Global FDTD Maxwell's Equations Modeling of Electromagnetic Propagation From Currents in the Lithosphere

Jamesina J. Simpson, *Member, IEEE*

***Abstract*—Electromagnetic wave propagation from electric currents within the Earth's crust is investigated using a three-dimensional finite-difference time-domain (FDTD) full-vector Maxwell's equations model of the global Earth-ionosphere cavity. The FDTD model employed extends from $\sim$100 km below sea level to an altitude of $\sim$100 km, and can account for arbitrary horizontal as well as vertical geometrical and electrical inhomogeneities and anisotropies of the ionosphere, lithosphere, and oceans. Using this model, the surface horizontal magnetic field is calculated for different depths and orientations of an electric current occurring below the epicenter of the 1989 Loma Prieta earthquake. Results show that the alignment and depth of the electric current within the Earth's crust yields significant differences for the calculated surface magnetic field time-waveforms and spectra. Further, it is found that EM wave phenomena measured at the Earth's surface due to electric currents buried in the Earth's crust will only have significant spectra below $\sim$ 1 Hz.**

***Index Terms*—Earth, earth-ionosphere waveguide, earthquake, earthquake precursors, electric current, finite-difference time-domain (FDTD), Loma Prieta earthquake.**

I. Introduction

MANY CASES OF anomalous electromagnetic (EM) phenomena occurring prior to and during earthquakes have been reported in the literature [1]–[3]. One notable example is that recorded by Prof. Fraser-Smith *et al.* prior to the 1989 California Loma Prieta earthquake [4]. To explain such phenomena, numerous mechanisms have been proposed of both lithospheric and ionospheric origin [1]–[3]. Among these proposed mechanisms include electric currents occurring in the Earth's crust due to various processes, such as charge generation and dispersion and electrokinetic effects (see for example [2]). Currently, because comprehensive measurement data for a large number of earthquakes is still lacking, the mechanism(s) involved in generating the anomalous signals is not fully established [2], [3]. Further, because measurement results vary considerably depending on the region of the Earth where the earthquake occurs, recognizing hypothesized precursory EM signals has been a significant challenge.

Manuscript received April 29, 2007; revised July 27, 2007. The supercomputing resources for this work were provided by the Pittsburgh Supercomputing Center and supported under Grant EAR050012P.

The author is with the Electrical and Computer Engineering Department, University of New Mexico, Albuquerque, NM 87131 USA (email: simpson@ece.unm.edu).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TAP.2007.913149

In this study, a 3-D latitude-longitude finite-difference time-domain (FDTD) [5] model of the Earth-ionosphere cavity is used to calculate the response of the Earth-ionosphere system to hypothetical electric currents in the Earth's crust independent of the mechanism involved in generating those currents. The FDTD grid employed extends from 100 km below sea level to an altitude of 100 km, and can account for arbitrary horizontal as well as vertical geometrical and electrical inhomogeneities and anisotropies of the ionosphere, lithosphere, and oceans. The model [6], [7] used in this paper, along with our geodesic FDTD model [8], [9] of the Earth-ionosphere cavity, has been used for a number of studies, including a propagation attenuation validation study [7], [9], and in developing a novel extremely low-frequency radar for oil deposits [9], [10] and ionospheric anomalies [11]. Three other groups have also developed 3-D FDTD models of the global Earth-ionosphere cavity [12]–[19] as described in [20].

Here, the impulse response, or space-time Green's function, of the global Earth-ionosphere system is calculated for four different cases of an electric current source occurring below the epicenter of the Loma Prieta earthquake: 1) horizontal current source at 5 km depth; 2) horizontal current source at 17 km depth; 3) vertical current source at 3 km depth; and 4) vertical current source at 14 km depth. Results for the surface horizontal magnetic (H) field at the epicenter of the Loma Prieta earthquake are shown for each of these current sources separately.

By way of calculating the impulse response of the entire Earth-ionosphere cavity as done in this study, the EM time-waveform at any location can be obtained for arbitrary currents via convolution. Hence, the FDTD calculations shown here may be used to better predict the orientation, depth, and duration of currents in the Earth's lithosphere from any signatures that may be present in measurement data. However, note that the impulse response results shown in this paper are for electric currents at specific depths below the epicenter of the Loma Prieta earthquake. The impulse response would not be exactly the same for currents occurring at other depths or locations around the Earth (because the FDTD model used in this study includes the Earth's topography, electrical details of the continents and oceans, as well as both day- and night-time conditions of the ionosphere).

