1997C

QE-7

Jpn. J. Appl. Phys. Vol. 36 (1997) pp. L 1558–L 1561
Part 2, No. 11B, 15 November 1997

A Model Experiment of Electromagnetic Wave Propagation over Long Distances using Waveguide Terminology

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(Received August 25, 1997; accepted for publication 1997)

Electromagnetic (EM) waves observed by telecommunication engineers ahead of earthquakes are controversial because they should not propagate over long distances from the hypocenter due to dissipation in the conductive Earth. A model of an earth crust dielectric waveguide was proposed and discussed with an earth atmospheric waveguide and tested in a laboratory scaling simulation experiment using a granite slab and an EM generator antenna at the hypocenter for the Kobe Earthquake. The mappings of evanescent and wave-ripple standing waves were obtained by scanning a detector antenna over the Japanese island archipelago model. Theoretical relations of the field intensity ΔV, such as $\log \Delta V = 0.375 M_W + c$, where M_W and c are the moment magnitude and a constant, respectively have been derived by considering EM waves from an ensemble of dipolar charges at a fault zone. The theoretical scaling law is consistent with the empirical one.

KEYWORDS: electromagnetic wave, waveguide, simulation, scaling law, earthquake, SES

1. Introduction

Electromagnetic (EM) waves at ultra low and very low frequencies (ULF and VLF) which should be dissipated in the conductive Earth have been observed ahead of earthquakes.[1–3] They seem to be correlated with large earthquakes, but no scientifically credible theory can explain the propagation of the underground EM waves over the distances of hundreds of km from the epicenter. The origin has been found to be closely related with atmospheric lightning.[1] The seismic electric signal (SES) which detects the DC electric field claims success in earthquake prediction in Greece,[4] but is controversial as is seen in the proceeding book.[5] The main cause of the controversy is the lack of physical background of a long distance propagation.

This paper does not make a claim for earthquake prediction from the SES because the detailed physics on rock ruptures at the hypocenter before the major shock has not yet been established. We only suggest a model experiment on waveguides considering that the Earth crust between the conductive Moho plane (or Conrad plane between the upper and lower crust boundary) and the ground surface may constitute a dielectric slab "earth crust waveguide" just as the conductive ionosphere-ground surface make an "earth atmospheric waveguide". This allows us to discuss the long distance propagation of seismic EM waves using waveguide terminology in electrical engineering[6] A model experiment using a granite slab was made in an attempt to clarify the underlying physics behind the phenomena related to the long distance propagation of EM waves in nature.

2. Experimental

We have modeled the Japanese island archipelago using a 1:1,360,000 map with a granite slab 22 mm thick simulating 30 km thick upper crust as shown in Fig. 1. The loop antenna 7 mm below the upper surface simulate the 10 km deep hypocenter of the Kobe Earthquake on January 17, 1995. EM waves were emitted at two frequencies from an antenna in a hole in the granite slab. A small detecting antenna was moved 5 mm above the slab, with the aid of an X-Y plotter under computer control, over the model surface to map the intensity of EM waves emitted from the hypocenter.

The conductive sea and lake areas of the surface were covered with aluminum foil; an aluminum plate simulating the conductive Moho plane was placed in addition against the lower surface of the granite slab. The ionosphere located at 60–120 km above the sea level was simulated with a flat aluminum plate at 73±4 mm above the granite slab corresponding 100 km above the ground.

3. Result and Discussion

3.1 Earth atmospheric and earth crust waveguides

Scaling of sizes and frequency may be made to get an insight in a model experiment of electromagnetic phenomena. The modeling both ionosphere and Moho plane with magma (or Conrad plane at the surface of underground ductile zone at the depth of about 10–30 km) using an aluminum plate may seem oversimplification. The depth of sea is also neglected by using the aluminum cooking foil having a low resistivity. The resistivity of Magma or ductile zone would be around 1 Ω m much larger than that of aluminum, 10^{-5} Ω m. These are allowed in a modeling experiment when the place of interests is around the ground surface and not around the ionosphere and Moho plane. Their role is simply to reflect EM waves and slight penetration of EM waves into the ionosphere and into the underground conductive zone does not affect the overall results; the effective separation between the conductive plates is slightly elongated for the actual ionosphere.

