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Ultra-slow tails of sprite-associated lightning flashes

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Abstract. We describe the terrestrial excitation of horizontal magnetic field variations in the Pc1 frequency range (0.2-5.0 Hz) by tropospheric, sprite-associated lightning flashes, measured ~1900 km west from the source. These variations, which we call ultra-slow tails, exhibit amplitudes on the order of tens of pT, they have a duration of ~3 seconds, and they occur immediately following the initial pulse of the sprite-associated lightning flash. The ultra-slow tails exhibit two peaks in the frequency domain at 0.67 Hz and 1.67 Hz. The mean polarization ellipses at these two frequencies are oriented ~45° clockwise from geographic north and exhibit right-hand and left-hand polarization respectively with a weak ellipticity of ~0.1. The horizontal magnetic intensity of the initial pulse is related to the horizontal magnetic intensity of the ultra-slow tail, in agreement with the interpretation of ultra-slow tails as ionospheric Alfven resonances.

Introduction

Argus nuclear detonations in the atmosphere provided the first experimental evidence for anthropogenic, terrestrial excitation of ULF waves in the Pc1 range (0.2 to 5.0 Hz) and their subsequent propagation within the ionospheric waveguide [*Berthold et al.*, 1960, and references therein]. The ionospheric waveguide is centered around the F_2 peak of the ionosphere [*Tepley and Landshoff*, 1966]. Naturally occurring ULF waves in the Pc1 range tend to propagate in this waveguide from high latitudes equatorward along geomagnetic meridians in the nighttime hemisphere with velocities ~1000 km/s [*Wentworth et al.*, 1966]. Greifinger and Greifinger [1968] suggested an analytical model for this phenomenon and summarize earlier theoretical descriptions. Magnetometer networks enable studies of the ionospheric propagation of ULF waves in the Pc1 range [*Campbell and Thornberry*, 1972], and triangulation of their source locations [*Fraser*, 1975] has led to characterization and tracking of the polar cusp [*Menk et al.*, 1992; *Neudegg et al.*, 1995]. An ionospheric waveguide with well defined boundaries, makes possible the existence of resonance phenomena [*Watanabe*, 1959], a concept which was put forward theoretically by Greifinger and Greifinger [1976], and references therein. Other analytical and numerical models of the ionospheric Alfven resonator have been proposed [*Belyaev et al.*, 1990; *Lysak*, 1993, and references therein], but little experimental evidence has been reported. One example of magnetospheric ULF waves in the Pc1 range at high latitude exhibits three coherent bands of similar group velocities and dispersion from 0.5 to 2.0 Hz [*Feygin et al.*, 1994]. Stratospheric balloon measurements of the vertical electric field at auroral latitudes show comparable multiple spectral peaks from 0.5 to 3.5 Hz [*Bering and Benbrook*, 1995]. Hickey *et al.* [1996] presented dynamic spectra with up to 15 peaks from 3 to 15 Hz. The last result was interpreted as excitations of ionospheric Alfven resonances by terrestrial sources, in this case by thunderstorm activity. Sukhorukov and Stubbe [1997] extend the model of Greifinger and Greifinger [1976] to suggest that particularly strong lightning flashes can excite sprites [*Sentman and Wescott*, 1993], elves [*Fukunishi et al.*, 1996], and ionospheric Alfven resonances. Experimental evidence is provided by digital recordings of the time derivative of the magnetic field with a sampling frequency of 10 Hz by use of one induction coil aligned in the geographic north-south direction, ~500 km away from the thunderstorm, producing sprites and elves [*Fukunishi et al.*, 1997]. In this letter, we quantify for the first time the physical properties, i.e. magnetic field amplitudes and polarization parameters, of sprite-associated ULF waveforms remotely observed in California, ~1900 km west of a sprite-producing mesoscale convective system, and we compare the results to theoretical predictions of Sukhorukov and Stubbe [1997].

