VLF Remote Sensing of Lightning-induced Effects in the Ionosphere and the Radiation Belts

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Abstract: Electromagnetic energy released in lightning discharges produces a host of physical effects in the lower ionosphere and the radiation belts, including heating of ambient electrons, electrical conductivity changes, a variety of optical emissions, and the precipitation of energetic electrons from the Earth's radiation belts.

1. Introduction

Recent evidence indicates that thunderstorms and lightning discharges are strongly coupled to the overlying upper atmospheric regions. Lightning discharges at cloud altitudes (<20 km) affect altitudes >40 km either via the release of intense electromagnetic pulses (EMPs) and/or the production of intense quasi-static electric (QE) fields. The intense transient QE fields of up to ~1 kV/m, which for positive CG discharges is directed downwards, can avalanche accelerate upward-driven runaway MeV electron beams, producing brief (~1 ms) flashes of γ-radiation. A spectacular manifestation of these intense fields is the so-called 'Sprites', large luminous discharges in the altitude range of ~40 km to 90 km, which are produced by the heating of ambient electrons for a few to tens of milliseconds following intense lightning flashes. The so-called 'Elves' are optical flashes which last much shorter (<1 ms) than sprites, and are typically limited to 80-95 km altitudes with much larger (up to 600 km) lateral extent, being produced by the heating, ionization, and optical emissions due to the EMPs radiated by both positive and negative lightning discharges.

While these new phenomena provide luminous evidence of physical effects on the lower ionosphere of energy released in lightning discharges, VLF radio remote sensing has long been effectively used to measure transient and localized disturbances of the lower ionosphere that are produced by lightning discharges. In this paper, we provide a review our current knowledge and recent results in the area of physical effects of lightning discharges on the upper atmosphere and the radiation belts, with specific emphasis on the effects revealed and measured via VLF remote sensing.

2. Subionospheric VLF Remote Sensing

Subionospherically propagating VLF waves are uniquely suited for the investigation of the night-time D-region, also known as the 'ignorosphere' (40-100 km altitudes) so named due to the difficulty of making systematic measurements [*Sechrist*, 1974]. To appreciate this difficulty, one should note that this altitude range is too low for satellites to complete an orbit (due to high atmospheric drag) and too high for even the largest balloons (~30 km) and even the highly specialized extremely high altitude aircraft (~20 km) and is thus only accessible by rockets in the course of a single brief traverse through the region. Such measurements do not allow the systematic study of variability of the region and is specifically unsuited for the localized and highly transient type of lightning-induced disturbances that are the subject of our proposed study.

In general, the only remaining means of measurement of the properties of this region is by means of *remote sensing* using radio, radar and/or optical means. However, most ionospheric HF radars, even the most powerful ones (e.g., the Incoherent Scatter radar in Arecibo, Puerto Rico) requires background electron densities of at least 1000 el/cc in order to detect useful echoes, while the ambient night-time electron density in the D-region (<90 km altitude) is typically only a few to tens of el/cc. Radio methods aimed at measurement of total electron content (TEC) (for example using tomographic techniques using GPS or other signals) are similarly not useful, since by far most of the electron content along a line of sight is dominated by the much higher electron densities in the E and F regions, so that the much smaller variations in the *D*-region lie well below the noise level in such measurements. Optical remote sensing can in principle be used, but only the most energetic events, such as the high altitude luminous discharges known as 'sprites' are detectable by such means, while the bulk of the ionospheric disturbances produced by lightning discharges, specifically the so-called Early/fast events (localized conductivity changes) and lightning-induced electron precipitation effects which are the subjects of the proposed study, do not exhibit detectable optical signatures.

