# SUBIONOSPHERIC VLF IMAGING OF TRANSIENT DISTURBANCES: EARLY/FAST AND LIGHTNING-INDUCED ELECTRON PRECIPITATION EVENTS

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## ABSTRACT

Very Low Frequency (VLF) remote sensing is uniquely suited for measurement of localized disturbances in the nighttime D-region, especially at altitudes below ~100 km, where the ambient electron density is typically below $10^3$ el/cc. A common cause of such localized disturbances at mid- and low-latitudes are lightning discharges, producing transient conductivity changes due to electrodynamic and/or quasi-electrostatic processes that they excite, both locally in the ionosphere and also in the radiation belts. These disturbances typically endure for tens of seconds, until the ionosphere recovers (chemically) back to its ambient state, during which time they can be detected and measured as sub-ionospheric VLF signal amplitude and phased changes. Recent advances in GPS-based timing allow the resolution of the complete wave guide mode structure of VLF signals, facilitating quantitative interpretation of the observed VLF signatures in terms of altitude profiles and lateral extent of the associated ionospheric disturbances. Most recent application of the sub-ionospheric VLF method include the first observation of energetic electron precipitation induced by nonducted and magnetospherically reflecting whistler waves.

## VLF REMOTE SENSING OF LIGHTNING-INDUCED EFFECTS IN THE LOWER IONOSPHERE

Intense electromagnetic and quasi-electrostatic fields released in lightning discharges are now known to disturb the lower ionosphere (<100 km) in manner of ways, leading to direct effects such as intense heating, production of optical emissions, ionization, gamma-rays, and conductivity changes, as well as indirect effects (such as secondary ionization) produced by induced precipitation of energetic electrons from the overlying radiation belts. The first experimental evidence of such ionospheric effects of lightning discharges were realized during 1970s and 1980s in the form of transient sub-ionospheric VLF signal perturbations. These initial observations were followed by a literal explosion of new results in the 1990s, involving observations of optical emissions (sprites, blue jets, elves, sprite-halos) and terrestrial gamma ray flashes. In the meantime, the sub-ionospheric VLF method has steadily been developed to a point where simultaneous observations at closely spaced sites are now used to image the altitude profile and spatial extent of the associated ionospheric disturbances. High-time resolution VLF measurements have allowed the easy identification of disturbances produced by different mechanisms by which energy released in lightning discharges interacts with the ionosphere and the radiation belts, including Early/fast events, LEP events produced by ducted whistlers, and LEP phenomena driven by non-ducted whistlers. In this paper, we present the latest results realized via the use of the Stanford University Holographic Imaging of Ionospheric Lightning (HAIL) network, involving 13 closely spaced (~30 to 60 km spacing) observation sites configured along a North-South line in the Central United States. Measurements with HAIL can now be used to quantify the ionospheric disturbances in unprecedented detail, thanks to the advent of GPS timing, which allows the VLF data from the different sites to be used in a wideband phase-coherent fashion to determine the wave guide mode structure of the ambient and disturbed VLF signals. HAIL observations indicate that the resolution of the wave guide mode structure requires the simultaneous broadband recording of coherent VLF transmitter signals at distances along the propagation path, preferably with relatively large separations (to allow for significant phase differences between wave guide modes having phase velocities very close to one another) of ~100 km or more. At distances of ~3 Mm from the sources, and over all-land or all-sea based paths, the VLF signal (~24 kHz) consists of ~5 dominant modes, requiring simultaneous measurements at 10 or more sites. Measurements at more sites would increase accuracy by allowing the identification of >5 modes and would be required in order to resolve the mode structure at shorter distances from the source. In addition to advances in the area of quantitative inversion of VLF signatures, first observations of qualitatively new effects continue to be realized with the sub-ionospheric VLF technique. Latest results include the observation of energetic electron precipitation induced by magnetospherically reflecting whistlers, confirming recently reported low altitude satellite observations of drift-loss-cone energetic electron flux enhancements associated with active thunderstorm regions. These new results indicate that electron precipitation induced by whistler waves originating in individual lightning discharges may persist for tens of seconds.