CHARGE REMOVAL PRODUCED BY INTNESE LIGHTNING DISCHARGES FROM ELF MEASURMENTS

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ABSTRACT

Red sprites, elves and blue jets are upper atmospheric optical phenomena associated with thunderstorms that have only recently been documented and investigated. Sprites are massive but weak luminous flashes that appear directly above an active thunderstorm system and are coincident with cloud-to-ground or intra-cloud lightning strokes. Lightning discharges produce electromagnetic radiation at all frequencies. At Extremely Low Frequencies (ELF) this radiation propagates in the earth-ionosphere wave-guide with little attenuation, traveling around the Earth a number of times before decaying. Hence, theoretically we can detect these waves at any location on the Earth’s surface. Furthermore, due to the constructive interference between ELF waves in the wave-guide, resonant standing waves exist. O.W. Schumann knows these resonant modes as the Schumann resonance after the theoretical prediction of their existence in 1952. The aim of our research is to determine the characteristics of the lightning responsible for generating and associating with sprites, based on the quantitative analysis of the distant (a few mega-meters) electromagnetic fields produced by the lightning and sprite event. Current theories suggest that the most important factor in sprite generation is the vertical charge moment change in a lightning stroke. The relatively sustained (~1 ms) quasi-electrostatic field in the mesosphere after a lightning stroke is proportional to the lightning charge moment change, and it is this electric field that can drive electric breakdown and streamer development and runaway relativistic electron breakdown. We investigate ELF/VLF radiation of lightning, with a focus on improving methods to calculate the charge moments of distant lightning discharges. This parameter appears to be crucial in determining which lightning discharges produce sprites at the time of its initiation, and which do not.

ELF/VLF: ADVANTEGES AND DISADVANTEGES

Charge moment transfer associated with intense sprite-producing lightning strokes can be evaluated from the electromagnetic radiation produced by its parent lightning in ELF and VLF bands [1-5]. For each band some advantages and disadvantages arise. The main focus of this paper is the ELF band, mainly its lower part, known as 'Schumann Resonance band' below 50Hz. In ELF (3-3000Hz) the attenuation rate is very low - less than 1dB/Mm, where 1Mm=1000km. Hence the wave propagation path is prolong- several thousands kilometers, so therefore charge moment calculation can be preformed for globally monitored lightning strokes. Another advantage in the lower ELF band is the quasi transverse electromagnetic (q-TEM) mode assumption: near lightning origin all higher order modes attenuated so the only effectively radiated mode in the earth-ionosphere cavity is the q-TEM mode (the lower ELF band is below the waveguide initial cutoff frequency which determined by its geometric height and the speed of light - $f=c/(2h) \sim 1.6kHz$, where assuming the height of the ionosphere is $h=90km$). But since sampling frequency in ELF is rather low time resolution is not good: Lightning discharge phenomena has a transient stage with an order of microseconds and a relaxation stage of tens of milliseconds while the system sampler time period is only with an order of milliseconds. Therefore in ELF the fast impulse rise time cannot be recorded accurately but the long-tail continuing current which contributes to the charge transfer amount the most can be clearly observed at the time series. In the Very Low Frequency band (VLF: 3-30 kHz) the electromagnetic signal can propagate for several hundreds of km, and sometimes even several thousands of km, but since the attenuation rate in VLF is not as low as in ELF charge moment calculation cannot be preformed for a globally monitored lightning strokes. Also, when calculating the charge transfer in VLF, higher modes should be considered so the analysis becomes complicated. But in VLF band the time resolution is very good (several microseconds) so most of the discharge process is covered.

