Excitation of Earth-ionosphere cavity resonances by sprite-associated lightning flashes

Martin Füllekrug
Institut für Meteorologie und Geophysik, Universität Frankfurt/Main, Germany

Steven C. Reising
Microwave Remote Sensing Laboratory, University of Massachusetts at Amherst, Massachusetts

Abstract. Simultaneously recorded discrete excitations of Earth-ionosphere cavity resonances at Silberborn, Germany, and Hollister, California, ~9.1 Mm apart, are used to triangulate source locations of lightning flashes in the continental United States with an accuracy of ~0.8 Mm, as verified by the National Lightning Detection Network. The identified lightning flashes are mainly associated with positive cloud-to-ground discharges with first return stroke peak currents ~20-70 kA. 80% of these particular lightning flashes are associated with sprites, as verified by simultaneous low-light level TV camera observations at Yucca Ridge, Colorado. This high probability of sprite detection is attributed to particularly large cloud-to-ground lightning currents, simultaneously exciting both Earth-ionosphere cavity resonances and sprites.

Lightning flashes and Earth-ionosphere cavity resonances

Natural electromagnetic field variations in the 6-60 Hz transition zone between the Ultra Low Frequency (ULF) and Extremely Low Frequency (ELF) ranges are characterized by interference of propagating waves in the Earth-ionosphere cavity. These Earth-ionosphere cavity (or Schumann) resonances are mainly excited by globally occurring cloud-to-ground lightning flashes [Sentman, 1995, and references therein] which can be located using single station measurements of the vertical electric and horizontal magnetic fields [Jones and Kemp, 1970; Kemp and Jones, 1971]. In this letter, we make use of simultaneously recorded time series of horizontal magnetic field variations in the frequency range 0.2-16 Hz at Silberborn, Germany (51.8° N, 9.5° E), and Hollister, California (36.8° N, 121.4° W), on August 1, 1996. Discrete excitations of Earth-ionosphere cavity resonances, which exceed the natural noise background by a factor of two at both locations, are detected and they are denoted “discrete events” in the following text. Since the source location of one discrete event observed worldwide remained ambiguous [Ogawa et al., 1967], precise times and locations of lightning flashes in the continental United States reported by the National Lightning Detection Network (NLDN) [Cummins et al., 1998] are used to verify that simultaneously occurring discrete events at both locations are excited by lightning flashes. The reported times of lightning flashes are corrected for the time delay introduced by the wave propagation (at a velocity of 0.8 c) along the great circle path to the receiving stations, and simultaneous occurrence tests (< ±15 ms) result in 560 verified discrete events. The horizontal magnetic field of these discrete events is rotated in the direction of maximum magnetic intensity to maximize their signal-to-noise ratio for display. In general, the discrete events exhibit transient pulses at Hollister and damped oscillations of 8 Hz at Silberborn (see Figure 1). Differences in the wave forms arise from higher order modes in the near field at Hollister (~1.9 Mm from the source) and Earth-ionosphere cavity resonances at Silberborn (~3.9 Mm from the source). Arrival azimuths of discrete events are obtained from the angle to rotate the magnetic field vector in the direction of maximum magnetic intensity at both locations. The lightning flash locations reported by the NLDN are used to calculate the mean arrival azimuth deviation from the expected orientation of the Poynting vector along the great circle path. The mean arrival azimuth deviations are 5.85° ± 3.10° and 1.14° ± 5.08° clockwise from geographic north at Silberborn and Hollister respectively. These deviations are

Figure 1. Simultaneously recorded discrete events at Hollister, California (H01), and at Silberborn, Germany (SIL), displayed in the direction of maximum magnetic intensity. At t=+125 ms, a strong positive lightning flash was reported by the NLDN.
presumably accumulated from anisotropic conductivities during the propagation along the great circle path in the Earth-ionosphere cavity. Source location triangulation reveals a spatial accuracy of ~0.8 Mm after removal of the mean arrival azimuth deviation (see Figure 2). Both the arrival azimuth deviation and the spatial accuracy are in agreement with previous estimates [Burke and Jones, 1995; Füllekrug et al., 1996], and we conclude from the coincidence in time and space that these 569 lightning flashes effectively excited Earth-ionosphere cavity resonances.

All lightning flashes recorded by the NLDN in the United States on August 1, 1996, are shown in Figure 3, left panel. For comparison, the NLDN locations of lightning flashes which simultaneously excite discrete events at Silberborn and Hollister, are displayed in Figure 3, right panel. It is evident that the subset of lightning activity derived from globally observable excitations of Earth-ionosphere cavity resonances reflect the main centers of thunderstorm activity in the studied area. In addition to the times and locations of lightning flashes, the NLDN reports the peak current ($I_p$) in the first return stroke of each individual flash. Figure 4 shows the distribution of this peak current for all lightning flashes reported by the NLDN (4A), and for those lightning flashes which excite Earth-ionosphere cavity resonances (4B). The latter are mainly associated with positive first return stroke peak currents ~20-70 kA, and we conclude that the discrete events are excited by the occurrence of lightning continuing current, in agreement with the work of Burke and Jones [1996].

