TIME EVOLUTION OF SEISMIC ELECTROMAGNETIC WAVE EMISSION BY FULL-WAVE ANALYSIS

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ABSTRACT : Electromagnetic wave radiation from an underground current source related to some seismic activity is discussed. In order to estimate the ionospheric effects on the electromagnetic waves associated with seismic activity, the intensities and spatial evolution in the ionosphere of waves radiated from a possible seismic source modeled as a transient electric dipole located underground, are rigorously computed by using full-wave analysis. In this computation, the ionosphere is assumed to be an inhomogeneous and anisotropic medium, and Earth's crust is assumed to be isotropic. Especially, the effects of the geomagnetic field on the waves are considered. The computed results show that the differences of the wave intensities in spatial regions in the magnetized ionosphere are due to the propagation characteristics of the plasma wave modes.

INTRODUCTION

A variety of electromagnetic phenomena associated with earthquakes have been reported in a wide frequency range. Examples of intriguing events over seismic areas include the change of ULF or ELF/VLF signals onboard satellites in the ionosphere and the lower magnetosphere [e.g., *Molchanov et al.*, 1993; *Parrot*, 1994]. Moreover, theoretical calculations have been proposed to analyze the seismic electromagnetic wave intensities [*Molchanov et al.*, 1995; *Grimal'skii and Rapoport*, 2000]. However, these works have not clearly shown the effects of the geomagnetic field on the wave propagation. It is a well known fact in space plasma physics that the geomagnetic field affects the ionospheric wave propagation, so considering the effects of the geomagnetic field is very important. In fact in our work, the results which considered the effects of the geomagnetic field show both a difference in the direction of wave propagation and that the waves propagate in characteristic plasma wave modes in the ionosphere.

We use the electromagnetic model of a fault zone studied by M. Ikeya et al. [1997]. In this model, the underground charge density is determined by the seismic stress. When the charge density appears on both side of the stressed area, the electric dipole moment is transiently formed. The seismic electromagnetic waves radiated from the transient dipole are calculated by using full-wave analysis. The full-wave analysis was developed to compute rigorously wave propagation in the ionosphere [*Nagano et al.*, 1975]. We have several advantages by using full-wave analysis. The primary advantage is that the calculated electromagnetic field completely includes all of the static, induction, and radiation fields radiated from an underground dipole source and the effects of the magnitude and direction of the geomagnetic field. Thus we can rigorously examine the ionospheric propagation of the characteristic plasma wave modes. The secondary advantage is that the full-wave analysis does not require large-size memory for accurate analysis. The expansion of a spherical wave to a large number of plane waves by using spherical Bessel functions does not require defining a 3-D spatial grid like as in a FDTD analysis. In this study, we present some results of investigations on the seismic electromagnetic wave propagation in order to predict the wave intensities related with seismic moments.

FULL-WAVE ANALYSIS

The earth–free space–ionosphere calculation model that we consider is shown in Figure 1. It is assumed that each medium such as the ionosphere and the earth is formed of multiple layers of horizontally stratified materials. The ionosphere is assumed to be a cold plasma medium without any thermal motion of the plasma particles which has the electron density and the collision frequency between the electrons and the neutral particles that vary with altitude. The dielectric constant and the conductivity of the earth are treated in the same way. For the calculation coordinates, the vertical axis is designated the z axis and the y axis is chosen to be perpendicular to the z axis and to be in the geomagnetic field B_0-z plane. The positive y direction is chosen to be in the northerly direction. The x axis is perpendicular to the y axis and the z axis.

The electromagnetic waves are assumed to follow the mathematical model of a fault in seismology [*Ikeya et al.*, 1997]. This model has been adopted to explain anomalous electromagnetic phenomena at the time of earthquake occurrences [*Ikeya et al.*, 1998; *Sasaoka et al.*, 1998]. Charge densities, $+q$ and $-q$ in C/m^2, are generated at a fault zone by the change in the seismic stress, σ in N/m^2, as [see *Ikeya et al.*, 1997, equation (6)]

$$\frac{\mathrm{d}q}{\mathrm{d}t} = -\alpha\frac{\mathrm{d}\sigma}{\mathrm{d}t} - \frac{q}{\varepsilon\rho}, \tag{1}$$

where α, ε, and ρ are the piezoelectric coefficient (neglecting the tensor properties) in C/N, the earth's dielectric constant, and the earth's resistivity in Ω m, respectively. The condition $q = 0$ at $t = 0$ gives

$$q(t) = \alpha\Delta\sigma\frac{\varepsilon\rho}{\tau - \varepsilon\rho}\left[\exp\left(-t/\tau\right) - \exp\left(-t/\varepsilon\rho\right)\right], \tag{2}$$

where $\Delta\sigma$ and τ are the stress drop by the displacement and the displacement time [from *Ikeya et al.*, 1997, equation (7)]. The current density in A/m^2 is described as

$$i(t) = \frac{\mathrm{d}q}{\mathrm{d}t} = \alpha\Delta\sigma\frac{\varepsilon\rho}{\tau - \varepsilon\rho}\left[\frac{-1}{\tau}\exp\left(-t/\tau\right) + \frac{1}{\varepsilon\rho}\exp\left(-t/\varepsilon\rho\right)\right]. \tag{3}$$