THEORY: CHARGE MOMENT CALCULATION IN ELF

In ELF, the radio wave propagated within the isotropic geocentric spherical earth-ionosphere cavity consists of only two field components: radial electric field E_r and horizontal magnetic field H_φ. The electromagnetic fields origin is a vertical electric dipole located on the earth shell, i.e. lightning discharge from cloud to ground. The frequency-dependant normal mode equations given by [6, 7, 8] in polar coordinates system:

$$E_r(\omega)=i\frac{Ids(\omega)\nu(\nu+1)P_\nu^0[\cos(\pi-\theta)]}{4a^2\varepsilon_0\omega h\sin(\pi\nu)} \qquad (1)$$

$$H_\varphi(\omega)=-\frac{Ids(\omega)P_\nu^1[\cos(\pi-\theta)]}{4ah\sin(\pi\nu)} \qquad (2)$$

where ω denotes the angular frequency; θ, great circle angle from lightning to the observer; ε_0, vacuum permittivity; a, radius of the Earth; h, the height of the ionosphere; ν, the complex modal eigenvalue related to the propagation constant of the Earth-ionosphere spherical-shell cavity; $P_\nu^0(x)$ and $P_\nu^1(x)$ are Legendre and associated Legendre functions of complex degree $\nu(\omega)$ and order 0,1 respectively and $Ids(\omega)$ is the vertical current moment spectrum of the source lightning flash. The last plays a key role in charge transfer calculation where I denote the lightning stroke current and ds is the channel length. To compute the current moment spectrum $Ids(\omega)$ we need to measure the horizontal magnetic field $H_\varphi(\omega)_{measured}$, to evaluate the distance from the observatory to the lightning source θ, and to estimate the height of the ionosphere h. Then, by division:

$$Ids(\omega)_{measured}=\frac{H_\varphi(\omega)_{measured}\cdot 4ah\sin(\pi\nu)}{P_\nu^1[\cos(\pi-\theta)]} \qquad (3)$$

By the knowledge of $Ids(\omega)_{measured}$ one can use an optimized curve fit technique to compare it with $Ids(\omega)_{theory}$ and then to calculate the charge moment.

CHARGE MOMENT – A SIMPLE MODEL

The simple current moment, demonstrated by Burke and Jones [1], assumes exponential model it time domain:

$$Idl(t) = A \cdot e^{-t/\tau} \qquad (4)$$

The straightforward charge moment calculation in time domain is by the basic definition $Q = \int_{-\infty}^{+\infty} I(t)dt$.

In our case the lightning discharge occurred in *t=0*, so:

$$Qds = \int_0^{\infty} Ids(t)dt = \int_0^{\infty} A \cdot e^{-t/\tau} dt = A \cdot \left[-\frac{e^{-t/\tau}}{1/\tau} \right]_0^{\infty} = A \cdot \tau \qquad (5)$$

Alternative way to calculate charge moment is from frequency domain using the Fourier transform:

$$F(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} f(t) \cdot e^{i\omega t} dt \;\rightarrow\; \int_{-\infty}^{+\infty} f(t)dt = \sqrt{2\pi} \cdot F(\omega = 0) \qquad (6)$$

Hence,

$$Ids(\omega) = F\{Ids(t)\} = F\{A \cdot e^{-t/\tau}\} = A \cdot \sqrt{\frac{2}{\pi}} \cdot \frac{\tau}{1 + \omega^2 \tau^2} \qquad (7)$$

where *F{x}* is the transform Fourier of *x*.
And now, for ω=0:

$$\int_{-\infty}^{+\infty} f(t)dt = \sqrt{2\pi} \cdot A \cdot \sqrt{\frac{2}{\pi}} \cdot \frac{\tau}{1+0} = 2A\tau \qquad (8)$$

Due to symmetry consideration of the expression in (7), we can divide (8) by 2 to get the result as in (5). The fitting of $Ids(\omega)_{measured}$ should be done with the expression (7), i.e. $Ids(\omega)_{theory}$.

CHARGE MOMENT – AN IMPROVED MODEL

Although a single exponential model is sufficient to characterize ELF event in most cases (Burke and Jones [1] reported on 96% of all signals they processed) the general model consists of exponential functions of the form:

$$i(t) = \sum_j I_j \cdot \exp(-t/\tau_j) \qquad (9)$$

I_j, the current amplitude, is from the order of tens of kA and τ_j, the relaxation time, ranges from a few microseconds up to a few milliseconds. Several papers suggested different waveform parameters [9, 10, 11, 12, 13, 14]. When using three exponents the first term represents the contributions from the leader and the final stage of the lightning flash, the second is due to the return stroke, and the third accounts for the continuous currents following the return strokes. The last term with the slowest relaxation time is the one contributes the most energy in ELF. In addition there are also lateral corona currents which are caused by the high potential differences between the leader sheath and the return channel in the first stroke of a lightning flash. Those corona currents shown to radiate significant amount of ELF energy as well.