**Sprites and Earth-ionosphere cavity resonances**

Transient optical emissions in the meso- and ionosphere, denoted sprites [Sentman et al., 1995; Lyons, 1990] and elves [Fukunishi et al., 1996] respectively, are also associated with strong positive cloud to ground discharges [Hartmann et al., 1985]. Slow tails of sprite-associated lightning flashes have been observed in the ELF range (Reising et al., 1996; Cummer and Inan, 1997), in the lower ELF range [Boccioppio et al., 1995], and in the ELF/ULF transition range [Füllekrug et al., 1996]. A natural question is whether the global excitations of Earth ionosphere cavity resonances reported in this contribution are related to sprites. Low light level TV (LLTV) camera observations, part of Stanford University’s Fly’s Eye experiment at Yucca Ridge, Colorado (40.7° N, 104.9° W), observed sprites above a mesoscale convective system in the midwestern United States on August 1, 1996 [Bell et al., 1998]. The NLDN lightning flashes were preselected in time and space such that any sprites associated with these lightning flashes would have been observed during the operation of the LLTV camera and within its field of view. During the time interval 06:36 to 08:13 UT, 30 lightning flashes met this criterion and excited Earth-ionosphere cavity resonances. 24 (80%) of these lightning flashes were associated with sprites. The high probability of sprite detection by global excitations of Earth-ionosphere cavity resonances can be explained by particu-
spectives. Times and locations of lightning flashes have been reported by the VLF time of arrival difference system of the British Meteorological Office [Lee, 1986]. It is evident that thunderstorm activity on the southern side of the Pyrenees and Alps are promising regions of sprite occurrences.

Discussion

Lightning flashes associated with particularly large currents can simultaneously excite Earth-ionosphere cavity resonances and sprites. This observation may be a consequence of highly variable current within the lightning channel, for example as a result of the redistribution of charges within the thundercloud [Bell et al., 1998]. On the other hand, Cummer et al. [1998] reported enhancements of ELF slow tails ~5 ms after the initial lightning discharge, coincident with sprite luminosity as verified by use of a high speed photometer. The authors attributed their results to current within the sprite. We extend their ELF observations to measurements in the ELF/ULF transition range from 0.2-16 Hz.

One LLTV frame has a time duration of 33 ms and in 5 cases out of 66 (7.6%), the sprite occurred 2-6 TV frames after the positive lightning flash (see Table 1). At Silberborn and Hollister, the horizontal magnetic intensity $B_h = \sqrt{B_z^2 + B_z^2}$ is sampled at frequencies of 100 Hz and 40 Hz, respectively. For example, Figure 6A and 6B show the horizontal magnetic intensities associated with sprite (S) number 1 (6A) and 2 (6B) at 0.0 seconds. Both are preceded by positive lightning flashes (+) at t=-75 ms and t=-150 ms, respectively. Interestingly, the horizontal magnetic intensity during the sprite occurrence is larger than the horizontal magnetic intensity associated with the positive lightning flash. This is a common property of all events listed in Table 1. A third positive lightning flash (48.4 kA) occurs at t= 450 ms in event number 1 (see Figure

Figure 5. Locations of lightning flashes recorded by the British Meteorological Office, selected by using simultaneously occurring discrete events at Silberborn, Germany, and Hollister, California. The southern side of the Pyrenees and Alps are promising regions of sprite occurrences.

Figure 6. Horizontal magnetic intensity at Silberborn (upper panels) and Hollister (lower panels). Sprites (S) are reported at 0.0 seconds, preceded by positive lightning flashes (+) at t=-75 ms (A) and t=-150 ms (B). A positive lightning flash and a sprite occur simultaneously at t=+125 ms (H) and excite Earth-ionosphere cavity resonances at Silberborn (compare to Figure 1).
Table 1. Occurrence times of sprites which occur 2-6 TV frames after a positive lightning flash reported by the NLDN on August 1, 1996.

<table>
<thead>
<tr>
<th>sprite no.</th>
<th>hh:mm:ss.ms</th>
<th>NLDN hh:mm:ss.ms</th>
<th>lat. °</th>
<th>lng. °</th>
<th>Ip (kA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>06:41:33.512</td>
<td>06:41:33.421</td>
<td>38.11°</td>
<td>-99.39°</td>
<td>+102.7</td>
</tr>
<tr>
<td>2</td>
<td>07:33:43.822</td>
<td>07:33:43.675</td>
<td>38.04°</td>
<td>-99.03°</td>
<td>+42.6</td>
</tr>
<tr>
<td>3</td>
<td>07:41:47.820</td>
<td>07:41:47.700</td>
<td>38.15°</td>
<td>-98.93°</td>
<td>+33.2</td>
</tr>
<tr>
<td>4</td>
<td>07:55:36.881</td>
<td>07:55:36.783</td>
<td>37.76°</td>
<td>-98.48°</td>
<td>+33.6</td>
</tr>
<tr>
<td>5</td>
<td>08:08:15.380</td>
<td>08:08:15.093</td>
<td>38.43°</td>
<td>-99.24°</td>
<td>+23.0</td>
</tr>
</tbody>
</table>

6A), unrelated to sprites. No remarkable horizontal magnetic intensity is evident at Silberborn (Figure 6A and 6B, upper bars). The horizontal magnetic intensity of event 2, associated with a simultaneously occurring positive lightning flash and a sprite, took ±125 ms, can be clearly be observed at Hollister and excites Earth-ionosphere cavity resonances at Silberborn (see Figure 6B and compare to Figure 1). These results are an extension of and in agreement with the work of Cummer et al. [1998]. In this view, superimposed currents of tropospheric positive lightning flashes and mesospheric sprites may effectively excite the Earth-ionosphere cavity.

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References


M. Füllekrug, Institut für Meteorologie und Geophysik, Feldbergstr. 47, Universität Frankfurt/Main, D-60023 Frankfurt/Main, Germany

S.C. Reising, Microwave Remote Sensing Laboratory, University of Massachusetts at Amherst, Amherst, MA 01003-4410, USA

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