Under the above assumptions that the current source term is derived from the described electromagnetic model of a fault zone, Maxwell's equations for each frequency, ω, are:

$$\boldsymbol{E}(\boldsymbol{r},\omega) = \nabla\nabla\cdot\boldsymbol{\Pi}(\boldsymbol{r},\omega) + k^2\boldsymbol{\Pi}(\boldsymbol{r},\omega), \tag{4}$$

$$\boldsymbol{H}(\boldsymbol{r},\omega) = j\omega\varepsilon\nabla\times\boldsymbol{\Pi}(\boldsymbol{r},\omega), \tag{5}$$

where $\boldsymbol{E}$ is the electric field, $\boldsymbol{H}$ is the magnetic field, $\boldsymbol{\Pi}$ is the Hertz vector, $\boldsymbol{r} = (x, y, z)^t$ is observation point, and ^{t} means the transform of a vector. The Hertz vector is defined by the current source at each frequency, here the total current source is assumed to initiate at the location $(0, 0, z_0)^t$ and flow toward the direction $\boldsymbol{m} = (m_x, m_y, m_z)^t$ within an area A as $\boldsymbol{J}(t) = \boldsymbol{m}Ai(t)$. Then the Hertz vector (of the frequency spectrum of current source $\boldsymbol{J}(\omega)$ with the length l, which is the Fourier-analyzed $\boldsymbol{J}$(t)) becomes

$$\boldsymbol{\Pi}(\boldsymbol{r},\omega) = \frac{1}{j4\pi\varepsilon\omega}\int_0^l \boldsymbol{J}(\boldsymbol{r'},\omega)\frac{\mathrm{e}^{-jkR}}{R}\mathrm{d}l', \tag{6}$$

where $x' = m_x l'$, $y' = m_y l'$, and $z' = z_0 + m_z l'$, k is the wave normal, R=$|\boldsymbol{R}|$, $\boldsymbol{R} \equiv \boldsymbol{r} - \boldsymbol{r'}$, and $\boldsymbol{r'} = (x', y', z')^t$ is the current source location. It should be noted that the Hertz vector is not defined for the DC component, because we add the inverse current source at the end of original one. So we do not have to clearly include the DC component [see *Nagano et al.*, 2003].

The basic technique of this full-wave analysis is to represent the spherical wave by a large number of plane waves. Then using spherical Bessel functions in the calculation coordinates shown in Figure 1, we can write

$$\frac{e^{-jkR}}{R} = -\frac{jk}{2\pi}\int_0^{2\pi}\int_0^{\frac{\pi}{2}+j\infty}\mathrm{e}^{-j\boldsymbol{k}\cdot\boldsymbol{R}}\sin\alpha\mathrm{d}\alpha\mathrm{d}\beta. \tag{7}$$

The Hertz vector is rewritten by applying the plane wave expansion of the spherical wave in equation 7 and integrating with l', as

$$\boldsymbol{\Pi}(\omega) = \frac{jk}{8\pi^2\varepsilon}\int_0^{2\pi}\int_0^{\frac{\pi}{2}+j\infty}\boldsymbol{P}(\omega)\cdot\exp\left(-j\boldsymbol{k}\cdot\boldsymbol{r}\right)\sin\alpha\mathrm{d}\alpha\mathrm{d}\beta, \tag{8}$$

$$\begin{aligned}\boldsymbol{P}(\omega) &= \boldsymbol{m}\frac{\alpha M_0}{j\omega}\cdot\frac{\varepsilon\rho}{\tau - \varepsilon\rho}\left[\frac{-1}{\tau}\exp\left(-t/\tau\right) + \frac{1}{\varepsilon\rho}\exp\left(-t/\varepsilon\rho\right)\right] \\ &\times \frac{\sin\left(\frac{l}{2}(\boldsymbol{k}\cdot\boldsymbol{m} - \frac{\omega}{v_i})\right)}{\frac{l}{2}(\boldsymbol{k}\cdot\boldsymbol{m} - \frac{\omega}{v_i})}\cdot\exp\left(j\frac{l}{2}(\boldsymbol{k}\cdot\boldsymbol{m} - \frac{\omega}{v_i}) + jkz_0\right),\end{aligned} \tag{9}$$

where $M_0 \equiv \Delta\sigma Al$ is the earthquake moment and v_i is the speed of the current stroke. The moment magnitude, M_w, is defined as $M_w = (\log M_0 - 9.1)/1.5$ in seismology, so we can estimate the wave intensities correlated with the seismic activity.

