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WHITE OAK LABORATORY

ELECTROMAGNETIC BACKGROUND NOISE IN THE OCEAN DUE TO GEOMAGNETIC ACTIVITY IN THE PERIOD RANGE 0.5 TO 1000 SECONDS

BY
M.B. Kraichman

MARCH 1977

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A summary is given of some of the characteristics of geomagnetic micropulsations. Based on a knowledge of micropulsation data measured at surface land stations, expressions are presented for obtaining estimates of the horizontal and vertical components of the electric and magnetic fields in the open ocean in the period range of interest, 0.5 to 1000 sec. Numerical results are presented for a seawater layer over an earth bottom. Perturbations in the open ocean field components by the proximity of a coastline are discussed.

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ELECTROMAGNETIC BACKGROUND NOISE IN THE OCEAN DUE TO GEOMAGNETIC ACTIVITY IN THE PERIOD RANGE 0.5 TO 1000 SECONDS

The work was done in the Electromagnetics Branch of the Radiation Division, Code WR43, and funded jointly under Task No. B0005 Task 001 Element No. 11221N of Project LINEAR CHAIR managed by the Naval Sea Systems Command (SEA 03424) and sponsored by the Naval Material Command (PM-2) and Task No. SF33-300-31B (Electric and Magnetic Sensors for Moored Mines) sponsored by Naval Sea Systems Command (SEA 0333C).

Paul R. Wessel

Paul R. Wessel
By direction

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Introduction

A significant part of the natural electromagnetic background noise in the ocean in the period range 0.5 to 1000 seconds is due to geomagnetic micropulsations and the telluric currents they induce in seawater. The origin of these micropulsations detected at the earth's surface is thought to be the near field effects of electric currents in the lower ionosphere produced by decaying hydromagnetic waves that result from the interaction of solar particles and the earth's magnetic field. The magnitude of the telluric currents induced in the ocean by the resulting electromagnetic near field along the earth's surface depends not only on the period of the micropulsations and the conductivity structure below the ocean surface, but also on the spatial extent of the ionospheric current sheet.

A summary of some of the characteristics of geomagnetic micropulsations is presented in this report. It is, however, the primary purpose of the present report to obtain estimates of the magnitudes of the horizontal and vertical components of the electric and magnetic fields in the ocean in the period range 0.5 to 1000 seconds. These estimates are based on available geomagnetic micropulsation data measured at surface land stations. Those magnetic field spectral data that show negligible contamination by the discontinuity of conductivity at the coast may be converted to open ocean surface and subsurface component field values by using the theoretical expressions previously given by the author in references (a) and (b) and applicable to a seawater layer over an earth bottom.

(a) Kraichman, M.B., The Propagation of Geomagnetic Micropulsations into a Two-Layer Conducting Earth, Naval Ordnance Laboratory, White Oak, Silver Spring, MD, Technical Report NOLTR 72-261, 27 October 1972.
(b) Kraichman, M.B., Handbook of Electromagnetic Propagation in Conducting Media, Headquarters Naval Material Command, NAVMAT P-2302, U.S. Government Printing Office, Washington, D.C., Second Printing, (1976), p. 2-15.

Numerical results are presented for the magnitude of the ratio of the vertical to horizontal magnetic field at the surfaces of a 200m and a 1500m layer of seawater over an earth bottom for various pulsation periods in the range of interest. Also given as a function of period for the above seawater layers are curves showing the attenuation of the magnetic and electric field components at a field point depth of 100m in the shallow layer and 300m in the deep layer.

Because of the discontinuity of conductivity at a coastline, perturbations occur in the values of both the surface and subsurface open ocean electric and magnetic fields. The magnitude and spatial extent of these perturbations depend on the conductivity contrast between the land and sea, the pulsation period, the bottom configuration, and the relative orientation of the coastline and the ionospheric current. Quantitative results for the surface field perturbations are available in the literature for various bottom configurations and those results for the most realistic configurations are given here. To the author's knowledge, only qualitative results are available for the subsurface field perturbations, and a brief discussion of these results is included in the present report.

1. CHARACTERISTICS OF GEOMAGNETIC MICROPULSATIONS AT THE EARTH'S SURFACE.

Two broad types of geomagnetic micropulsations observed at the earth's surface are considered here. They are the Pc (continuous) and the Pi (irregular) pulsations. It should be noted that for practical reasons, these pulsations have been measured almost exclusively at the surface of land areas and not at the sea surface.

In the characteristics given below, the latitudes mentioned are geomagnetic latitudes. Their relationship to geographic latitudes is given in a map in reference (c). Also, the auroral zone mentioned is usually defined as the region from 65°-75° geomagnetic latitude. The amplitudes given are typical of the horizontal component. For the longer period events the N-S component dominates almost everywhere at most hours, while for the shorter period events the N-S and E-W amplitudes are comparable except at the equator where the N-S component dominates. The vertical component is usually the smallest everywhere for both long and short period pulsations.

<u>Pc 1</u>

<u>Description</u>

0.2-5 sec period

Constant or changing mid-frequencies of pulsations within a packet. Packets repeat every 2-5 min. Half of events last at least 35 min. Less than 1/10 of events are over 3 hr. duration. Period of pulsation shorter at night than during the day.

(c) Campbell, W. H., An Analysis of the Spectra of Geomagnetic Variations Having Periods from 5 min to 4 hours, Journal of Geophysical Research, Vol. 81, No. 7, March 1, 1976, pp. 1369-90.

Maximum Frequency of Occurrence

Daytime at latitudes 60°-77°

Nighttime at latitudes 28°-60°

Scarcity of signal at pole and equator

No apparent seasonal variation

Amplitude

Typically hundreds of milligammas at high latitudes

Tens of milligammas at mid-latitudes

Ten milligammas at the equator

Usually no equatorial enhancement

Pc 2

Description

5-10 sec period

Comparatively rare events associated with strongly disturbed magnetic conditions. Period shorter at night than during the day.

Maximum Frequency of Occurrence

Early morning at moderate latitudes

During the night at lower latitudes

Amplitude

50-200 milligammas at high latitudes

Smaller at lower latitudes

Equatorial enhancement not known

Pc 3

Description

10-45 sec period

Frequently observed events from equator to the auroral zone

Maximum Frequency of Occurrence

During the daytime at all latitudes

Minimum activity during the winter

At moderate latitudes, period increases from dawn to dusk

At low latitudes, a minimum period is found at noon

Amplitude

Typically 1 gamma at mid-latitudes

0.1 gamma at low latitudes

Maximum amplitude of several gammas often found at 60° latitude around noon

Equatorial enhancement of amplitude at all times

Pc 4

Description

45-150 sec period

Events usually last about 10 min to several hours, averaging about 1 hr.