II. 3-D Latitude-Longitude FDTD Grid

Reference [7] has a complete description of the 3-D latitude-longitude FDTD grid. Thus, in the text below only a brief description of the model is provided.

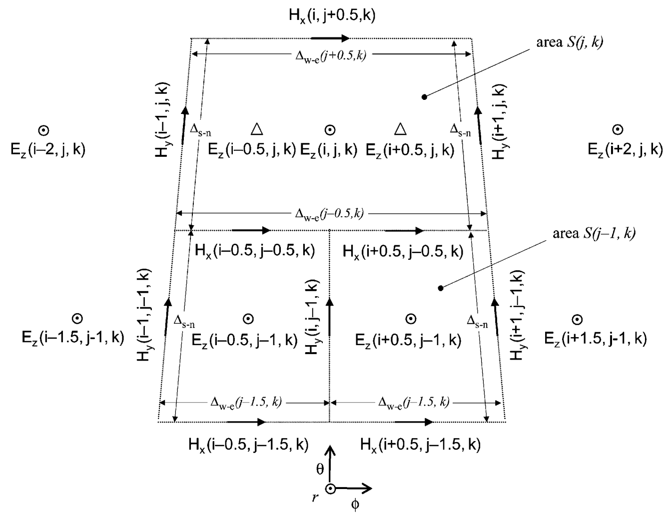

Fig. 1. Details of the TM_z-plane grid-cell geometry in the northern hemisphere at the transition between two adjacent regular cells and a single cell spanning twice the distance in the east-west direction.

The lattice is a $K \times M \times 2M$ cell arrangement in spherical coordinates, where M is a power of 2. The grid cells follow lines of constant latitude, $\theta = \text{constant}$, where θ is the usual spherical angle measured from the north pole; and along lines of constant longitude, $\phi = \text{constant}$, where ϕ is the usual spherical azimuthal angle measured from a specified prime meridian. In this manner, each transverse magnetic (TM plane) of the grid is comprised of isosceles trapezoidal cells away from the north and south poles, and isosceles triangular cells at the poles. Similarly, each transverse electric (TE) plane at a constant radial coordinate is comprised of isosceles trapezoidal cells away from the north and south poles, and a polygon cell at each pole [7].

The same radial increment, Δr, is chosen for every cell in the grid. Also, the same angular increment in latitude is chosen, $\Delta\theta = \pi/M$, so that the south-north span of each trapezoidal or triangular grid cell is $\Delta_{\rm s-n} = \pi R/M$, where R is the radial distance from the center of the Earth. To maintain square or nearly square grid cells near the equator, a baseline value of the angular increment in longitude, $\Delta\phi$, equal to $\Delta\theta$ is selected. However, this causes the west-east span of each cell, $\Delta_{\rm w-e} = R\,\Delta\phi\,\sin\theta$, to be a function of θ. This could be troublesome for cells near the North and South Poles where $\theta \to 0$ and $\theta \to \pi$, respectively. There, the geometrical eccentricity of each cell, $\Delta_{\rm s-n}/\Delta_{\rm w-e} = \Delta\theta/(\Delta\phi\,\sin\theta)$, would become quite large, and the numerical stability and efficiency of the FDTD algorithm would be degraded. This problem is mitigated by merging pairs of adjacent cells in the west-east direction, effectively halving the cell eccentricity as shown in Fig. 1 for the TM case [7]. A comparable figure for the TE case, as well as the update equations for the east-west cell merging field components, is provided in [7].

The east-west cell merging can be repeated at several selected latitudes as the grid approaches a pole, allowing the user to specify a maximum allowable cell eccentricity. For this study, using a resolution of $5\times\ 40\times\ 40$ km $(\Delta r \times \Delta\theta \times \Delta\phi)$ at the equator, the maximum number of cells in the r, θ, and ϕ directions are 40, 512, and 1024, respectively. Further, for the maximum cell eccentricity set to 1/2, cells are merged in the east-west direction 7 times each in the Northern and Southern Hemispheres, with the first case occurring from the equator at about 60° north and south.

