High-speed Observations and Modeling of Elves and Associated Ionospheric Effects

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We present observations of elves using the PIPER photometer instrument and compare these measurements to results of a Finite-Difference Time-Domain (FDTD) model of the lightning-ionosphere interaction in 2D and 3D. The model propagates lightning fields from the ground up, inherently including electrostatic, induction, and radiated components. In the ionosphere, we calculate heating, attachment, detachment, ionization, and optical emissions (elves). The model is used to investigate elve doublets and ring sprites, and provides simple physical explanations for both. The model is also applied to F-region heating from the lightning EMP fields and is used to predict possible "F-elves". Finally, we use the model to investigate lightning on Venus, and to study the effects of VLF transmitters on the overlying D-region ionosphere.

1. Elves

Reliable observations of elves require time resolution and sensitivity that are directly at odds with each other in optical instrumentation. A good compromise is found in the PIPER photometer instrument developed at Stanford in 2006 [1]. It provides minimal spatial resolution with kR sensitivity at 40 us time resolution. The latest incarnation of PIPER (2012) will provide the option for 20 us time resolution. PIPER has been used to show that typical TLE-producing storms yield 6 times as many elves as sprites [2], though elves are rarely seen in video-rate camera data. PIPER has also discovered "elve doublets", which are described in more detail below.

2. FDTD Modeling of VLF Wave Propagation

The FDTD method lends itself well to modeling of VLF waves (λ = ~15 km) in the earth-ionosphere waveguide (~90 km thick). However, the lower ionosphere is an anisotopic magnetized collisional plasma, and plasma effects must be included. We have developed 2D and 3D spherical-coordinate models of VLF wave propagation which solve Maxwell's equations and the Langevin equation:

$$\mu_0 \frac{d\bar{H}}{dt} = \nabla \times \bar{E}$$

$$\epsilon_0 \frac{d\bar{E}}{dt} = \nabla \times \bar{H} - \bar{J}_{tot}$$

$$\frac{d\bar{J}_n}{dt} + \nu_n \bar{J}_n = \bar{\omega}_{c,n} \times \bar{J}_n + \omega_{p,n}^2 \epsilon_o \bar{E}$$

The model may include n species of ions (including electrons); ν_n, $\omega_{c,n}$ and $\omega_{p,n}$ are the collision frequency, vector gyrofrequency and plasma frequency for species n, respectively.

The interaction of lightning VLF waves with the ionosphere is highly nonlinear. Detachment, attachment, ionization, electron heating, and optical emissions are all non-linear functions of the effective electric field (reduced by the Earth's magnetic field). Each of these effects is included in our model via lookup-table interpolation.

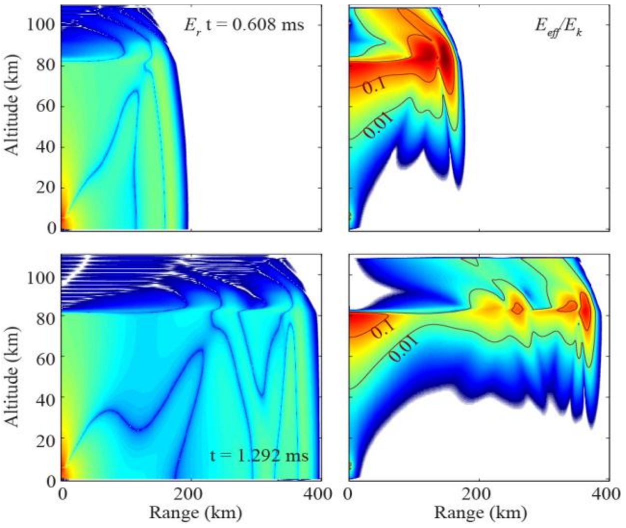

Figure 1: Example 2D simulation, demonstrating the vertical component of E and the field relative to the breakdown field E_{eff}/E_k at two time steps.

3. Model Applications

3.1 Elves and Elve Doublets

We apply the model to the study of elves from both cloud-to-ground and in-cloud lightning, in order to compare with prior models [3]. We find that the lightning source current waveform (rise time and fall time) controls the temporal signature of observed elves. Certain combinations of rise time and fall time lead to “elve doublets”, as observed by [4]. We show that using this model, the temporal signature of observed elve doublets may provide a remote-sensing measurement of the source lightning current waveform.

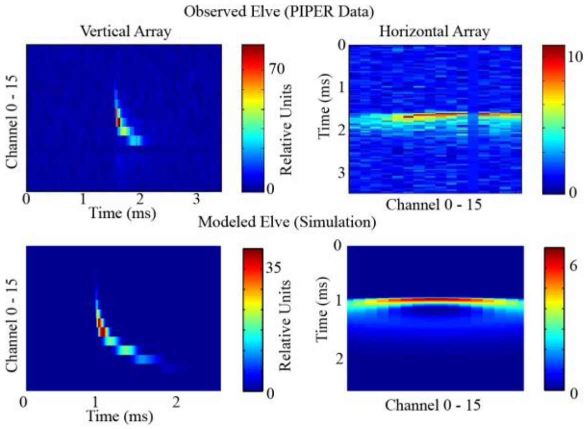

Figure 2: Example elve in PIPER data and simulation.

3.2. Ring Sprites

The model described here is used to estimate the reduced field *E/N* and E_{eff}/E_k at all altitudes. By varying the source current parameters, we find that the peak E_{eff}/E_k may occur away from the axis of the source lightning, in a ring with 20-40 km radius, at sprite-initiation altitude. We propose that particular lighting source currents may be responsible for “ring sprites”, in which sprite elements appear to be initiated in a ring centered above the source lightning.

3.3. F-region Elves

Optical emissions in the F-region due to lightning have been predicted by M. Kelley based on rocket measurements of parallel electric fields [5]. Because it solves the basic equations of waves in a cold, collisional plasma, our FDTD model can be extended to higher altitudes to study the effects of lightning-generated whistlers on the F-region ionosphere. To investigate observable effects, we include calculations of optical excitation rates of atomic oxygen emissions at 6300 A and 5577 A. We find that a 150 kA discharge may produce emissions in these wavelengths of 1-10 Rayleighs at altitudes above 200 km. We propose that simultaneous observations of D- and F-region emissions may elucidate the propagation of VLF waves through the lower ionosphere.

3.2. Venus Lightning

Measurements in the ULF/ELF frequency range of whistler-mode waves on Venus Express have provided indirect evidence for lightning on Venus; however, Venus lightning has not been observed visually. By modifying the atmosphere and ionosphere inputs to our model, we investigate lightning-generated whistlers on Venus. We investigate cloud-to-ground, in-cloud, and cloud-to-ionosphere lightning on Venus as possible sources for whistlers, and compare to those observed by Venus Express. Furthermore, we include non-linear calculations, but show that Venus lightning would need to be an order of magnitude more intense than on Earth in order to produce any nonlinear effects (attachment, ionization or optical emissions).

3.2. VLF Transmitters

By modifying our source current to be a continuous-wave sinusoid at ~20 kHz, we investigate VLF transmitter signal propagation in the Earth-ionosphere waveguide, and VLF transmitter heating of the overlying ionosphere. Heating is calculated above the VLF transmitter using the HF heating model of [6], modified for VLF waves. We find that VLF transmitters such as NPM can increase the electron temperature in the D-region by hundreds of Kelvins, and reduce the conductivity by 50% or more. Furthermore, the heating demonstrates spatial structure that is a combination of the VLF wave itself and the mode structure in the waveguide. We propose that this spatial structure may be responsible for wide-angle scattering of probe signals from the heated region.

4. References

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