Shortest period near noon

Maximum Frequency of Occurrence

Daytime during very quiet magnetic conditions (sunspot minimum)

Enhancement during spring and fall particularly at about 50° latitude and in the auroral zone.

Amplitude

5-20 gammas at high latitudes

Maximum at about 66° latitude around noon

Some daytime equatorial enhancement, particularly at dawn

Pc 5

Description

150-600 sec period

Known also as "giant pulsations"

Form is sinusoidal, often damped with typical damping time of 1000 sec

Lasts from 10 min to several hours

Shortest period near dawn

Event is local in latitude and not greatly extended in longitude

Maximum Frequency of Occurrence

Maximum at about 67° - 70° latitude

Decreases to about 1/5 maximum at 80° and 50° latitude

Near the auroral zone the occurrence has a maximum at 0600 and 1800 LMT

Amplitude

Typically from several tens to 100 gammas at high latitudes

Can at times reach several hundreds of gammas

Maximum amplitude at about 66° latitude near dawn

Rapid decrease of amplitude with distance from auroral zone

Daytime enhancement under equatorial electrojet

Pi 1

Description

1-40 sec period

Bursts of broadband emissions

Duration of minutes to tens of minutes

Maximum Frequency of Occurrence

Night and early morning in auroral zone

Also observed in low and middle latitudes

Amplitude

Varies from 0.01 to 1 gamma with maximum values in auroral zone

Amplitude decreases sharply with distance from auroral zone

Pi 2

Description

40-150 sec period

Separate trains or series of trains of duration 10-20 min

Maximum Frequency of Occurrence

Evening and nighttime with a maximum just before midnight

Amplitude

Varies from 0.5 gamma to 5 gammas with the larger amplitudes observed at the high latitudes

2. AVERAGE GEOMAGNETIC POWER SPECTRUM FOR THE PERIOD RANGE 0.5 TO 10,000 SECONDS IN MID-NORTHERN LATITUDES

Great variability exists in the day to day characteristics of power spectra of geomagnetic field fluctuations at the earth's surface. It is therefore useful for many purposes to have statistically stable average spectra. Such spectra have been obtained by both Davidson and Herron with a total field magnetometer and are reported in references (d) and (e) respectively. Davidson's average spectrum is based on 111 independent one hour records while that of Herron is based on eighty 6-hour records. The recording site for both measurements was the Lebanon State Forest on the New Jersey coastal plain (49.5°N geomagnetic latitude, 71° magnetic inclination). The site is within 40 km of the sea coast and is away from any industrial area. A comparison of the data with those from an identical magnetometer 650 km inland did not reveal any strong bias due to the conductivity discontinuity of the ocean. The power spectra of Davidson and Herron are combined and presented here in figure 1, for the period range 4.5 to 10,000 seconds.

In order to extend the period below 4.5 seconds, the average north-south power spectra as measured by Fraser-Smith and Buxton at Stanford, California (43.5° N geomagnetic latitude) using a component magnetometer and reported in reference (f) are included here in figures 2 and 3 for local night and local

(d) Davidson, M.J., Average Diurnal Characteristics of Geomagnetic Power Spectrums in the Period Range 4.5 to 1000 Seconds, Journal of Geophysical Research, Vol. 69, No. 23, Dec. 1, 1964, pp. 5116-19.
(e) Herron, T. J., An Average Geomagnetic Power Spectrum for the Period Range 4.5 to 12,900 Seconds, Journal of Geophysical Research, Vol. 72, No. 2, Jan. 15, 1967, pp. 759-61.
(f) Fraser-Smith, A.C., and Buxton, J.L., Superconducting Magnetometer Measurements of Geomagnetic Activity in the 0.1 to 14Hz Frequency Range, Journal of Geophysical Research, Vol. 80, No. 22, Aug. 1, 1975, pp. 3141-47.

day conditions respectively. Fraser-Smith and Buxton's data were recorded on 24 days during the winter months of 1974 for the 2 hour intervals shown in the figures. It should be noted that the peaks at 1Hz are due to the calibration system.