The wrap-around or joining of the east and west edges of the lattice occurs along a specific line of constant longitude, or meridian. This joining is, in effect, a periodic boundary condition applied at each j-row of lattice cells, whether trapezoids or triangles [7].

Given the above assumptions, Ampere's Law in integral form can be applied to develop an FDTD time-stepping relation for each electric E field components of the grid. Similarly, Faraday's Law in integral form can be applied to develop an FDTD time-stepping relation for the H field components of the grid [7].

III. Details of the Lithosphere Current Study

To generate the fully 3-D FDTD model of the Earth-ionosphere waveguide, topographic and bathymetric data from the NOAA-NGDC "Global Relief CD-ROM" [21] are mapped onto the space lattice briefly described above at a resolution of $5\ \times\ 40\ \times\ 40$ km at the equator. For the lithosphere, conductivity values are assigned according to [22], depending upon the location of the E component (i.e., below an ocean or within a continent). For the atmosphere, both day- and night-time exponential conductivity profiles used in [23] are assumed, with early evening (the timing of the Loma Prieta earthquake) occurring along the San Andreas Fault. The complete FDTD grid used in this study extends to a depth of 100 km into the lithosphere and to an altitude of 100 km above sea level. Extending the grid 100 km into the lithosphere provides ample space for attenuation in the conducting lithosphere to prevent any reflections from the lower PEC boundary. For the upper grid boundary, the exponential conductivity ionosphere profile rapidly increases and terminates with a perfect electric conductor (PEC) at 100 km. This upper PEC boundary provides a succinct way of modeling the Earth's upper ionosphere causing substantial reflection of EM waves (thereby forming the Earth-ionosphere waveguide). Previously, this grid was shown to provide agreement in the frequency range of 50–500 Hz to within about ± 1.0 dB/Mm [7] with the results of [24]. The results of [24] showed good agreement with measurements.

Previously, Simpson and Taflove used this latitude-longitude FDTD Earth-ionosphere model to study EM propagation from electrokinetic currents occurring in the Earth's crust below the epicenter of the Loma Prieta earthquake [25]. They were able to provide a more rigorous analysis than previously published because their full-vector Maxwell's equations model permitted accommodation of the complete physics introduced by impulsive EM wave propagation through the conductive Earth and subsequent reverberation through the entire Earth-ionosphere waveguide [25].

Here, the work of [25] is expanded upon to examine EM propagation from current sources having different orientations in the Earth's crust. Specifically, four cases of current sources occurring along electric field components at 121.88° W, 37.04° N, below the epicenter of the Loma Prieta earthquake, are simulated. The surface horizontal H-field at the epicenter of the

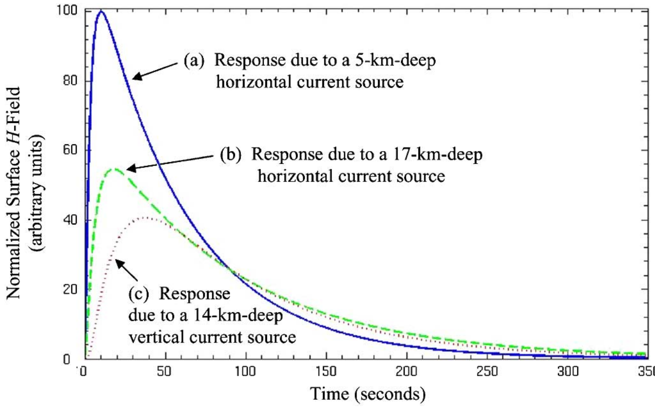

Fig. 2. Comparison of the FDTD-calculated time waveforms for the horizontal surface H-field component resulting from: (a) a horizontal 5-km-deep current source; (b) a horizontal 17-km-deep current source; and (c) a vertical 14-km-deep current source. All are normalized relative to the peak of waveform (a).