Data acquisition

In collaboration with the Seismological Laboratory, the Department of Materials Science and Mineral Engineering at UC Berkeley installed an electromagnetic measurement station at Hollister, California (36.8° N, 121.4° W). The horizontal magnetic field components are recorded with geographically oriented induction coils at a sampling frequency of 40 Hz. The polarity of the coils is set to be positive in the north (B_x) and east (B_y) directions, according to magnetotelluric conventions, and GPS timing is precise to within <1 ms. The noise level of the instrument is ~200 fT/$\sqrt{}$Hz at 1 Hz and ~40 fT/$\sqrt{}$Hz at 10 Hz. The received time series are corrected for instrumental response and band pass filtered in the frequency range 0.2 to 19 Hz. Low light level TV (LLTV) images are recorded with a sampling frequency of 30 Hz as a part of Stanford University's Fly's Eye Experiment at Yucca Ridge, Colorado (40.7° N, 104.9° W), and 105 sprites were observed above a mesoscale convective system in the midwestern United States from 06:36 to 09:06 UT on August 1, 1996. During the same time interval, the National Lightning Detection Network (NLDN) reported occurrence times of first cloud-to-ground return strokes of lightning flashes with a time resolution of 1 ms.

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Ultra-slow tails

88 % of the observed sprites (92 out of 105) are preceded by a positive lightning flash within a time interval <200 ms, and these positive lightning flashes are referred to as sprite-associated lightning flashes in the following text. At the occurrence time of sprite-associated lightning flashes, the recorded ULF waveform exhibits in general a single pulse starting at 0.0 seconds and lasting <0.4 seconds (see Figure 1a). The B_x component is larger because it is nearly perpendicular to the Poynting vector of the electromagnetic wave, which propagates along the great circle path within the Earth-ionosphere cavity. Occasional superposition of successive sprite-associated lightning flashes results in a series of individual pulses. More precisely, it is found that 28 of the sprite-associated lightning flashes cluster in 13 events with two or three successive sprite-associated lightning flashes within a time interval <550 ms. All remaining sprite-associated lightning flashes are separated by time intervals >5.5 seconds. 9 of the 13 cluster events exhibit more complex ULF waveforms (see Figure 1c): Following the initial pulse of the causative sprite-associated lightning flash at 0.0 seconds, both the B_x and B_y components exhibit oscillations with amplitudes on the order of tens of pT for ~3 seconds. Since these oscillations are related to a causative lightning discharge, and to the Extremely-Low Frequency (ELF) slow tail of a radio atmospheric (sferic), we suggest that this particular ULF waveform be referred to as an ultra-slow tail. Visual inspection of all 92 sprite-associated lightning flashes reveals only 3 additional ultra-slow tails, related to single sprite-associated lightning flashes. The occurrence times of the first sprite-associated lightning flash determined by the NLDN, and characteristics of subsequent ultra-slow tails are listed in Table 1.

The initial pulses of the 12 ultra-slow tails are among the strongest pulses of all 92 sprite-associated lightning flashes. A natural question is whether ultra-slow tails of weaker initial pulses are concealed in ongoing magnetospheric noise. To investigate, the method of superposed epochs is applied to 61 occurrences of single sprite-associated lightning flashes. The 28 successive and 3 single sprite-associated lightning flashes are excluded from this analysis to avoid multiple averaging of the same time interval and interference with obvious excitations of ultra-slow tails. The resulting mean waveform is displayed in Figure 1b for comparison and it clearly exhibits a weak ultra-slow tail. To investigate the relationship between the initial pulse and the ultra-slow tail further, the mean horizontal magnetic intensity $B_h = < \sqrt{(B_x^2(t) + B_y^2(t))} >$ is quantified for the initial pulse and the ultra-slow tail in the time interval from -0.15 to 0.25 seconds and from 0.50 to 3.50 seconds respectively (see Table 1). The horizontal magnetic intensity of the initial pulse of the sprite-associated lightning flash is related to the horizontal magnetic intensity of the ultra-slow tail with a correlation coefficient 0.76 (see Figure 2).