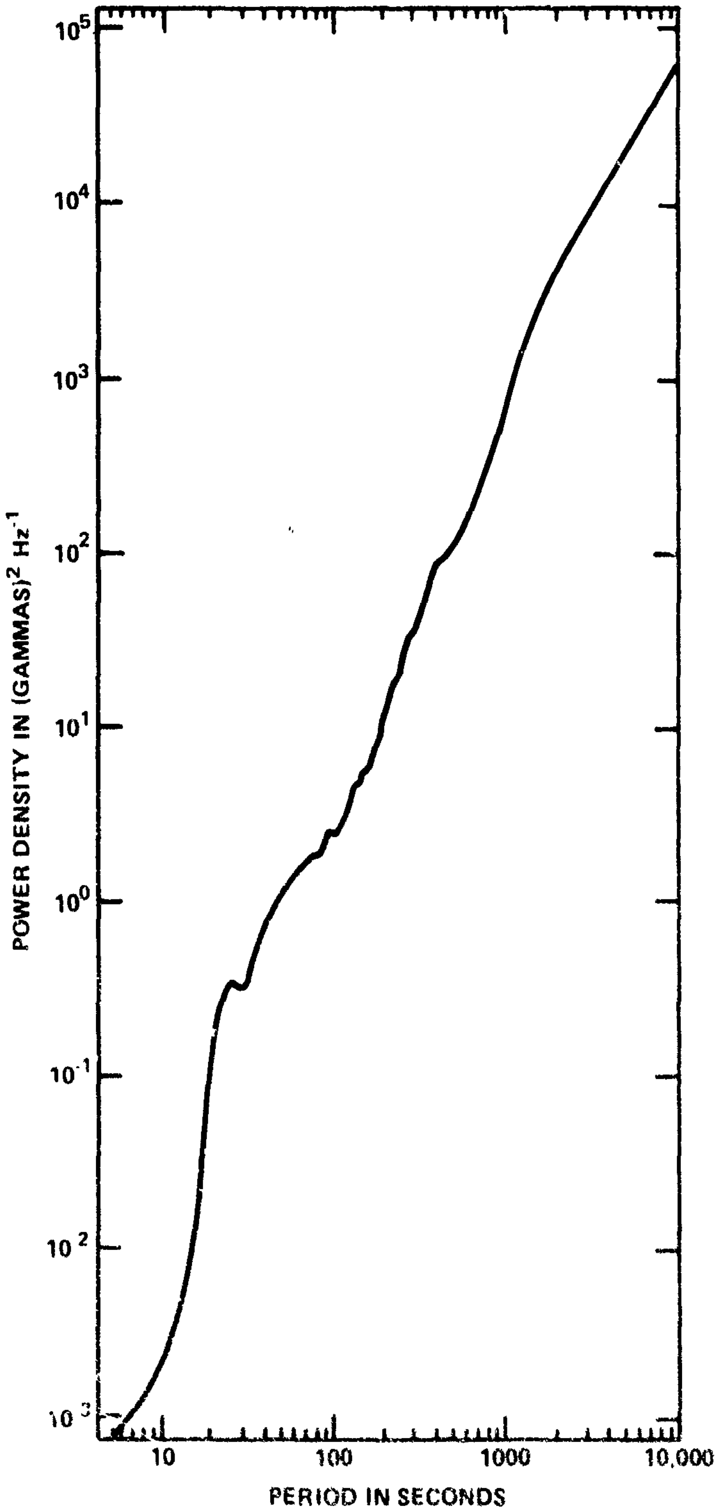

FIG. 1 AVERAGE POWER SPECTRAL DENSITY OF GEOMAGNETIC VARIATIONS IN THE TOTAL FIELD

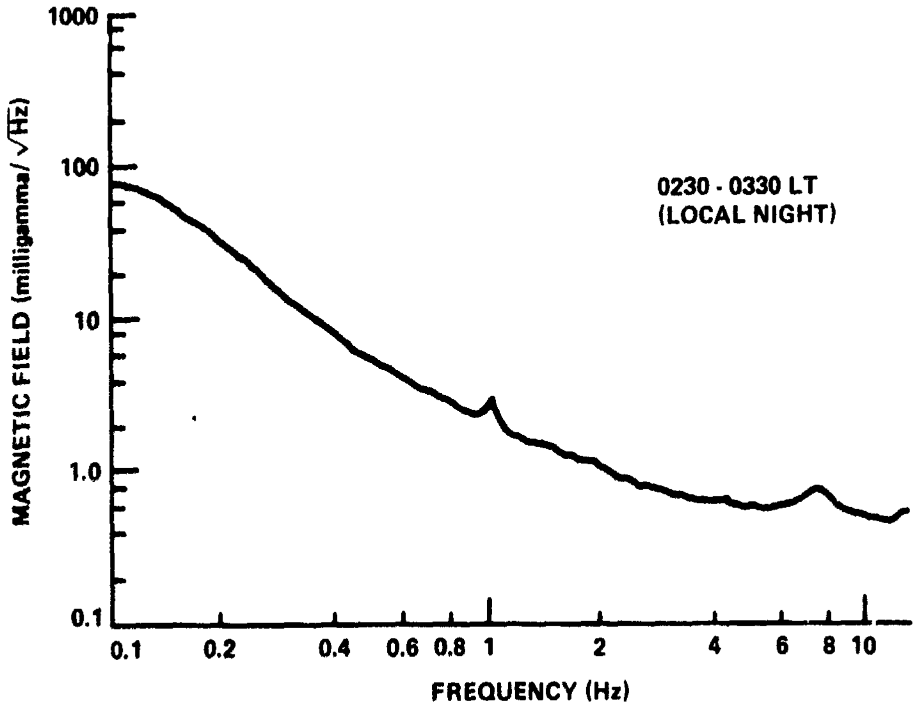

FIG. 2 AVERAGE LOCAL NIGHT VALUES OF N-S GEOMAGNETIC VARIATIONS DURING THE WINTER MONTHS

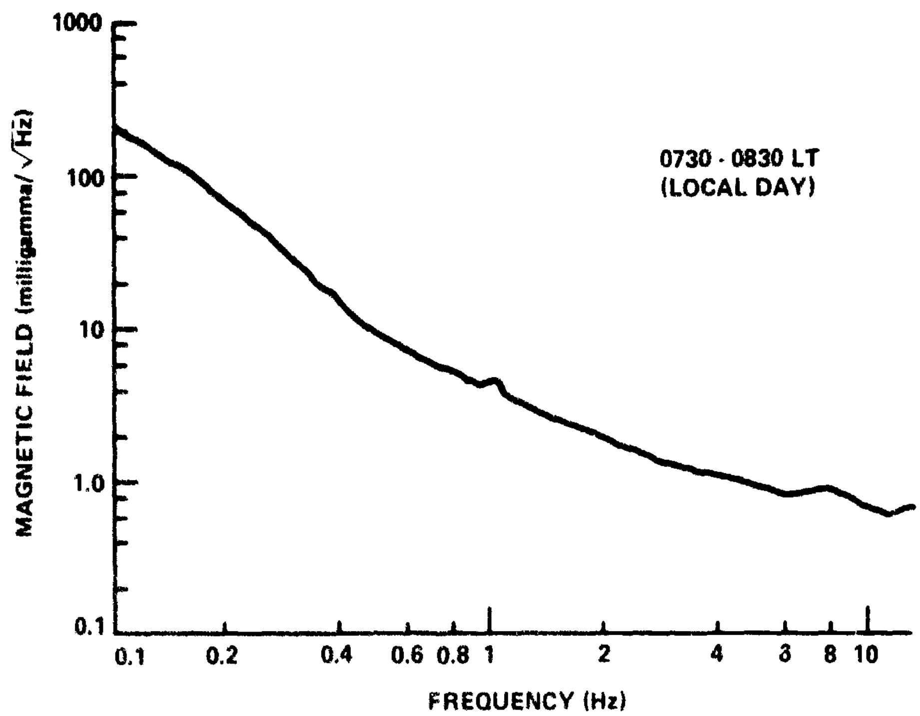

FIG. 3 AVERAGE LOCAL DAY VALUES OF N-S GEOMAGNETIC VARIATIONS DURING THE WINTER MONTHS

3. CALCULATION OF THE MAGNETIC AND ELECTRIC FIELD FLUCTUATIONS IN THE OPEN OCEAN

It is possible from the land surface values of the horizontal component of the geomagnetic field variations described in the above section to estimate the horizontal and vertical components of both the magnetic and electric field in the open ocean. The term open ocean is used here to designate the absence of any perturbations due to the discontinuity of conductivity at the shoreline.