Thick sediments with a low resistivity might be considered as a part of the expanded sea and will not affect much, especially the granitic area around Kobe. The depth of sea less than 1 or 2 km at most is less than one tenth of the thickness of the dielectric slab and does not perturb in the first-order approximation. The ionosphere and the Earth's surface constitute a parallel plate

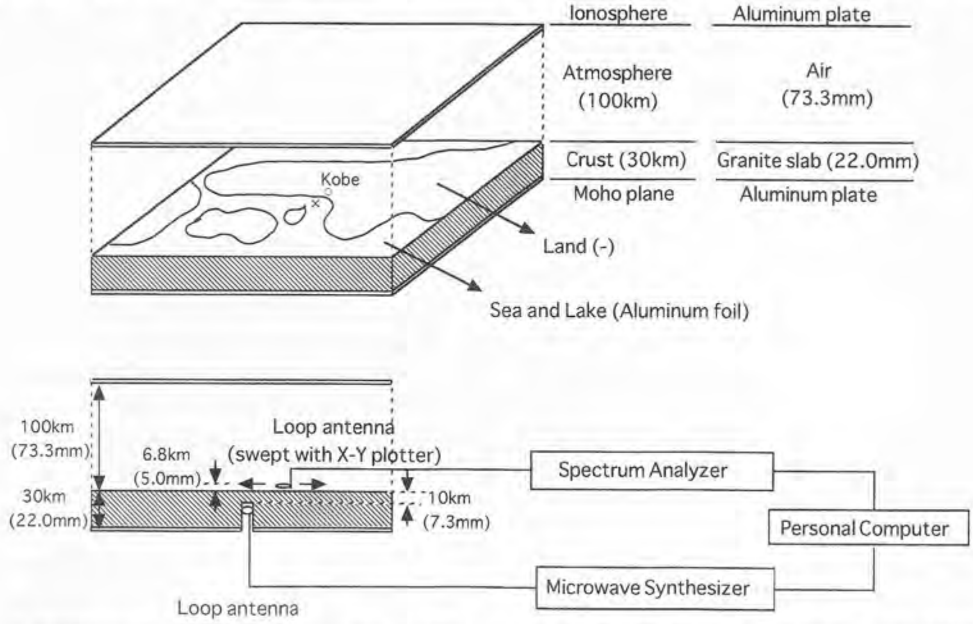

Fig. 1. A schematic drawing of the Japanese island archipelago model simulating the ionosphere, the Earth surface and Moho plane using aluminum plates and foil and a 22 mm thick granite slab. Electromagnetic waves were emitted from a small antenna below the slab surface and detected using another antenna 5 mm above the surface.

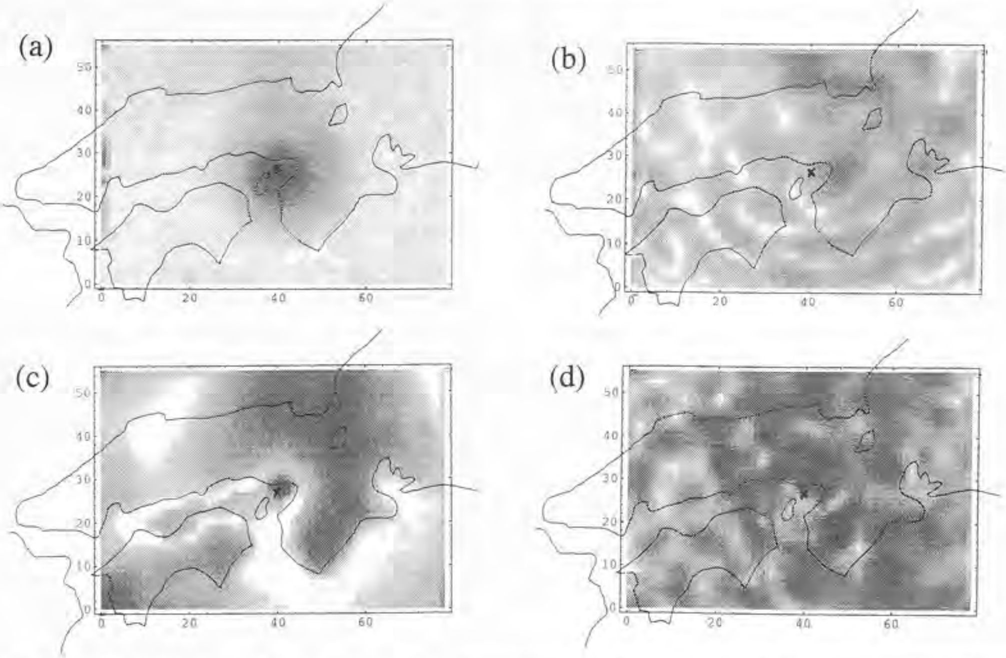

Fig. 2. The measured intensity of the electromagnetic waves over the Japanese island archipelago model. (a) Evanescent waves at 0.25 GHz below the cut-off frequency f_c of the granite dielectric slab, (b) standing waves at 4 GHz above f_c, (c) and (d) correspond to (a) and (b), respectively disturbed by the presence of aluminum sea surface. Used frequencies correspond to 184 Hz and 2.94 kHz in the Earth crust dielectric waveguide.

waveguide well-known by telecommunication engineers as "earth atmospheric waveguide".[7] It has a cut-off frequency of $f_{ca} = c/2d = 1.25 - 2.5$ kHz using the speed of light, c and the separation of the conductive plates d for $d = 60$ km to 120 km.