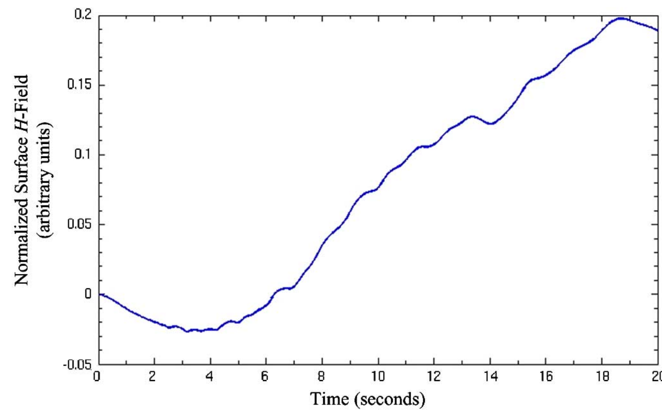

Fig. 3. Time waveform for the horizontal surface magnetic field component due to a 3-km deep vertical current source. The waveform is normalized relative to the peak of waveform (a) in Fig. 2.

Loma Prieta earthquake is then calculated for each of the current sources separately. Essentially, these calculated H-field time-waveforms are the space-time Green's function of the global Earth-ionosphere waveguide for the four different excitations in the Earth's crust. To ensure a smooth onset of the excitation, the current is assumed to linearly increase to its maximum value at 2000 Δt, where $\Delta t = 3.0\,\mu s$.

The present grid resolution at $5 \times 40 \times 40$ km requires modeling of the current source onto a ~40-km-long horizontal electric field component or a ~5-km-long vertical electric field component. It is interesting to note that after normalization, the Earth-ionosphere cavity impulse response due to the ~40-km or ~5-km-long current would be identical to that of any shorter current source in space occurring at the same location. In addition, the impulse response for any number of cascading (in time), parallel current sources within the span of one grid-cell component is simply the superposition of multiple time-delayed versions of the response caused by a single current source. This is because current sources occurring along the same direction will contribute linearly in the far-field to the overall dipole moment [25].

IV. Discussion of Results

Results for the full-vector, 3-D FDTD Maxwell's equations Earth-ionosphere model are now reported. Fig. 2 compares the time-waveforms of the horizontal surface H-field component generated by: (a) a horizontal 5-km-deep current source; (b) a horizontal 17-km-deep current source; and (c) a vertical 14-km-deep current source. All three time-waveforms are normalized relative to the peak of waveform (a). Using the Bigben parallel processing supercomputer at the Pittsburgh Supercomputing Center, the response for each case is calculated until just after the peak of the waveform using the FDTD model (~25 s for both horizontal sources, and ~50 s for the 14-km-deep vertical source); thereafter Prony's method [26] is applied to extend the tail of the response to its ultimate decay. These time waveforms are used as an equivalent Green's function in the discussion below.

The results in Fig. 2 show that the alignment and depth of the electric current within the Earth's crust yields significant differences for the calculated surface H-field time-waveforms. Interestingly, the late-time response of both the vertical and horizontal deeper sources (curves b and c) are higher than the shallower source (curve a) due to the longer diffusion time within the lossy crustal medium.

The time waveform for the horizontal surface magnetic field component due to a 3-km deep vertical current source is shown separately in Fig. 3. Only the first 20 s as calculated directly using FDTD is shown. The response due to the 3-km-deep vertical current is shown separately in Fig. 3 from those in Fig. 2 because its relative strength is ~500 times lower than that of the horizontal 5-km-deep current source. This result is counter-intuitive because the strength of the response in Fig. 3 is significantly less than that of the 14-km-deep vertical current source shown in Fig. 2 (for which the EM wave has 11 km less distance of the lossy Earth's crust to propagate through before reaching the Earth's surface). However, it is not surprising considering the radiation characteristics of a monopole antenna in space, which has virtually no horizontal magnetic field component directly above the antenna, and considering for deeper sources there is more potential of reflections from other structures that would yield higher fields at the Earth's surface.

We also see that the waveform in Fig. 3 is not as smooth as those shown in Fig. 2. This is because much of the signal energy at the Earth's surface from the shallow vertical current source will couple into the transverse eletromagnetic (TEM) mode capable of traveling completely around the Earth-ionosphere waveguide. Since the TEM mode travels around the Earth ~7 times each second with little attenuation, many reverberations of the signal energy around the globe are evident in the waveform of Fig. 3. Therefore, the time-waveform in Fig. 3 is not a smooth function as was the case for the time-waveforms of Fig. 2, which had deeper and/or horizontal current sources and less coupling into the Earth-ionosphere waveguide TEM mode.