If the current sheets in the lower ionosphere as well as the conductivity structure at the earth's surface (X-Y plane) are assumed to be two dimensional, then the resulting electric fields and currents in both seawater and land areas that are remote from a coastline will be parallel to the direction of the current flowing in the ionosphere. For an ionospheric current assumed to be flowing parallel to the Y-axis there will also be H_X and H_Z components of the magnetic field at the earth's surface where the positive Z-axis is assumed to point into the land or seawater. Since for the period range 0.5 to 1000 sec only near fields are possible on the earth's surface, both uniform and non-uniform plane waves are needed to describe the electric and magnetic field variations resulting from ionospheric current sheets of finite width. These field variations are in the horizontal X-direction as well as vertical direction and are described in detail by Kraichman in reference (a) for a horizontal two-layer conducting medium. In addition, Kraichman derives expressions for the field attenuation with depth in the top layer, the ratio of the vertical to horizontal magnetic field at the surface of the layers, and the surface impedance of the layered medium, for a single micropulsation frequency and a single spatial wavelength in the Y-direction. It is further shown in reference (a)

(a) Kraichman, M.B., Ibid.

that in the period range 0.5 to 1000 sec, a two-layer medium consisting of seawater and a continental crust of conductivity 4×10^{-3} mho/m has a horizontal spatial variation that is significant only in the initial factor of the expression for the ratio of the vertical to horizontal magnetic field at the surface of the two-layered medium. In the expressions for the field attenuation in the seawater and for the surface impedance, the electromagnetic field is essentially a uniform plane wave that propagates vertically into the conducting layers.

Since the intrinsic impedance of seawater and of the land in the period range of interest is at least two orders of magnitude smaller than that of free space, it follows that the incident horizontal magnetic field is almost totally reflected back in phase. This means that for open ocean and open land areas, the horizontal magnetic field will have essentially the same value, although the surface vertical magnetic fields, which are a much more sensitive function of the conductivity and frequency will differ considerably between land and sea.

An interesting question arises as to whether the vertical magnetic field at the surface of open land areas makes a significant contribution to the measured total magnetic field data reported in references (d) and (e) in the period range of interest, namely 0.5 to 1000 sec. If not, then reasonably good estimates of the average values of the horizontal magnetic field may readily be recovered from the measured total field values by simply dividing by the cosine of the 71 degree dip angle at the measurement site. The expression

(d) Davidson, M.J., Ibid.
(e) Herron, T.J., Ibid.

for the ratio of the vertical to horizontal magnetic field at the surface of a conducting half-space is given in reference (a) as

$$\frac{H_Z}{H_X} = \frac{-j^{1/2}\sqrt{2}\,\pi\delta}{\lambda_s} \qquad (1)$$

where $j = \sqrt{-1}$

λ_s = horizontal spatial wavelength

δ = skin depth

It is seen from (1) that this ratio is greater for the longer period oscillations and that the vertical field is 45 degrees out of phase with the horizontal field. These results are a consequence of the eddy currents induced in the conducting half-space by the fluctuations of the vertical magnetic field. Using a conductivity of 4×10^{-3} mho/m for the half-space, a period of 1000 sec for the fluctuation, and a horizontal spatial variation characterized by a dominant half wavelength of 3×10^{6} meters (2000 miles), it may be shown from (1) that the contribution of the vertical magnetic field to the total magnetic field is small even for the large dip angle of 71 degrees, and that consequently the measured total field represents mainly the contribution of the prevalent and larger N-S horizontal field. An experimental verification of the dominant contribution to the total field by a N-S horizontal field is found in reference (c) where the measured N-S values at the 300, 600, and 900 sec periods are found

(a) Kraichman, M.B., Ibid.
(c) Campbell, W.H., Ibid.

to be well within a factor of two of the total field values reported in references (d) and (e) for the same geomagnetic latitude. It is therefore reasonable to conclude that the total magnetic field values of references (d) and (e) may simply be divided by the cosine of the dip angle to obtain representative average values of the horizontal magnetic field at an open land surface in the mid-northern latitudes. For short period oscillations, the contribution of the vertical field will be even smaller and the same conclusion holds. Measured data of the horizontal magnetic field at other latitudes in the period range of interest are reported in references (c) and (g), although not every measurement site is clearly representative of open land conditions.

With a knowledge of the horizontal magnetic field at the surface of the open sea, it is possible to calculate the vertical magnetic field at the surface of a seawater layer (medium 1) with an earth bottom (medium 2). From reference (a), the surface vertical magnetic field $H_{1Z}(0)$ is given in terms of the surface horizontal field $H_{1X}(0)$ by

$$\frac{H_{1Z}(0)}{H_{1X}(0)} = \frac{j^{1/2}\sqrt{2}\,\pi\delta_1}{\lambda_s}\left(\frac{1 + \rho_{12}\, e^{\frac{-2Z_1}{\delta_1}}}{-1 + \rho_{12}\, e^{\frac{-2Z_1}{\delta_1}}}\right) \tag{2}$$

(a) Kraichman, M.B., Ibid.
(c) Campbell, W.H., Ibid.
(d) Davidson, M.J., Ibid.
(e) Herron, T.J., Ibid.
(g) Wertz, R., and Campbell, W.H., Integrated Power Spectra of Geomagnetic Field Variations with Periods of 0.3-300s, Journal of Geophysical Research, Vol. 81, No. 28, October 1, 1976, pp. 5131-40.

where $j = \sqrt{-1}$

λ_s = dominant horizontal spatial wavelength

δ_1 = skin depth in seawater

ρ_{12} = reflection coefficient at the interface between seawater of conductivity σ_1 and an earth bottom of conductivity σ_2

$$= \frac{\sigma_1^{1/2} - \sigma_2^{1/2}}{\sigma_1^{1/2} + \sigma_2^{1/2}}$$

Z_1 = depth of the seawater layer

In the two dimensional TE propagation mode applicable to horizontal ionospheric current sheets, there is only a horizontal electric field $E_{1Y}(0)$ at the surface of the seawater layer. Furthermore, in the absence of a coastline effect, that is in open ocean, there is only a horizontal electric field below the surface as well. The value of $E_{1Y}(0)$ may be expressed in terms of $H_{1X}(0)$ by means of a surface impedance. Thus from reference (a)

$$\frac{E_{1Y}(0)}{H_{1X}(0)} = \frac{j^{1/2}\omega\mu_o\delta_1}{\sqrt{2}} \left(\frac{1 + \rho_{12}\, e^{-\frac{2Z_1}{\delta_1}}}{-1 + \rho_{12}\, e^{-\frac{2Z_1}{\delta_1}}} \right) \tag{3}$$

where

ω = angular frequency of oscillation

μ_o = permeability of free space

(a) Kraichman, M.B., Ibid.