Dynamic spectra of ±10 seconds length, centered at the occurrence time of the sprite-associated lightning flash, are calculated for events 1-4 (see Table 1) and scaled with respect to the maximum spectral power for comparison in Figure 3 (left panel). Each spectrum is based on time intervals of 3 seconds length with a frequency resolution of 1/3 Hz. Event 2 exhibits two different ultra-slow tails. The ultra-slow tail at 0.0 seconds occurs after an initial lightning discharge within the investigated thunderstorm (see Table 1, event 2). The preceeding ultra-slow tail can be related to a positive lightning discharge at 07:33:40.654 UT within a thunderstorm in northern Mexico. Although we do not have any optical confirmation, the occurrence of an ultra-slow tail may indicate that this lightning discharge was associated with a sprite. The mean spectrum of ultra-slow tails 1-4 is calculated for the time interval 0.5-3.5 seconds and exhibits spectral enhancements at 0.67 Hz and 1.67 Hz (see Figure 3, right panel, bars). The spectral amplitudes at 0.67 Hz and 1.67 Hz can be distin-

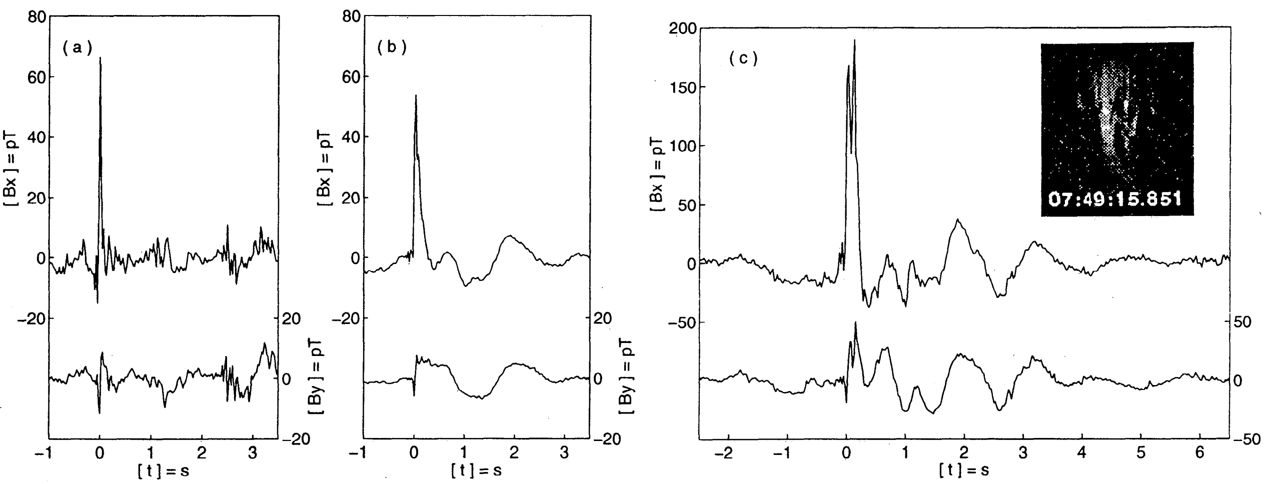

Figure 1. Time series of magnetic field variations in the geographic north (B_x) and east (B_y) components at Hollister, California. LLTV observations at Yucca Ridge, Colorado, reported sprite-associated lightning flashes at 0.0 seconds. The left panel (a) shows the ULF waveform of a single sprite-associated lightning flash and superposed epoch analysis of 61 similar events reveals subsequent occurrence of a weak ultra-slow tail (b). Two successive sprite-associated lightning flashes are followed by a particularly strong ultra-slow tail (c). The LLTV picture of the second sprite is shown in the upper right of Figure 1c.