Fig. 4 compares the horizontal surface H-field frequency spectra from 0.01–1.0 Hz for the three sets of FDTD data shown in Fig. 2: (a) the horizontal 5-km-deep current source; (b) the horizontal 17-km-deep current source; and (c) the vertical 14-km-deep current source. Also shown as curve (d) in Fig. 4 is the measured spectrum by Fraser-Smith *et al.* [4] (personal

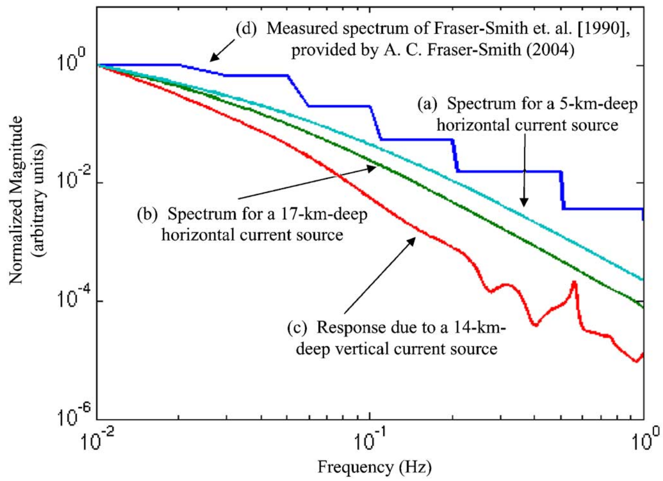

Fig. 4. Comparison of the spectra for the horizontal surface H-field component: (a) FDTD result for an horizontal 5-km-deep current source; (b) FDTD result for an horizontal 17-km-deep current source; (c) FDTD result for an vertical 14-km-deep current source; and (d) measured by Fraser-Smith [1990] and A. C. Fraser-Smith (person communications, 2004). Each is normalized relative with respect to its own peak at 0.01 Hz.

communication, 2004). Each of the 4 waveforms is normalized with respect to its peak magnitude at 0.01 Hz. The spectrum for the 3-km-deep vertical source is not shown because its amplitude is insignificant compared to the others cases, so such a shallow vertical current source could not have produced the large changes in the background magnetic field as observed by Fraser-Smith *et al.* [4].

The results of Fig. 4 show that, when assuming the Earth crustal conductivity values used in the present FDTD model, EM fields recorded at the Earth's surface due to any hypothesized electric currents occurring in the Earth's crust 5 km or deeper will only have significant frequency spectra below ~1 Hz. This implies that any anomalous EM phenomena recorded in measurements around the world having spectra above ~1 Hz must be generated by other means, such as by ionospheric processes [3] or by positive-charge carriers flowing in the Earth's crust that actually reach the Earth's surface as proposed by Freund and Sornette [27]. In [27], Freund and Sornette suggest that an outflow of p-holes from a stressed rock volume towards the Earth surface can lead to a number of affects, including even infrared emissions [27].

The result of Fig. 4 also shows that it may be unlikely that the measured spectrum by Fraser-Smith *et al.* [4] was caused by current sources within the lithosphere. The slope of the measured spectrum does not agree with the slopes of the calculated FDTD spectra for any of the orientations/depths of the lithosphere current sources considered (for the case of the shallow vertical current source, the weak magnetic field at the Earth's surface could not have produced as significant of a change in the background magnetic field as was recorded by Fraser-Smith *et al.*). It is worth noting, however, that there are two factors [25] that may be affecting the comparison of the calculated spectrum of the FDTD data with the measured Fraser-Smith data: (1) the assumed lithosphere conductivity values in the FDTD grid; and (2) a measurement artifact reported by Fraser-Smith *et al.* [1990] wherein instrumentation saturation likely occurred at the lowest observed frequencies. In the first case, an excessive lithospheric conductivity would cause the FDTD-calculated spectra at higher frequencies to be unduly attenuated, thereby bending the calculated curves downward below the Fraser-Simth *et al.* data. In the second case, the Fraser-Smith *et al.* data point at 0.01 Hz would have too small a value, thereby unduly flattening their measured spectra. As a result, and because there are numerous cases of anomalous electromagnetic signals prior to and during earthquakes well above 1 Hz, other mechanisms besides current sources in the lithosphere should be considered and studied in detail.