Expressions giving the attenuation of the surface horizontal magnetic and electric fields with depth in the seawater layer are available in reference (b). Thus for a depth $0 \leqq Z \leqq Z_1$, in the seawater layer

$$\frac{H_{1X}(Z)}{H_{1X}(0)} = \frac{\left[\sigma_2^{1/2} + \sigma_1^{1/2} \tanh \gamma_1 (Z_1 - Z)\right] \cosh \gamma_1 (Z_1 - Z)}{\left[\sigma_2^{1/2} + \sigma_1^{1/2} \tanh \gamma_1 Z_1\right] \cosh \gamma_1 Z_1} \tag{4}$$

and

$$\frac{E_{1Y}(Z)}{E_{1Y}(0)} = \frac{\left[\sigma_1^{1/2} + \sigma_2^{1/2} \tanh \gamma_1 (Z_1 - Z)\right] \cosh \gamma_1 (Z_1 - Z)}{\left[\sigma_1^{1/2} + \sigma_2^{1/2} \tanh \gamma_1 Z_1\right] \cosh \gamma_1 Z_1} \tag{5}$$

where γ_1 = propagation constant in seawater = $(j\omega\mu_o\sigma_1)^{1/2}$. Since it is shown in reference (a) that the vertical magnetic field $H_{1Z}(Z)$ attenuates in the seawater layer in the same manner as the horizontal electric field $E_{1Y}(Z)$, equation (5) may be used to calculate $H_{1Z}(Z)$.

The magnitude of the ratio in (4) is obtained from the expressions

$$|H_{1X}(Z)| = \left(\frac{u}{2}\right)^{1/2} \left[\left(\sigma_2^{1/2} + \frac{\sigma_1^{1/2} \sinh 2p}{u}\right)^2 + \left(\frac{\sigma_1^{1/2} \sin 2p}{u}\right)^2\right]^{1/2} \tag{6}$$

$$|H_{1X}(0)| = \left(\frac{w}{2}\right)^{1/2} \left[\left(\sigma_2^{1/2} + \frac{\sigma_1^{1/2} \sinh 2q}{w}\right)^2 + \left(\frac{\sigma_1^{1/2} \sin 2q}{w}\right)^2\right]^{1/2} \tag{7}$$

(a) Kraichman, M.B., Ibid.
(b) Kraichman, M.B., Ibid.

where $u = \cosh 2p + \cos 2p$

$$p = \frac{Z_1 - Z}{\delta_1}$$

$$w = \cosh 2q + \cos 2q$$

$$q = \frac{Z_1}{\delta_1}$$

The magnitude of the ratio in (5) is obtained from (6) and (7) by interchanging the quantities σ_2 and σ_1.

4. SOME NUMERICAL RESULTS FOR OPEN OCEAN CONDITIONS

Using (2), the magnitude of the ratio of the vertical to horizontal magnetic field at the surface of a seawater layer (4 mho/m) with an earth bottom (4×10^{-3} mho/m) is calculated for three depths of the seawater layer, 200, 1000, and 1500 meters at pulsation periods of 10, 100, and 1000 seconds. The value of the dominant horizontal spatial wavelength in the Y direction is assumed to be 6000 km or about 4000 miles. This value, which should be prominent in many micropulsations in the mid-latitudes, falls in order of magnitude between the earth's circumference at the equator and four times the 100 km height of the lower ionosphere in which the source current flows. The latter two distances are the bounding wavelengths estimated by Price in reference (h), for a global and a very local current source respectively. Table 1 presents the results for the ratio $|H_{1Z}(0)/H_{1X}(0)|$. Entries less than 0.001 in magnitude have been omitted.

Table 1. Ratio $|H_{1Z}(0)/H_{1X}(0)|$ for a two-layer conducting medium consisting of seawater (4 mho/m) over an earth bottom (4×10^{-3} mho/m) and a prominent horizontal spatial wavelength of 6000 km.

	Pulsation Period in Seconds		
Depth of Seawater Layer in Meters	10	100	1000
200	.0015	.013	.091
1000	--	.0031	.028
1500	--	.0022	.014

(h) Price, A.T., Effects of Induced Earth Currents on Low Frequency Electromagnetic Oscillations, Radio Science, Vol. 69D, No. 8, (1965), pp. 1161-88.

Two cases are considered here in the numerical results for the attenuation of the magnetic and electric field components in a seawater layer over an earth bottom. In the first case, the seawater layer has a depth of 200m and the depth in the layer at which the attenuation is calculated is 100m. In the second case, the seawater layer is 1500m deep and the attenuation is calculated for a depth of 300m in the layer. Both cases assume a conductivity of 4 mho/m for seawater, a conductivity of $4x10^{-3}$ mho/m for the earth bottom, and pulsation periods ranging from 0.5 to 1000 sec. Figures 4 and 5 show the attenuation ratios $|H_{1X}(Z)/H_{1X}(0)|$ and $|E_{1Y}(Z)/E_{1Y}(0)|$, respectively, as a function of the logarithm of the period in seconds for the case where Z_1 = 200m and Z = 100m. Similarly, figures 6 and 7 show these same ratios for the case where Z_1 = 1500m and Z = 300m. It should be noted that the attenuation ratio of the vertical magnetic field $|H_{1Z}(Z)/H_{1Z}(0)|$ is the same as that for the horizontal electric field.