The electromagnetic fields radiated from an underground transient current source are represented as follows,

$$\boldsymbol{E} = -\frac{jk}{8\pi^2\varepsilon}\int_0^{2\pi}\int_0^{\frac{\pi}{2}+j\infty}\left\{-(\boldsymbol{k}\cdot\boldsymbol{P}(\omega))\boldsymbol{k}+k^2\boldsymbol{P}(\omega)\right\}\cdot\exp\left(-j\boldsymbol{k}\cdot\boldsymbol{r}\right)\sin\alpha \mathrm{d}\alpha\mathrm{d}\beta, \quad (10)$$

$$\boldsymbol{H} = -\frac{j\omega k}{8\pi^2}\int_0^{2\pi}\int_0^{\frac{\pi}{2}+j\infty}\left\{\boldsymbol{k}\times\boldsymbol{P}(\omega)\right\}\cdot\exp\left(-j\boldsymbol{k}\cdot\boldsymbol{r}\right)\sin\alpha \mathrm{d}\alpha\mathrm{d}\beta. \quad (11)$$

In equations 10 and 11, the integrand is equivalent to a plane wave in the x-y plane. Thus we can rigorously calculate the propagation of the elementary plane waves at each frequency in the ionosphere by using a full-wave analysis [*Nagano et al.*, 1975].

SPATIAL STRUCTURE AND TIME EVOLUTION OF ELECTROMAGNETIC WAVES

To estimate the ionospheric penetration characteristics of the seismic electromagnetic waves radiated from an underground dipole, we assume that the seismic source is placed at its top edge 16 km underground, and has 20 km length as a transient vertical dipole. The profiles of the electron density N_e and the collision frequency ν_{eff} in the ionosphere are shown in Figure 2. The electron density profile is derived from the international reference ionosphere model for mid-latitudes. The collision frequency is calculated to be proportional to the atmospheric pressure [*Nagano et al.*, 1982].

Figure 3 (a) shows the spatial evolution of the horizontal (north-south component of) electric field E_y. Each figure shows the intensity distribution of the E_y over the horizontal north-south range of ±100-km and at the altitude range of 0- to 120-km above the epicenter. Also the spatial evolution of the horizontal (east-west component of) magnetic field B_x is shown in Figure 3 (b). The waves are slightly reflected at the altitude of about 80 km. We can see that a specific null appears above the epicenter in both Figure 3 (a) and (b). Moreover, we see that the electromagnetic field intensities have a north-south asymmetric distribution above the altitude of 70 km in the lower ionosphere, due to the whistler-mode propagation along the geomagnetic field lines.

CONCLUSION

Through the theoretical calculation of the time-evolution of electromagnetic wave radiation from the Earth using full-wave analysis, we could estimate anomalous electromagnetic radiation intensities associated with a given moment magnitude [*Ikeya et al.*, 1997], and examine the effect of the magnetized ionosphere by taking into account the direction and magnitude of the geomagnetic field along geomagnetic field lines [*Nagano et al.*, 1975]. In order to evaluate the wave intensities, we computed the time and spatial evolution of the waves through the use of Fourier-analysis and by using spherical Bessel functions.

In the time and spatial evolution of the electromagnetic field [in Figure 3], we see that the null clearly appears above the epicenter, and the waves propagate in the whistler-mode in the magnetized ionosphere. The wave intensities for moment magnitude 7.8 are as follows: the electric field is 50 mV/m and the magnetic field 10 pT at a maximum on the ground. On the other hand, the electric field is 65 μV/m and the magnetic field is 4 pT in the ionosphere (z=120 km).

REFERENCES

[1] Grimal'skii, V. V. and Yu. G. Rapoport (2000), Penetration of electrostatic field from surface sources into the lower ionosphere, *Kinematics and Physics of Celestial Bodies*, *16*, 5–10.

[2] Ikeya, M., S. Takaki, H. Matsumoto, A. Tani, and T. Komatsu (1997), Pulsed charge model of fault behavior producing seismic electric signals (SES), *Journal of Circuits, Systems, and Computers*, *7*, 153–164.

[3] Ikeya, M., H. Matsumoto, and Q. -H. Huang (1998), Alignment silkworms as seismic animal anomalous behavior (SAAB) and electromagnetic model of a fault: a theory and laboratory experiment, *Acta Seismologica Sinica*, *11*, 365–374.

[4] Molchanov, O. A., O. A. Mazhaeva, A. N. Goliavin, and M. Hayakawa (1993), Observation by Intercosmos-24 satellite of ELF-VLF electromagnetic emissions associated with earthquakes, *Annales Geophysicae*, *11*, 431–440.

