VLF Electromagnetic Wave Propagation over Large Distances using Time-domain Segmented Long Path Technique

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Abstract

A three-dimensional Segmented Long Path (SLP) technique [1] is used to study both sub-ionospheric and trans-ionospheric electromagnetic wave propagation at Very Low Frequencies (VLF). This approach allows for the efficient calculation of transient electromagnetic fields radiated by impulsive sources (e.g. lightning) over great distances (hundreds of wavelengths) and utilizes the Finite-Difference Time-Domain (FDTD) method. Maxwell's equations are used to solve for the electromagnetic fields and are coupled with the method of [2] for treating the anisotropic ionosphere. For the trans-ionospheric propagation study, comparisons are made between our method and the full wave solution of [3]. In addition, we examine the differences between existing mode based techniques such as the Long Wavelength Propagation Capability (LWPC) [4] and our model for several case studies.

Summary

Wave propagation in the Earth-ionosphere waveguide has been a topic of great interest for a number of years [5]. With the advent of numerical simulation techniques, solutions to some of the more complex problems in this area that cannot be treated analytically are now accessible. However, despite recent advances in the field, there are many problems that remain challenging due to the computational requirements imposed. Such problems include the determination of wave propagation characteristics over great distances and in the case of a waveguide, its mode structure.

This problem has previously been treated by some authors. For instance, [6] studied Extremely Low Frequency (ELF) wave propagation in the waveguide cavity bounded by the ground and ionosphere due to an impulsive source. The authors of [6] used a spherical FDTD mesh which covered the entire globe; however the frequency range of interest produced fields with wavelengths comparable to the entire simulation domain. In the VLF regime, [7] used a 2-dimensional cylindrically symmetric grid to determine field distribution along a path that was hundreds of free-space wavelengths. In order to circumvent the numerical difficulties imposed by such a large simulation domain, [8] addresses the problem by using a 'moving window' technique which tracks the initial wave front of the propagating pulse. However, the velocity of the windowing method must be chosen so as to capture the dominant modes in the system and neglecting the rest.

In this paper, we present a novel technique for treating 3-dimensional transient electromagnetic wave propagation based upon the Segmented Long Path (SLP) method [1]. In this method, the entire computational grid is broken up into a series of discrete segments in which the fields are solved locally until a steady-state situation is reached. In this way, all of the mode structure as in the case of a waveguide is still intact. The communication of information between adjoining segments is performed by sharing the tangential surface fields at the boundary of each segment using a total-field scattered-field (TFSF) formulation. Our method thus provides a computationally efficient alternative for treating long-path propagation problems with the build in flexibility and generality of the FDTD solution technique.

The efficacy of our method is first demonstrated in the context of trans-ionosphere wave-guide propagation in which the ionospheric plasma medium is represented by a series of horizontally stratified layers with dynamics governed by the cold-plasma formulation of [2]. In this case, we compare our simulation results with the full-wave theory of [3] by examining propagation characteristics for a series of incident wave-normal vectors impinging on the lower D-region ionosphere. Lastly, we compare results of our simulation tool with those obtained using mode-based techniques [4] demonstrating the strengths of our approach.

References

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