azimuth and the ELF distance estimation allow the location of the source to be determined.

RESULTS

On 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 (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 1a). 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.

Figure 2 shows the two components of the ELF and VLF horizontal magnetic field recorded at the time of a sprite observed at 05:52:05 UT from YRFS. The x-axis represents 0.5 seconds for the ELF but only 1 millisecond of data for the VLF. Using standard geometry with the VLF signal to calculated the azimuth, the direction of this pulse is calculated to originate from –34.6 degrees from geographic North.

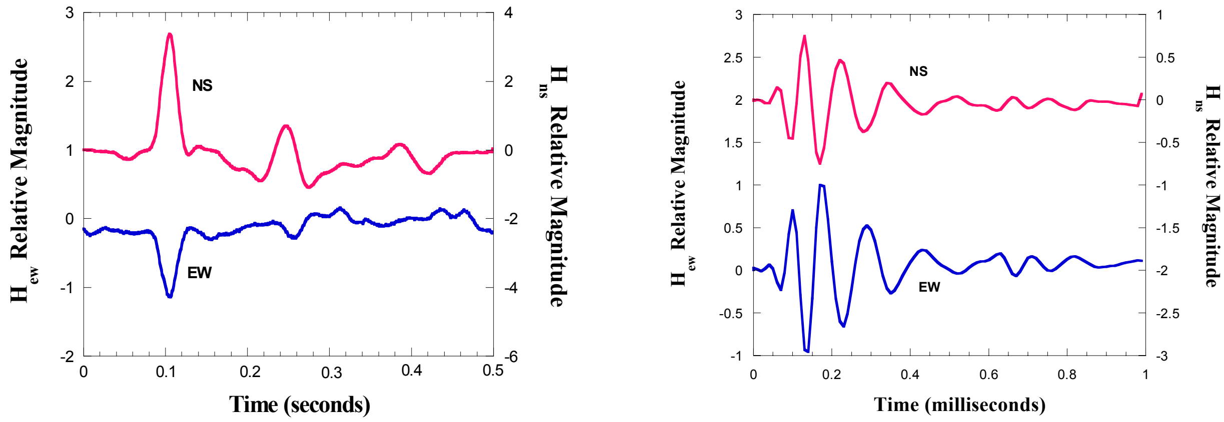

Figure 2. The NS and EW components of the ELF (left) and VLF (right) magnetic fields observed in Israel, associated with the sprite that occurred above the storm in Figure 1, at 05:52:05 UT.

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 [2]. 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).

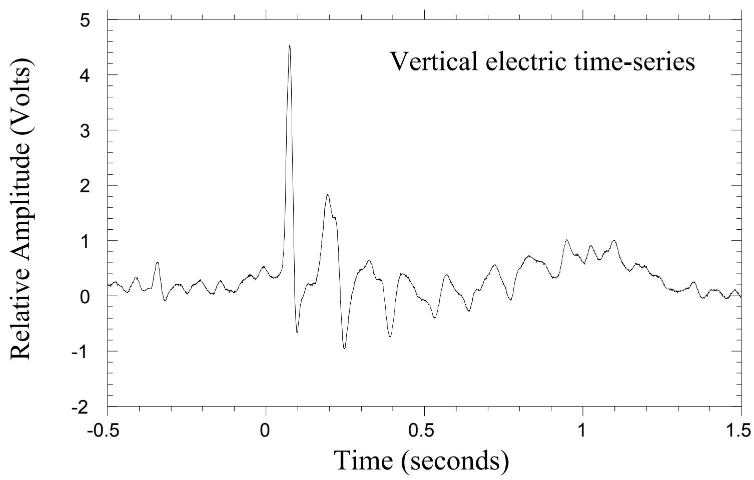

Figure 3. The vertical electric ELF signal associated with the sprite observed at 05:52:05 UT

The impedence spectrum is the ratio of the vertical electric and horizontal magnetic spectra (E/H). The periodicity of the impedence spectrum is uniquely related to the distance traveled by the ELF electromagnetic wave [11]. Using the model of [12], 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 T= 0.078 seconds resulting in D= 10.711 Mm (10711 km).

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. All events observed show positive polarity, implying that the parent lightning was a positive cloud-to-ground discharge. The mean error for all events is 183 km, or 1.6 %.

In Figure 1b the ELF/VLF locations of the parent lightning for 15 events are indicated (white triangles), together with the locations determined using the bearings only from the ELF horizontal magnetic components (black diamonds). 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. Using the new method all the locations of the parent lightning fall within the area of the storm. Depending on the threshold used for the ELF detection times, the number of ELF transients detected can vary greatly. Using our optimum threshold, we found that we overestimated the positive transients originating from this storm by approximately 10% (false alarm rate) [6].

CONCLUSIONS

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 10000 km. The errors could be reduced even further by improving the model used to calculate the distance of the source [10], 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.

ACKNOWLEDGMENTS

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