The cut-off frequency of "earth crust waveguide" proposed in this work is $f_{cc} = c/2d\varepsilon^{*1/2}$ and the specific dielectric constant $\varepsilon^* = 8$ of bedrock granite giving $f_{cc} = 1.768$ kHz and $d = 30$ km at the epicenter area of the Kobe Earthquake. Above two frequencies for two earth waveguides correspond to $f'_{ca} = 4.08$ GHz and $f'_{cc} = 2.4$ GHz in the model experiment. The two waveguides couple through the land and islands.

3.2 Detected intensity map of EM waves

The images in Figs. 2(a) and 2(c) at 0.25 GHz are for corresponding frequency of 184 Hz which is far below the cut-off frequencies f'_{ca} and f'_{cc}, while those of (b) and (d) at 4 GHz corresponding to 2,940 Hz is marginal to $f'_{ca} = 4.08$ GHz.

The field intensity map at 0.25 GHz in (a) characterizes exponentially decaying evanescent waves from the epicenter. The pattern changes as the frequency increases and showed clear propagation above 4 GHz as a wave-ripple pattern suggesting the formation of standing waves spreading over from the epicenter as shown in Fig. 2(b). The disturbed wave ripple would be presumably due to the intentionally used granite slab consisting of large quartz grains, feldspar and mica.

Non-uniform distribution of EM waves is expected for an island archipelago due to their reflection by the conductive sea area. This was demonstrated by covering the granite surface by aluminum foil from which the land and island parts were removed. Geography effects of the ground surface on the propagation is clear for the intensity mapping obtained in (c) and (d) at the same frequencies as in (a) and (b), respectively. The images are considerably disturbed. The original images using granite with grains including quartz, feldspar and mica having different specific conductivities and dielectric constants were further blurred by the presence of aluminum sea. The intensity is naturally high on the land side. The image due to reflection by sea might correspond to the "selectivity" asserted in the SES by DC method.[4)]

This result suggests that seismic EM waves at a frequency higher than the cut-off frequencies of both earth waveguides can propagate over long distances. Standing waves might be formed if EM waves at a frequency is emitted for some time long enough as to interact with the reflected waves, i.e., in a longer time than a few times of $1/f$.

3.3 Decay of seismic EM waves

The power of EM waves is dissipated in the conductive earth with resistivity ρ and the dielectric constant ε due to the skin-depth or decay arising from the imaginary part of the wave vector, k″

$$k'' = \omega\left(\mu'\varepsilon/2\right)^{1/2}\left[\left(1+(1/\omega\varepsilon\rho)^2\right)^{1/2}-1\right]^{1/2} \quad (1)$$

using the permeability μ', where $\omega = 2\pi f$ for the frequency, f;[6)] the displacement current effect is included in this equation. Note that simplified relation for $\omega\varepsilon\rho \ll 1$ in estimating the skin effect is not appropriate in a granite with $\rho = 10^6\,\Omega$ m for $f > 10^3$ Hz. The effect of decay could, unfortunately, not be simulated for the complex inhomogeneous earth in the scaling experiment. The decay rates, $\exp(-k''R)$ at the ground distance $R = 10$ km and 100 km were calculated for a granitic crust of $\rho = 10^6\,\Omega$ m in Fig. 3(a).

The wavelength in the waveguide, λ_g, is

$$1/\lambda_g^2 = 1/\lambda_0^2 - (1/2d)^2 \quad (2)$$

where λ_0 is the wavelength in the atmosphere ($\lambda_0 = c/f$) or in the dielectric earth ($\lambda_0 = c/f(\varepsilon^*)^{1/2}$).[6)] If f is less than f_{cc}, the imaginary wavelength λ_g or wavevector ($k_g = 2\pi/\lambda_g$) appears leading to the exponential decay of the field intensity known as "evanescent waves". The total travelling distance for the direction of the propagation in the earth waveguide by reflection was further considered for evanescent waves to estimate the decay rate as shown in Fig. 3(b).