FUTURE PLAN

During the coming summer a sprite campaign will be conducted in the United States. We intend to detect the ELF and VLF transients associated with transient luminous events (TLEs) in the upper atmosphere and to calculate its charge moment. We are going to analyze signals which will arrive some 11,000km from its lightning source and be received at our ELF and VLF stations [15], and to improve our techniques to quantify parameters related to the parent lightning that triggered those luminous phenomena [16].

REFERENCES

[1] Burke, C. P., and D. Ll. Jones, 1996. On the polarity and continuing currents in unusually large lightning flashes deduced from ELF events. *J. Atmos. Terr. Phys.*, 58, 531-540.

[2] Cummer, S. A. and U. S. Inan, 1997. Measurement of charge transfer in sprite-producing lightning using ELF radio atmospherics. *Geophys. Res. Lett.*, 24, 1731-1734.

[3] Haung, H. G., E. Williams, R. Boldi, S. Heckman, W. Lyons, M. Taylor, T. Nelson and C. Wong, 1999. Criteria for sprite and elves based on Schumann resonance observations. *J. Geophys. Res*., 104, 16943-16964.

[4] Sato, M., H. Fukunishi, M. Kikuchi, H. Yamagishi, W.A. Lyons, 2003. Validation of sprite-inducing cloud-to-ground lighting based on ELF observations at Syowa station in Antarctica. *J. Atmos. Terr. Phys.*, 65, 607-614.

[5] Cummer, S. A., 2003. Current moment in sprite-producing lightning. *J. Atmos Terr. Phys.*, 65, 499-508.

[6] Jones, D. L., 1967. Schumann resonances and ELF propagation inhomogeneous isotropic Ionospheric profiles. *J. Atmos Terr. Phys.*, 29, 1037.

[7] Wait, J. R., 1970. *Electromagnetic waves in stratified media*. Pergamon Press, Oxford (2nd Edition), Chapter 6.

[8] Galejs, J., 1972. *Terrestrial propagation of long electromagnetic waves*. Pergamon Press, Oxford, Chapters 3, 4 and 7.

[9] Bruce, C. E. R., and R. H. Golde, 1941. The lightning discharge. *Inst. of Elect. Eng. J.* 88, Part II, 487-505.

[10] Hepburn, F., 1957. Atmospheric waveforms with very-low-frequency components below 1kc/s known as slow tails. *J. Atmosph. Terr. Phys.* 10, 266-287.

[11] Williams, J.C., 1959. Thunderstorms and VLF radio noise. Ph.D. thesis, Harvard University, Div. Engr. and Applied Phys.

[12] Berger, K., 1962. Front duration and current steepness of lightning strokes to the earth. *Gas Discharges and Electricity in Supply Industry*, *Proc. Intern. Conf. Central Electricity Res. Lab*., Leatherhead, Surrey, England, May 1962, Butterworth, London, pp. 63-73.

[13] Dennis, A. S., and E. T. Pierce, 1964. The return stroke of the lightning flash to earth as source of VLF atmospherics. *Radio Sci.*, 68D, 772-794.

[14] Rao, M., 1967. Corona currents after the return stroke and the emission of ELF waves in a lightning flash to earth. *Radio Sci.*, 2(2), 241-244.

[15] Price, C., M. Finkelstein, B. Satarobinets, and E. Williams, 1999. A new Schumann resonance station in the Negev Desert for monitoring global lightning activity. *Proceedings of the 11th International Conference on Atmospheric Electricity*, Guntersville, Alabama, pp. 695-699.

[16] Price, C., M. Asfur, W. Lyons, and T. Nelson, 2002. An improved ELF/VLF method for globally geolocating sprite-producing lightning. *Geophys. Res. Lett*., 29(3), 1.1-1.4.