Subionospheric VLF measurements are particularly suited for studies of this altitude range due to the fact that the night time reflection height is in the vicinity of ~85 km altitude. Measurements of the amplitude and phase of VLF signals propagating in the earth-ionosphere waveguide have long been used effectively for remote sensing of the ionosphere. VLF sounding has been established as a sensitive tool for the measurement of ionospheric conductivity (i.e., electron density and temperature), especially at altitudes below 90 km [e.g., *Sechrist*, 1974], and in recent years has been extensively utilized to study a variety of lower ionospheric disturbances, including those associated with lightning discharges [e.g., Inan *et al.*, 1993; Burgess *and Inan*, 1993], heating by HF [*Barr et al.*, 1985; Bell *et al.*, 1995] and VLF waves [*Rodriguez et al.*, 1994], the auroral electrojet [*Kikuchi and Evans*, 1983; *Cummer et al.*, 1994; 1997], and relativistic electron precipitation enhancements [*Demirkol et al.*, 1999].

Two different primary types of subionospheric Very Low Frequency (VLF) signatures have been identified, (i) the so-called Early/fast VLF conductivity changes in which the subionospheric VLF signal amplitude/phase changes [*Inan et al.*, 1988, and references therein] within <20 ms of the causative lightning flash, indicating an immediate effect of the lightning discharge in the overlying lower ionosphere, and (ii) VLF signatures of lightning-induced electron precipitation (LEP) events, in which the subionospheric VLF signal/amplitude changes *after* an onset delay of ~1 sec with respect to the causative lightning flash, consistent with the finite wave and particle travel times respectively to/from the regions of maximum cyclotron resonant pitch angle scattering of the energetic (>100 keV) radiation belt particles which causes them to precipitate into the lower ionosphere [*Burgess and Inan*, 1993, and references therein].

3. Early/fast VLF Conductivity Changes

VLF remote sensing revealed the very first evidence of the direct disturbance of the nighttimes lower ionosphere by lightning [*Inan et al., 1988* and references therein]. Since the serendipitous recording of the first video images of sprites [*Franz et al.*, 1990] and many others that followed [e.g., *Sentman and Wescott*, 1993; *Lyons*, 1994], the region above thunderstorms has been regularly observed by a range of optical sensors, typically during summer Sprites campaigns in the mid-western United States and in Europe. These luminous discharges known as sprites and other types of luminous events such as 'elves' [*Inan et al.*, 1997] indicate direct electrodynamic coupling between lightning discharges and the lower ionosphere. The coupling mechanisms in effect include (i) the heating of the ambient electrons by lightning electromagnetic pulses (EMP) leading to elves [*Inan et al.*, 1996] and (ii) heating of the ambient electrons by large quasi-electrostatic (QE) fields leading to sprites [*Pasko et al.*, 1996].

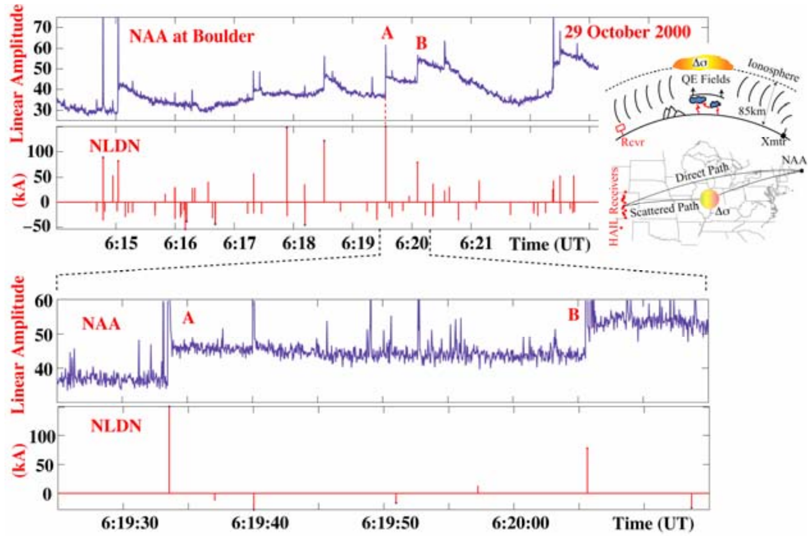

Figure 1: Early/fast VLF events observed in Boulder, Colorado on the 24.0 kHz signal from the NAA transmitter in Cutler, Maine. Top panel shows a ~10-minute record of several events. Lightning data from NLDN (second panel) shows the temporal association of events with particularly intense lightning flashes. Lower two panels show expanded records, of the VLF event onsets nearly simultaneous with the causative lightning discharges.