3.4 Physical basis of empirical relations of SES

Subduction zones and major fault planes might also be conductive and thus form a shunt in the underground waveguide and form a dielectric resonator. Standing waves at a resonant frequency may be observed by the reflection of waves as they propagate in the crust and might generate some wave-ripple phenomenon. Hence, the earth crust cavity might be formed.

The evanescent waves at ULF might be the SES measured as DC voltage and named as the VAN method following the initials of three authors started a systematic observation.[4)] The theoretical intensity is almost proportional to $1/R$ for the distance R from the epicenter rather than to $1/R^3$ for a dipolar charge model in agreement with the empirical relation. It may also be proportional to the electrode separation, less than the wavelength, λ_g. The selectivity may be explained with the reflection of evanescent waves in the island archipelago as shown in Figs. 2(c) and 2(d).

One might wonder how EM waves were generated from the epicenter area. An ensemble of electric dipoles, p_i, may be generated from piezo-compensating dipolar charges of quartz grains.[8)] Piezoelectricity used to explain earthquake lightning was once discarded because of free charges which compensate the polarization in a

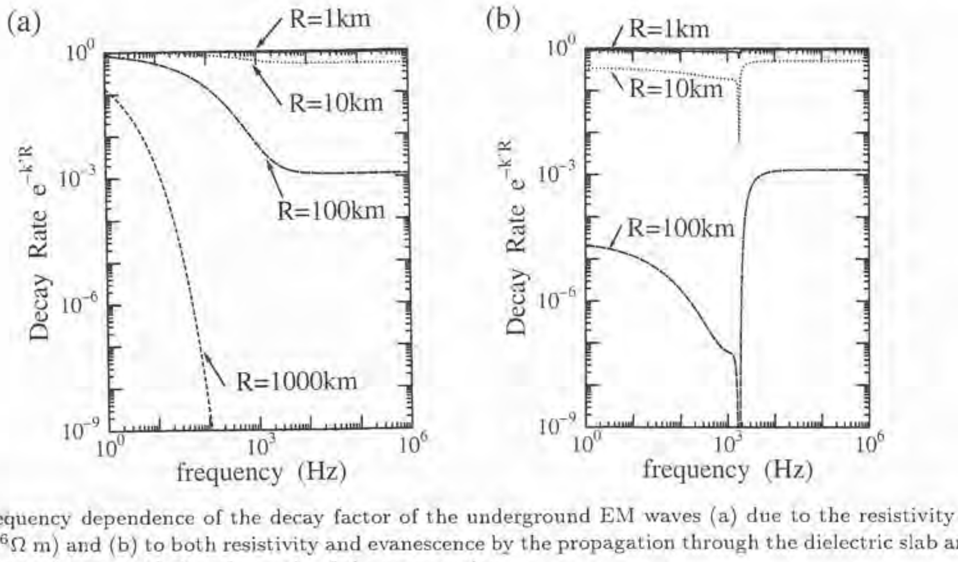

Fig. 3. Frequency dependence of the decay factor of the underground EM waves (a) due to the resistivity of granite ($\rho = 10^6\Omega$ m) and (b) to both resistivity and evanescence by the propagation through the dielectric slab and parallel plate waveguides considering the angle of the propagation.

short time of $\varepsilon\rho$.[10] It is these free charges that are released by the stress changes in our model.[11] Some other mechanism to produce dipolar charges is also plausible so long as EM waves are generated.

There are arguments that dipolar charges are cancelled electrostatically for a random orientation ($P = \sum p_i = 0$), and so the charges should not appear at the edges of a fault zone as in the electromagnetic model of fault behavior.[8,11] A light bulb consisting of n excited atoms with dipole moment p may be approximated as a single dipole with the moment $|P| = n^{1/2}|p|$ in optics. The EM power, i.e., the magnitude of the Poynting vector N is proportional to the energy, i.e., the square of the total dipole moment P and to $1/\tau$, where τ is the time of fracture ($|N| \propto P^2/\tau$). A virtual fault with length $2a$, stress drop $\Delta\sigma$, and stress σ_0 gives $\tau = (\Delta\sigma/\sigma_0)(a/\beta)$ using the velocity of S-waves β.[8] The field intensity of EM waves is $F \propto N^{1/2} \propto |P|/\tau^{1/2} = n^{1/2}|p|/\tau^{1/2}$.