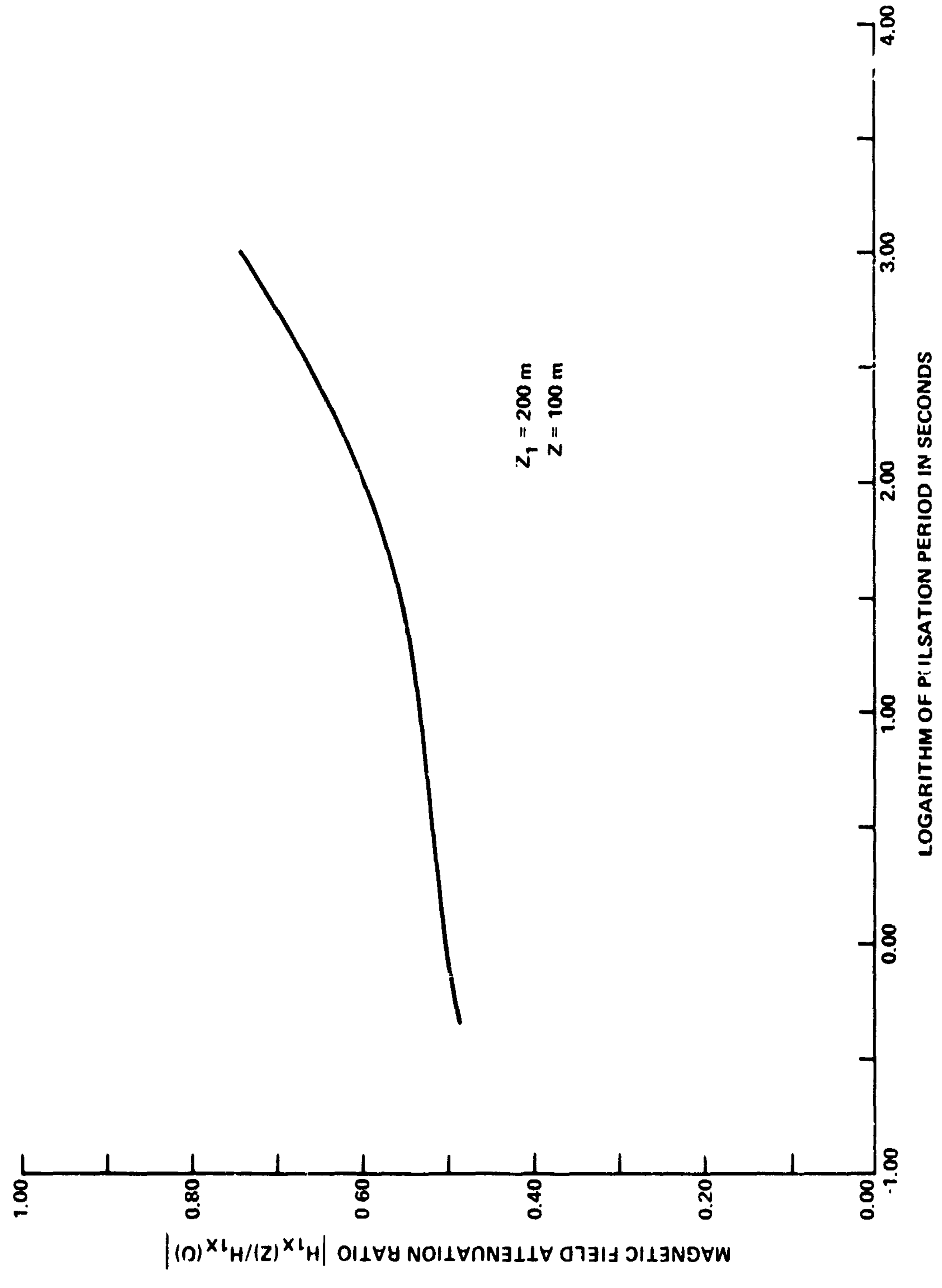

FIG. 4 HORIZONTAL MAGNETIC FIELD ATTENUATION RATIO VS THE LOGARITHM OF THE PULSATION PERIOD FOR $Z_1 = 200$ m AND $Z = 100$ m

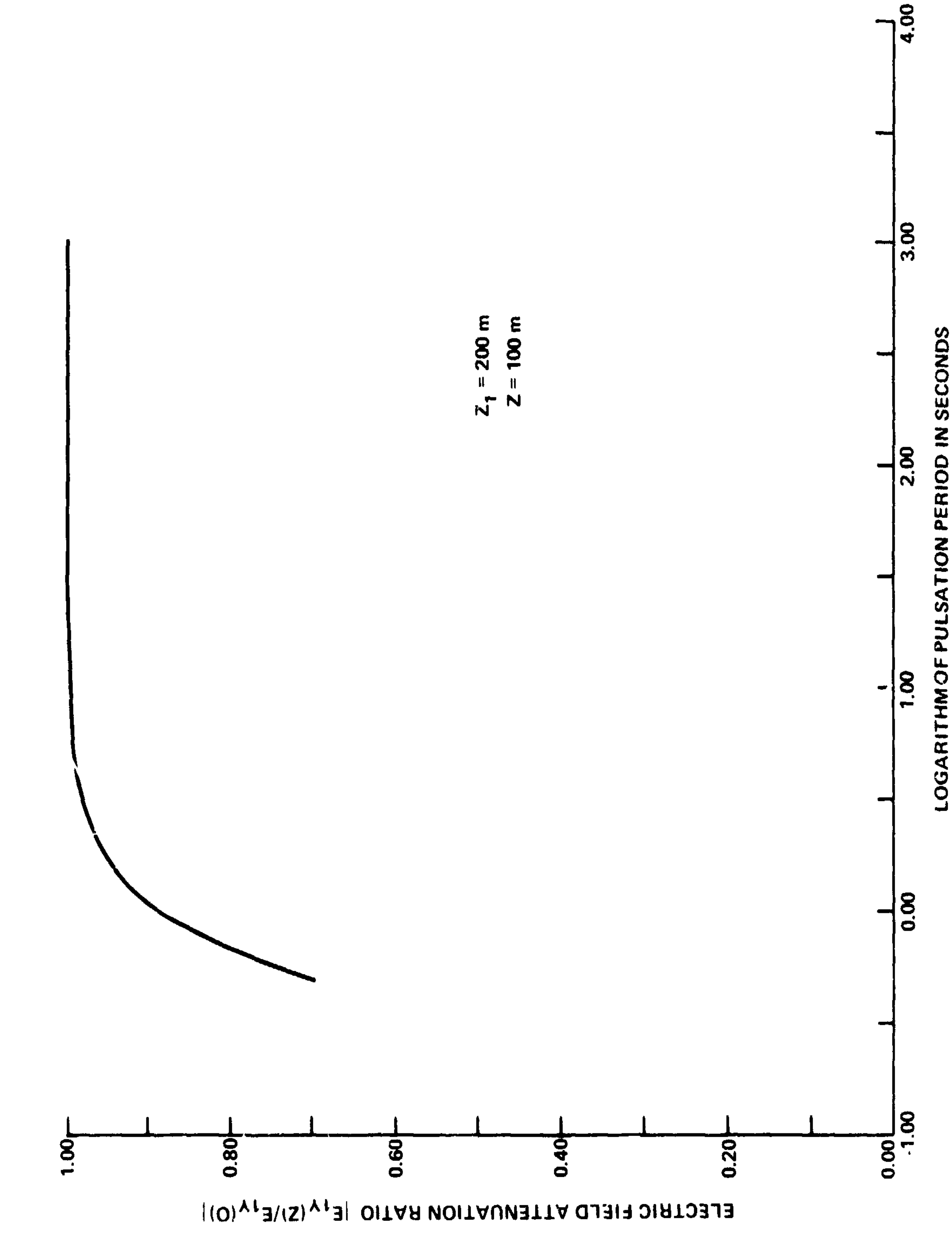

FIG. 5 HORIZONTAL ELECTRIC FIELD ATTENUATION RATIO VS THE LOGARITHM OF THE PULSATION PERIOD FOR Z_1 = 200 m AND Z = 100 m