Early/fast VLF events are believed to be manifested by a combination of the EMP and QE processes, and they occur much more commonly than the luminous events (sprites, elves), so that the quantitative understanding of their properties is crucial to the overall quantification of the global effect of thunderstorms and lightning discharges on the mesosphere and lower ionosphere. Examples of Early/fast VLF events measured in Central United States are shown in Figure 1.

3. Lightning-induced Electron Precipitation (LEP) Events

Subionospheric VLF remote sensing provided the earliest evidence of *indirect* ionospheric effects of lightning discharges [*Helliwell et al.*, 1973; *Inan et al.*, 1988; *Burgess and Inan*, 1993, and references therein], via the process of whistler-wave-induced precipitation of energetic radiation belt particles. Lightning-induced electron precipitation (LEP) is a means of loss for the radiation belts. Individual bursts of precipitating energetic electrons has been measured on satellites, rockets, and via VLF remote sensing of associated ionospheric disturbances [*Voss et al.*, 1998 and associated references therein]. The transient and localized nature of the process renders satellite observations of LEP events difficult, whereas hundreds of LEP bursts can be measured on a given night with the subionospheric VLF method [*Lev-Tov et al.*, 1995].

Prior to 1999, theoretical [e.g., *Inan et al.*, 1989] and experimental [e.g., Burgess *and Inan*, 1993; Voss *et al.*, 1998] work on the LEP phenomena emphasized interactions with 'ducted' whistler waves which propagate in field-aligned ducts of enhanced ionization (left hand panel of Figure 2). LEP events were believed to be produced *only by ducted* whistlers, which propagate within (and thus affect only the electrons within) filamentary ducts <400 km wide at the geomagnetic equator [e.g., Burgess *and Inan*, 1993]. Detection of LEP events on the ground via the associated *D* region ionisation indicates that tens to hundreds of LEP events may be produced by a single thunderstorm [e.g., *Inan et al.*, 1988b; *Inan et al.*, 1990; *Lev-Tov et al.*, 1995].

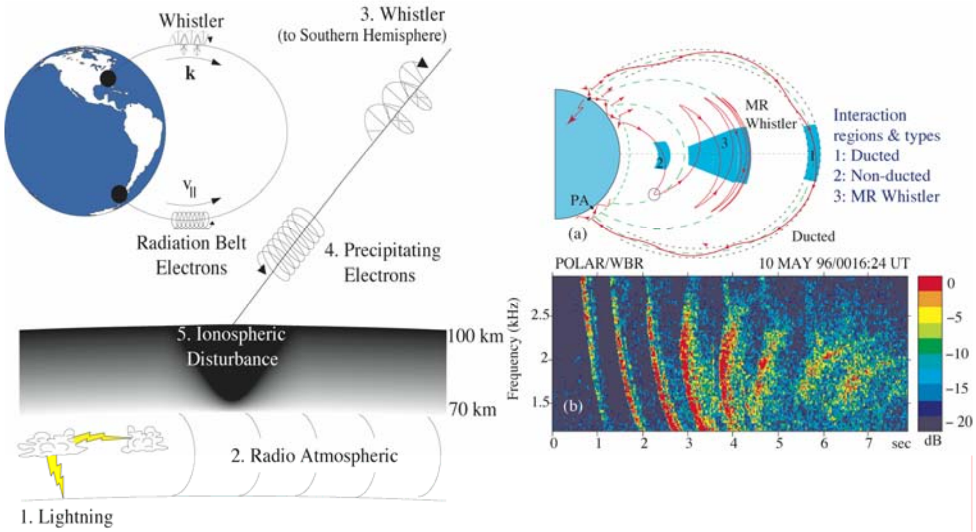

Figure 2: The LEP Process. Left panel shows the LEP process in the 'ducted' mode (Type 1), resulting in the production of a localized and transient ionospheric disturbance. Type 2 scattering is caused by non-ducted oblique whistlers in their first pass of the geomagnetic equatorial plane and were first observed in [*Johnson et al.*, 1999]. Type 3 scattering is not discussed here.

