Integrated Modeling of D-region Ionospheric Response: Application to Solar Flare Events and Quiet-Time VLF Diurnal Profiles

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The D-region ionosphere exhibits strong variability under both disturbed and quiet solar conditions, directly influencing the propagation of Very Low Frequency (VLF) radio signals. Characterizing this variability is essential for accurate modeling of sub-ionospheric communication channels. In this work, we present an integrated modeling framework that couples (i) an electron continuity equation-based numerical model of the D-region ionosphere, (ii) Wait's empirical representation of the effective reflection parameters, and (iii) the Long-Wave Propagation Capability (LWPC) code for sub-ionospheric VLF propagation. This unified approach enables simultaneous exploration of ionospheric electron density variations and their impact on VLF signal amplitudes observed at multiple receiver stations.

The model has been employed to study two distinct cases: (a) solar flare–induced perturbations and (b) diurnal variations on magnetically quiet days. For flare events, the model successfully reproduces the temporal evolution of ionospheric reflection parameters (h',β), thereby capturing the observed perturbations in VLF amplitude. These results highlight the role of enhanced X-ray ionization and the subsequent recombination-driven recovery in shaping the transient ionospheric response.

For quiet solar conditions, the model is applied to multi-station observations conducted during ICSP summer and winter VLF campaigns. Using the integrated framework, we are able to reproduce the observed diurnal amplitude profiles across different receiver locations. Seasonal differences in sunrise and sunset transitions, as well as mid-day absorption levels, are consistently captured by the model, demonstrating its robustness. The results confirm that the coupled electron continuity and LWPC approach is capable of resolving fine-scale features of diurnal VLF propagation, including station-dependent variations along different great-circle paths.