V. Conclusions and Ongoing Work

A rigorous 3-D computational solution of the full-vector Maxwell's equations for EM phenomena propagated from electric currents in the Earth's crust has been investigated. Using the robust FDTD method, four cases of electric currents were modeled below the epicenter of the Loma Prieta earthquake. The surface horizontal H-field was calculated for each case and compared. Results showed that the alignment and depth of the electric current within the Earth's crust yields significant differences for the calculated surface H-field time-waveforms and spectra. Further, it was found that EM wave phenomena measured at the Earth's surface due to electric currents in the Earth's crust will only have significant spectra below ~1 Hz, so that any signals with spectra above 1 Hz prior to or during earthquakes must be generated by other means (such as by ionospheric processes [3] or by positive-charge carriers flowing in the Earth's crust that actually reach the Earth's surface as proposed by Freund and Sornette [27]).

Ongoing work in this area includes generating a 3-D FDTD model of the Earth-ionosphere waveguide that includes plasma phenomena in the ionosphere. This model will be applied to studying mechanisms for precursory EM signals of ionospheric origin, as well as to investigating the effects of coronal mass ejections on the ionosphere. Ultimate goals are to provide as rigorous as possible a physics basis for proposed earthquake prediction schemes employing either land-based or satellite-based detectors of EM anomalies, and to provide a means of predicting the early-time electrodynamic effects of coronal mass ejections on power grids and gas lines.

References

[1] S. K. Park, M. J. S. Johnston, Th. R. Madden, F. D. Morgan, and H. F. Morrison, "Electromagnetic precursors to earthquakes in the ULF band: A review of observations and mechanisms," *Rev. Geophys.*, vol. 31, pp. 117–132, 1993.

[2] M. J. S. Johnston, "Review of electric and magnetic fields accompanying seismic and volcanic activity," *Surv. Geophys.*, vol. 18, pp. 441–475, 1997.

[3] S. Pulinets and K. Boyarchuk, *Ionospheric Precursors of Earthquakes*. Berlin, Germany: Springer, 2004.

[4] A. C. Fraser-Smith, A. Bernardi, P. R. McGill, M. E. Ladd, R. A. Helliwell, and O. G. Villard Jr., "Low-frequency magnetic field measurements near the epicenter of the Ms 7.1 Loma Prieta earthquake," *Geophys. Res. Lett.*, vol. 17, pp. 1465–1468, 1990.

[5] A. Taflove and S. C. Hagness, *Computational Electrodynamics: The Finite-Difference Time- Domain Method*, 2nd ed. Norwood, MA: Artech House, 2000.

[6] J. J. Simpson and A. Taflove, "Two-dimensional FDTD model of antipodal ELF propagation and Schumann resonance of the Earth," *IEEE Antennas Wireless Propag. Lett.*, vol. 1, no. 2, pp. 53–56, 2002.

[7] J. J. Simpson and A. Taflove, "Three-dimensional FDTD modeling of impulsive ELF antipodal propagation and Schumann resonance of the Earth-sphere," *IEEE Trans. Antennas Propag.*, vol. 52, no. 2, pp. 443–451, Feb. 2004.

[8] J. J. Simpson and A. Taflove, "Efficient modeling of impulsive ELF antipodal propagation about the Earth sphere using an optimized two-dimensional geodesic FDTD grid," *IEEE Antennas Wireless Propag. Lett.*, vol. 3, no. 1, pp. 215–218, 2004.

[9] J. J. Simpson, R. P. Heikes, and A. Taflove, "FDTD modeling of a novel ELF radar for major oil deposits using a three-dimensional geodesic grid of the Earth-ionosphere waveguide," *IEEE Trans. Antennas Propag.*, vol. 54, no. 6, pp. 1734–1741, Jun. 2007.

[10] J. J. Simpson and A. Taflove, "A novel ELF radar for major oil deposits," *IEEE Geosci. Remote Sensing Lett.*, vol. 3, no. 1, pp. 36–39, 2006.

[11] J. J. Simpson and A. Taflove, "ELF radar system proposed for localized D-region ionospheric anomalies," *IEEE Geosci. Remote Sensing Lett.*, vol. 3, no. 4, pp. 500–503, Oct. 2006.

[12] M. Hayakawa and T. Otsuyama, "FDTD analysis of ELF wave propagation in inhomogeneous subionospheric waveguide models," *ACES J.*, vol. 17, no. 3, pp. 239–244, 2002.