[5] Molchanov, O. A., M. Hayakawa, and V. A. Rafalsky (1995), Penetration characteristics of electromagnetic emissions from an underground seismic source into the atmosphere, ionosphere, and magnetosphere, *Journal of Geophysics Research*, *100*, 1691–1712.

[6] Nagano, I., M. Mambo, and G. Hutatsuishi (1975), Numerical calculation of electromagnetic waves in an anisotropic multilayered medium, *Radio Science*, *10*, 611–617.

[7] Nagano, I., M. Mambo, and I. Kimura (1982), Estimation of collision frequency in the upper D and E regions from LF wave by means of a rocket experiment, *Journal of Geomagnetism and Geoelectricity*, *34*, 27–38.

[8] Nagano, I., S. Yagitani, K. Miyamura, and S. Makino (2003), Full-wave analysis of elves created by lightning-generated electromagnetic pulses, *Journal of Atmospheric and Solar-Terrestrial Physics*, *65*, 615–625.

[9] Parrot, M. (1994), Statistical study of ELF/VLF emissions recorded by a low-altitude satellite during seismic events, *Journal of Geophysical Research*, *99*, 23339–23347.

[10] Sasaoka, H., C. Yamanaka, and M. Ikeya (1998), Measurement of electric potential variation by piezoelectricity of granite, *Geophysical Research Letters*, *25*, 2225–2228.

FIGURES

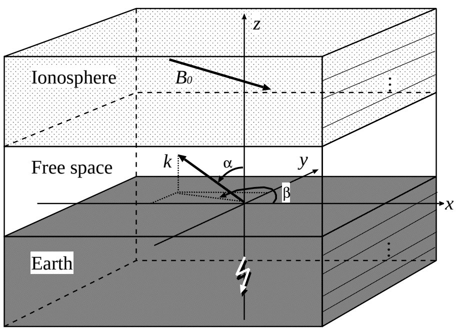

Figure 1: Calculation model and coordinate system

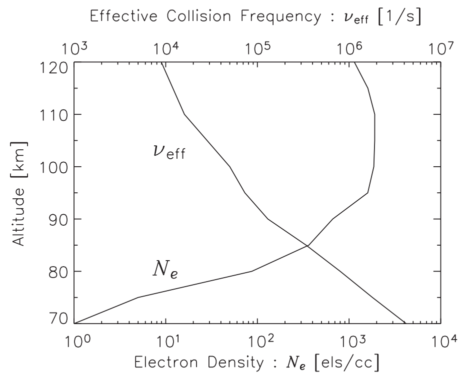

Figure 2: Ionospheric profiles

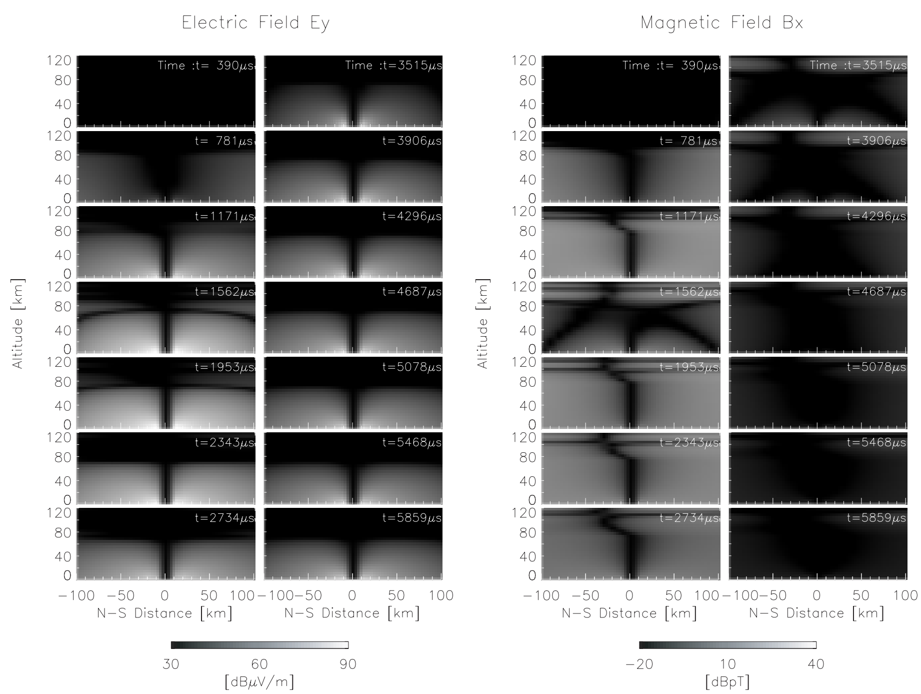

Figure 3: Time and spatial evolution of electromagnetic wave intensities ((a): electric field E_y, (b): magnetic field B_x