The earthquake moment, M_o is related to the fault length $2a$ considering that the stress accumulated width at the fault zone is proportional to $2a$ and so the area $(2a)^2$. It may be expressed as $M_o = 2a\Delta\sigma A$ for a fault with area A. For a small and a large earthquake, $M_o = (2a)^3\Delta\sigma$ and $M_o = (2a)^2 d$ were obtained condsidering the depth d of the ductile zone,[12] which leads to $2a = (M_o/\Delta\sigma)^{1/3}$ and $(M_o/\Delta\sigma d)^{1/2}$ for $M_{\rm W} < 6.3$ and $M_{\rm W} > 6.3$, respectively. The moment magnitude defined as $M_{\rm W} = (\log M_o - 9.1)/1.5$ are $M_{\rm W} = 6.3$ for $d = 2a = 10^4$ m and $\Delta\sigma = 5 \times 10^6\,{\rm N/m^2}$. This critical moment magnitude may differ ± 0.6 and ± 0.3 for the factor two changes of d and $\Delta\sigma$, respectively.

If the SES intensity ΔV is related to the electric field F of EM waves with Poynting vector N, $\Delta V \propto F \propto N^{1/2} \propto |P|/\tau^{1/2}$ leading to $\Delta V \propto M_o^{1/6}$ and $M_o^{1/4}$ using $\tau = (\Delta\sigma/\sigma_0)(a/\beta)$ and $2a = (M_o/\Delta\sigma)^{1/3}$ for $M_{\rm W} < 6.3$ and $2a = (M_o/\Delta\sigma d)^{1/2}$ for $M_{\rm W} > 6.3$, respectively. The definition of $M_{\rm W} = (\log M_o - 9.1)/1.5$ gives the scaling law of $\log \Delta V = 0.25 M_{\rm W} + c$ and $\log V = 0.375 M_{\rm W} + c$, respectively for $M_{\rm W} < 6.3$ and $M_{\rm W} > 6.3$, where c is a constant related with several parameters in seismology. The latter scaling law is very close to the empirical one $\log \Delta V = 0.37M + c$ in the DC SES work where M is the conventional magnitude.[4]

One might argue that the actual intensity of electric field is important and not the scaling law. The Poynting vector of EM waves, N at the distance 100 km from the hypocenter was calculated considering the piezo-compensating charges $+q$ and $-q$ in our recent work. Coseismic power of $2 \times 10^{-17}\,{\rm W/m^2}$ and preseismic $6 \times 10^{-13}\,{\rm W/m^2}$ at 100 km lead to 10^{-7} V/m and 10^{-5} V/m at 1 Hz in a good agreement with experiments.[11] Hence, we concluded that the DC measurement of SES is caused by evanescent EM waves at ULF which propagate through the earth-crust waveguide.

The discovery that the source of VLF (1–9 kHz) before earthquakes was in the atmosphere and close to the lower ionosphere surface[1] might indicate the reflection point of the EM waves in the earth atmospheric waveguide. It is hoped that the observation at extremely low frequencies (ELF)[13] using the clock of global positioning system (GPS) clarify the source of the underground evanescent electromagnetic waves.

Just like a taboo in a society has reasons to be born and inherited, old folk stories and proverbs on the earthquake clouds might have some scientific reasons. Ripple clouds which stay at the same position for a long time before earthquakes are observed by both Japanese and Chinese amateur seismologist as an earthquake precursor although no metrologist admit their existence due to the lack of physical mechanism of cloud appearance at a long distance from the epicenter. If an intense electric field of seismic EM waves could generate charged aerosols by ionization due to electron acceleration,[8] the nuclei of precipitation[13] and so wave-ripple clouds might be formed by the standing waves at a long distance from the epicenter. Such a romantic speculation is, however, far beyond the present work and might be a topic of future investigation in an interdisciplinary field.

4. Conclusion

A model experiment assuming a scaling law should be made for EM phenomena in geophysics to clarify the underlying physics. A long distance propagation of EM waves has been explained with a waveguide terminology in a model experiment simulating earth crust and earth atmospheric waveguides. Some empirical relations in the DC-SES method has theoretically been derived. Note that this paper does not make a claim for earthquake prediction neither from the SES nor earthquake clouds. We are not sure of the detailed underlying physics on rock ruptures and the generation of EM waves before the major shock of an earthquake. Deterministic earthquake prediction may not be possible as alleged in the controversy.[5] The SES might, however, be used as a warning signal though the exact time and place of ruptures would be difficult to predict at the moment. Uncertain forecast on earthquake might save lives of people and be better than no warning at all.

Acknowledgement

We thank Dr. A. G. Wintle at University of Wales for critical reading of the manuscript and the late Emeritus Prof. R. Ueda for his interests and encouragement in this interdisciplinary work.

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