[13] T. Otsuyama and M. Hayakawa, "FDTD analysis of ELF wave propagation for realistic subionospheric waveguide models," *IEEJ Trans. FM*, vol. 124, no. 12, pp. 1203–1209, 2004.

[14] Y. Ando, M. Hayakawa, A. V. Shvets, and A. P. Nickolaenko, "Finite difference analyses of Schumann resonance and reconstruction of lightning distribution," *Radio Sci.*, vol. 38, no. 6, p. 1103, 2003, DOI: 10.1029/2002RS002752.

[15] H. Yang and V. P. Pasko, "Three-dimensional finite difference time domain modeling of the Earth-ionosphere cavity resonances," *Geophys. Res. Lett.*, vol. 32, p. L03114, 2005, DOI:10.1029/2004GL021343.

[16] H. Yang, V. P. Pasko, and Y. Yair, "Three-dimensional finite difference time domain modeling of the Schumann resonance parameters on Titan, Venus, and Mars," *Radio Sci.*, vol. 1, no. 2, Sep. 2006, RS2S03.

[17] H. Yang and V. P. Pasko, "Power variations of Schumann resonances related to El Nino and La Nina phenomena," *Geophys. Res. Lett.*, vol. 34, p. L11102, 2007, DOI:10.1029/2007GL030092.

[18] A. Soriano, E. A. Navarro, D. L. Paul, J. A. Porti, J. A. Morente, and I. J. Craddock, "Finite-difference time domain simulation of the Earth-ionosphere resonant cavity: Schumann resonances," *IEEE Trans. Antennas Propag.*, vol. 53, no. 4, pp. 1535–1541, Apr. 2005.

[19] E. A. Navarro *et al.*, "A finite difference time domain model for the Titan ionosphere Schumann resonances," *Radio Sci.*, vol. 42, no. 2, 2007, paper RS2S04.

[20] J. J. Simpson and A. Taflove, "A review of progress in FDTD Maxwell's equations modeling of impulsive sub-ionospheric propagation below 300 kHz," *IEEE Trans. Antennas Propag.*, vol. 55, no. 6, pp. 1582–1590, Jun. 2007.

[21] *Global Relief CD-ROM*, [Online]. Available: http://www.ngdc.noaa.gov/mgg/global/global.html, NOAA-NGDC ETOPO5

[22] J. Hermance, "Electrical conductivity of the crust and mantle," in *Global Earth Physics: A Handbook of Physical Constants*. Washington, DC: American Geophysical Union, 1995.

[23] P. Bannister, "The determination of representative ionospheric conductivity parameters for ELF propagation in the Earth-ionosphere waveguide," *Radio Sci.*, vol. 20, no. 4, pp. 977–984, 1985.

[24] P. Bannister, "ELF propagation update," *IEEE J. Ocean. Eng.*, vol. 0E-9, no. 3, pp. 179–188, 1984.

[25] J. J. Simpson and A. Taflove, "Electrokinetic effect of the Loma Prieta earthquake calculated by an entire-Earth FDTD solution of Maxwell's equations," *Geophys. Res. Lett.*, vol. 32, p. L09302, 2005, DOI:10.1029/2005GL022601.

[26] MATLAB: The Language of Technical Computing. ver. 6.5.0.180913a Release 13, Jun. 18, 2002.

[27] F. Freund and D. Sornette, "Electro-magnetic earthquake bursts and critical rupture of peroxy bond networks in rocks," *Tectonophysics*, vol. 431, pp. 33–47, 2007.

Jamesina J. Simpson (S'01–M'08) received the B.S. and Ph.D. degrees in electrical engineering from Northwestern University, Evanston, IL, in 2003 and 2007, respectively.

In 2007, she joined the Electrical and Computer Engineering Department, University of New Mexico, Albuquerque, as a tenure-track Assistant Professor. Her research involves the solution of Maxwell's equations using the finite-difference time-domain (FDTD) method for a wide variety of scientific and engineering applications spanning much of the electromagnetic spectrum.

Dr. Simpson was a recipient of the National Science Foundation Graduate Research Fellowship, the IEEE AP-S Graduate Research Award, the IEEE MTT-S Graduate Research Award, the Walter P. Murphy Fellowship, and the Richter Fellowship to support her graduate studies.