Table 1. Occurrence times of successive sprite-associated lightning flashes in the midwestern United States on August 1, 1996, and characteristics of their subsequent ultra-slow tails. The mean horizontal magnetic intensities (B_h) of the initial pulse and the ultra-slow tail (UST) are calculated in the time intervals -0.15 to 0.25 seconds and 0.50 to 3.50 seconds respectively. The rms-magnetic field values (B_{rms}) at 0.67 Hz and 1.67 Hz, and the parameters of the polarization ellipse are calculated from spectral analysis of the time interval 0.5-3.5 seconds. The orientation of the polarization ellipse is measured in degrees (deg) clockwise from geographic north, and positive and negative ellipticity correspond to right-hand and left-hand polarization respectively.

event	time (UT)	no. of	no. of	B_h (pT)		B_{rms} (pT)		orientation (deg)		ellipticity	
No.	hh:mm:ss.ms	flashes	sprites	pulse	UST	0.67 Hz	1.67	0.67 Hz	1.67	0.67 Hz	1.67
1	07:32:04.827	1	1	38	14	13.0	4.7	40	49	.14	-.16
2	07:33:43.675	2	2	13	10	7.8	4.0	44	50	.09	-.04
3	07:33:59.636	1	1	30	09	8.3	4.7	37	47	.06	-.08
4	07:49:15.718	2	3	74	22	19.0	6.0	45	60	.20	-.07
5	07:52:33.058	2	2	38	10	8.5	2.8	46	52	.12	-.12
6	07:57:07.230	1	2	55	19	17.1	2.9	36	46	.18	.13
7	07:59:15.655	2	2	53	20	19.8	3.0	37	70	.02	.15
8	08:01:19.616	2	2	44	23	21.1	3.7	31	-23	.22	-.10
9	08:29:22.281	2	2	33	16	13.0	3.3	39	-17	.08	-.07
10	08:31:28.954	2	2	34	15	12.9	3.1	54	14	.10	.49
11	08:34:50.611	3	3	40	14	11.5	3.0	36	-7	.10	-.30
12	08:45:18.558	3	3	42	17	15.7	2.9	33	-14	.14	-.08

guished in all 12 events and they are used to calculate the rms-magnetic field, and the parameters of the polarization ellipse of each ultra-slow tail listed in Table 1. We use ultra-slow tails 1-4 to calculate mean parameters of the polarization ellipse since the rms-magnetic field of ultra-slow tails 5-12 at 1.67 Hz is comparatively small. The orientation of the polarization ellipse is measured in degrees clockwise from geographic north. The mean orientation at 0.67 Hz ($41.6° \pm 3.5°$) and 1.67 Hz ($51.7° \pm 5.6°$) nearly agree within their standard deviations. The mean ellipticities at the first and second spectral peak exhibit weak right-hand (0.12 ± 0.06) and left-hand (-0.09 ± 0.05) polarization respectively with a mean ellipticity $\sim$0.1.

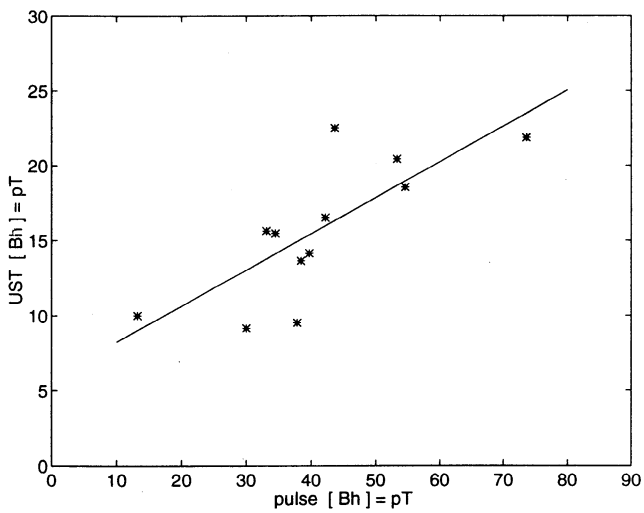

Figure 2. Correlation between the horizontal magnetic intensity B_h of the initial pulse and the ultra-slow tail (UST), calculated from the time intervals -0.15 to 0.25 seconds and 0.50 to 3.50 seconds respectively. The horizontal magnetic intensities are related to each other with a correlation coefficient 0.76.