An example of a VLF signature of an LEP event is depicted in Figure 3, occurring in time association with an intense lightning flash in Texas, and observed on a number of the VLF great-circle paths from Maine to the mid-western United States. This Type 2 event is produced by non-ducted whistler waves injected by lightning over a broad wave front (see the upper right inset). The precipitation occurs over a large region of ~1000 km extent in the ionosphere.

The expanded records (Figure 4) illustrate the ~1 second delay between the causative lightning flash and the onset of the VLF perturbation, consistent with the time it takes for the waves to travel up to the geomagnetic equator (where the strongest interactions occur) and the scattered electrons to travel down from there to the ionosphere.

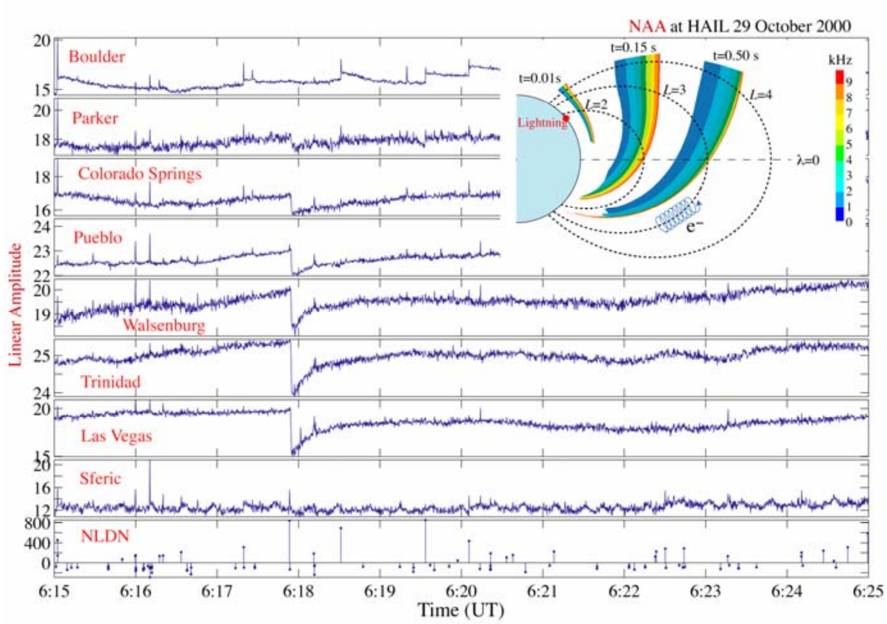

Figure 3: VLF signature of an LEP event observed with the HAIL system. Amplitudes of signals observed at different sites (ranging from North to South) are shown.