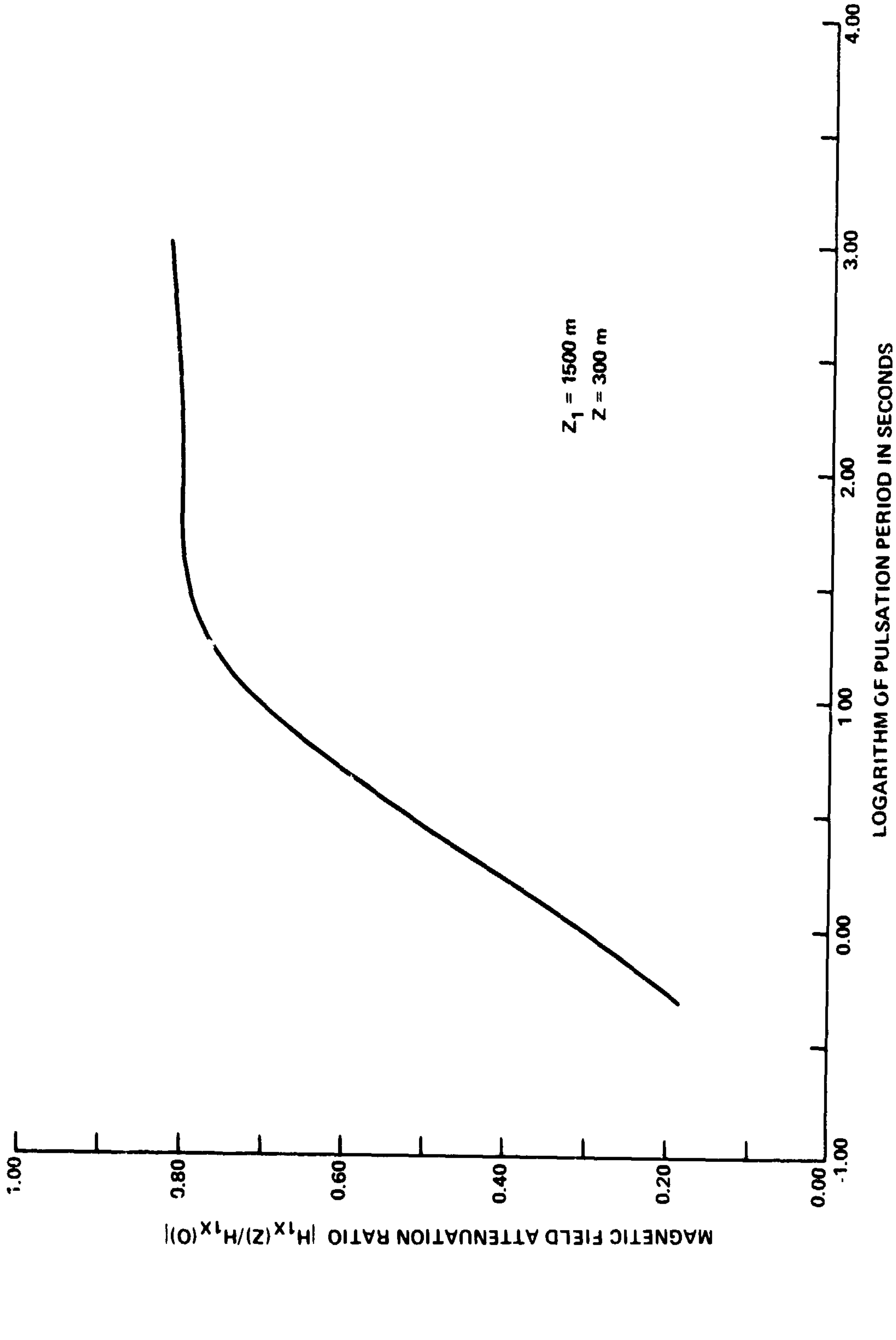

FIG. 6 HORIZONTAL MAGNETIC FIELD ATTENUATION RATIO VS THE LOGARITHM OF THE PULSATION PERIOD FOR Z_1 = 1500 m AND Z = 300 m

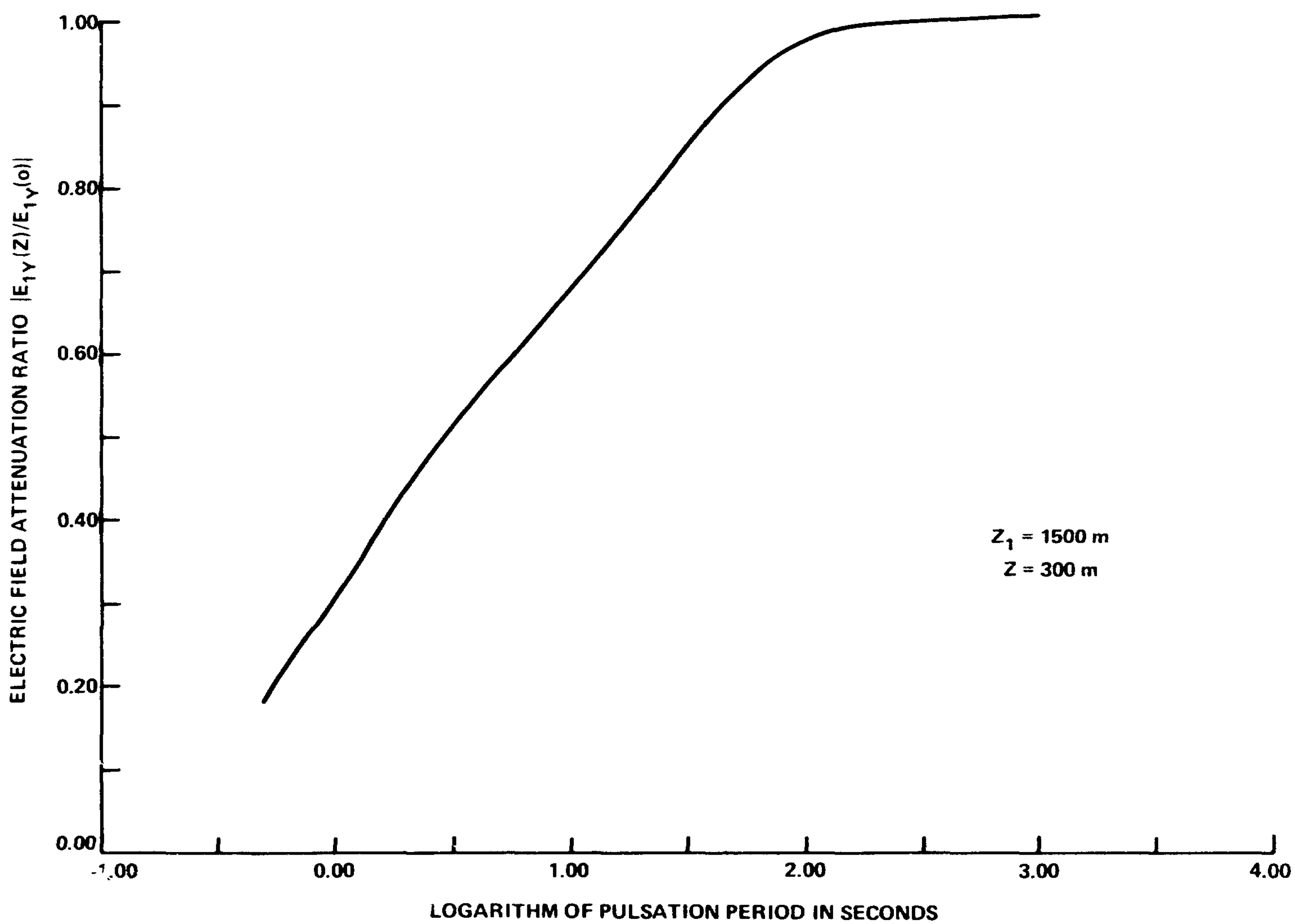

FIG. 7 HORIZONTAL ELECTRIC FIELD ATTENUATION RATIO VS THE LOGARITHM OF THE PULSATION PERIOD FOR Z_1 = 1500 m AND Z = 300 m