Discussion

Sukhorukov *et al.* [1996] show a relation between currents of lightning flashes and currents in the ionosphere associated with optical emissions in the mesosphere. Sukhorukov and Stubbe [1997] extend this work and relate the ionospheric currents to possible excitations of ionospheric Alfven resonances. Since these currents are proportional to the magnetic intensity in the near field, the relation between the horizontal magnetic intensity of sprite-associated lightning flashes and the horizontal magnetic intensity of the ultra-slow tails reported in this contribution supports their theoretical predic-

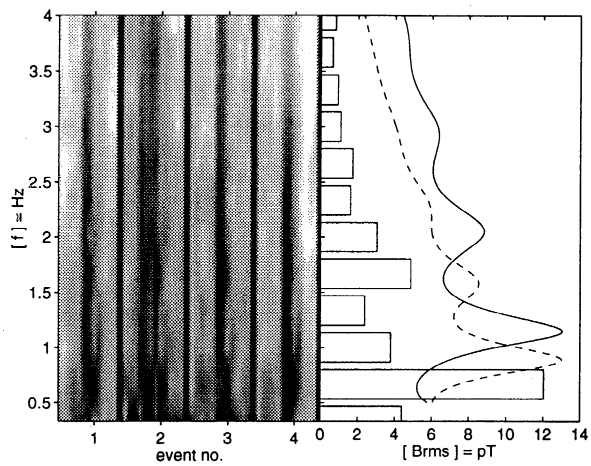

Figure 3. Dynamic spectra of ±10 seconds length, centered at the occurrence time of sprite-associated lightning flashes 1-4 (see Table 1), and scaled with respect to the maximum spectral power for comparison (left panel). The mean spectrum of ultra-slow tails 1-4 in the time interval 0.5-3.5 seconds exhibits two spectral enhancements at 0.67 Hz and 1.67 Hz (bars, right panel). The solid and dashed line show computed spectra of ionospheric Alfven resonances as described in the discussion.

tion in a quantitative way. The proposed theory makes possible the calculation of magnetic field density spectra above the source current at ionospheric heights. We compute this spectrum with the parameters specified in Sukhorukov and Stubbe [1997] for comparison (see Figure 3, right panel, solid line). The resulting spectrum exhibits larger frequencies of the first and second ionospheric Alfven resonance compared to the observed spectrum. The calculated resonance frequencies depend on the geometric dimension of the resonant system, i.e. the reflection height, which depends sensitively on the scale length for description of the Alfven velocity gradient. An increase of the scale length from 200 km to 300 km results in an increase of the reflection height for the first mode from 418 km to 533 km and in a decrease of the resonant frequency from 1.16 Hz to 0.90 Hz (see Figure 2, right panel, dashed line). The similarity of the computed and the observed spectrum suggests that the ultra-slow tails reported in this contribution are consistent with an interpretation as ionospheric Alfven resonances.

Summary

The quantified magnetic field amplitudes and polarization parameters of ultra-slow tails significantly extend the experimental work of Fukunishi *et al.* [1997]. The horizontal magnetic intensity of the initial sprite-associated lightning flash is correlated with the horizontal magnetic intensity of the ultra-slow tail. The mean spectrum of ultra-slow tails is similar to the spectrum of ionospheric Alfven resonances. Both results are consistent with an interpretation of ultra-slow tails as ionospheric Alfven resonances. The theoretical work of Sukhorukov and Stubbe [1997] does not provide any predictions for ground based magnetic field observations at large distances from the source and the reported polarization parameters. Therefore, improved model calculations are desirable to further elucidate the origin of ultra-slow tails, possibly related to discrete excitations of ionospheric Alfven resonances.

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