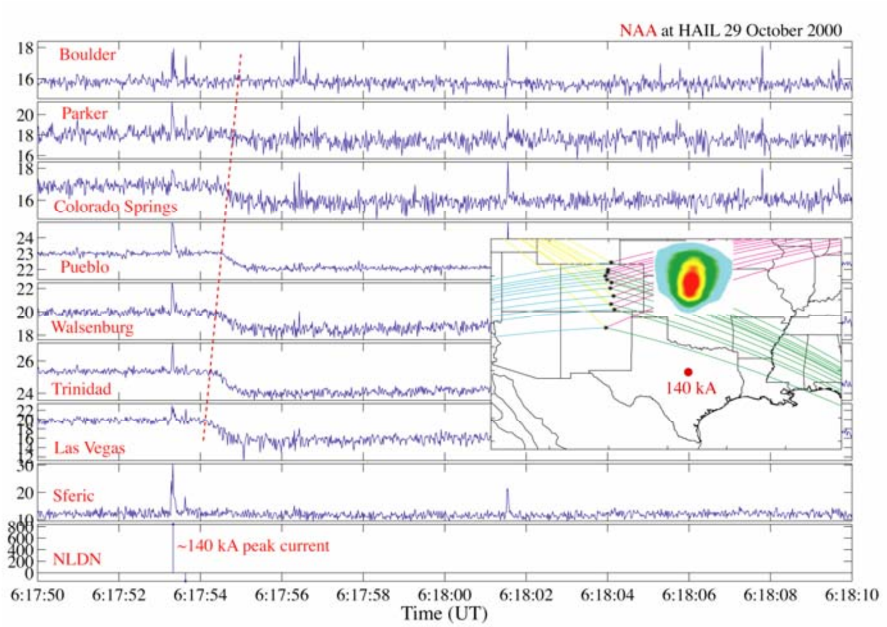

Figure 4: Expanded record showing the distinct delay between the causative lightning flash and the event onset. The inset shows the calculated layout of the electron precipitation region.

4. Summary

Subionospheric VLF measurements provides a powerful tool for the investigation of regions of the Earth's upper atmosphere that are not accessible by other means, and can be used to study transient and localized disturbances of the night-time D-region, produced either directly by electromagnetic energy released in lightning discharges, or indirectly via the precipitation of bursts of energetic electrons.

References

[1]. Franz, R.C., R.J. Nemzek, and J.R. Winckler, Television image of a large upward electrical discharge above a thunderstorm, *Science, 249,* 48-51, 1990.

[2]. Inan, U. S., D. C. Shafer, W. Y. Yip, and R. E. Orville, Subionospheric VLF signatures of nighttime D-region perturbations in the vicinity of lightning discharges, *J. Geophys. Res.*, *93*, 11455, 1988a.

[3]. Cummer, S. A., T. F. Bell, and U. S. Inan, VLF remote sensing of high-energy auroral particle precipitation, *J. Geophys. Res., 102*, 7477, 1997.

[4]. Demirkol, M. K., U. S. Inan, T. F. Bell, S. G. Kanekal, and D. C. Wilkinson, Ionospheric effects of relativistic electron enhancement events, *Geophys. Res. Lett., 26*, 3557, 1999.

[5]. Rodriguez, J. V., and U. S. Inan, Electron density changes in the nighttime *D* region due to heating by very-low-frequency transmitters, *Geophys. Res. Lett., 21* 93, 1994.

[6]. Bell, T. F., U. S. Inan, M. T, Danielson, and S. A. Cummer, VLF Signatures of ionospheric heating by HIPAS, D. S. Lauben, The heating of suprathermal ions above thunderstorm cell, *Radio Science, 30,* 1855-1867, 1995.

[7]. Barr, R., M. T. Rietveld, P. Stubbe, and H. Kopka, The Diffraction of VLF radio waves by a patch of ionosphere illuminated at a powerful HF transmitter, *J. Geophys. Res., 90,* 2861-2875, 1985.

[8]. Lauben, D. S., U. S. Inan, and T. F. Bell, Poleward-displaced electron precipitation from lightning-generated oblique whistlers, *Geophys. Res, Lett.*, *26*, 2633, 1999.

[9]. Inan, U. S. et al., Subionospheric VLF "Imaging" of lightning-induced electron precipitation from the magnetosphere, *J. Geophys. Res., 95*, 17217, 1990.

[10]. Inan, U. S., T. G. Wolf, and D. L. Carpenter, Geographic distribution of lightning-induced electron precipitation observed as VLF/LF perturbation events, *J. Geophys. Res., 93,* 9841, 1998b.

[11]. Inan, U. S., M. Walt, H. D. Voss, and W. L. Imhof, Energy spectra and pitch angle distributions of lightning-induced electron precipitation: analysis of an event observed on the S81-1 (SEEP) Satellite, *J. of Geophys. Res., 94*, 1379, 1989.

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