5. ELECTRIC AND MAGNETIC FIELD PERTURBATIONS DUE TO A COASTLINE

The presence of a conductivity discontinuity at a coastline results in perturbations in both the surface and subsurface open ocean electric and magnetic fields due to ionospheric current sources. These perturbations have a magnitude and a spatial extent that depends on the pulsation period, the conductivity contrast between the land and sea, the bottom configuration, and the relative orientation of the coastline and the ionospheric current. There are two important cases of interest in describing the two-dimensional coastline effect. In the first case, the horizontal electric field, $E_{1Y}(Z)$, is parallel to the coastline. In the second case, the horizontal electric field is normal to the coastline. When the ionospheric current direction is neither parallel nor normal to the coastline, a combination of both cases must be considered.

Laboratory analogue and finite-difference numerical surface field solutions to the two-dimensional coastline problem that employ realistic bottom configurations are reported in reference (i). These investigations consider the case where $E_{1Y}(0)$ is parallel to the coastline and use a model with a gradually sloping earth bottom (less than 3 degrees) that levels off to a constant depth of 2.5 km (8200 ft) below the sea surface. A second model with a vertical coastal boundary 2.5km deep provides results for the situation where there is a sharp drop in ocean depth at the shoreline. Analogue and numerical results for the field perturbations in both models are shown in figure 8 for a pulsation period of 17 sec, a seawater conductivity of 4 mho/m, and a bottom conductivity of 1.1×10^{-3} mho/m. The good agreement between the analogue and numerical

(i) Dosso, H.W., and Ramaswamy, V., Jones, F.W., and Thomson, D.J., On the Comparison of Laboratory Electromagnetic Analogue Model Measurements and Finite-Difference Numerical Calculations, Physics of the Earth and Planetary Interiors, Vol. 9, (1974), pp. 108-110.

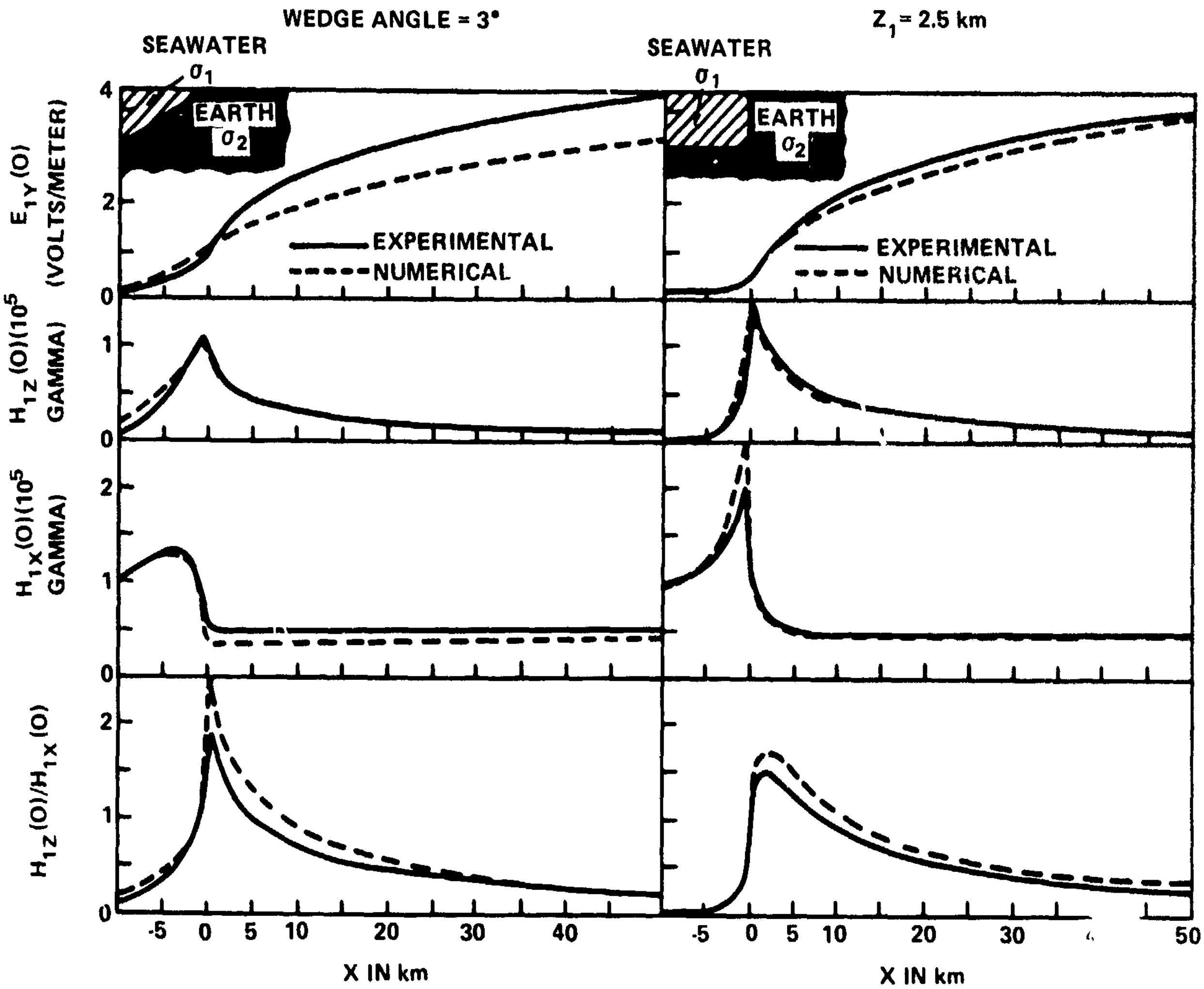

FIG. 8 A COMPARISON OF EXPERIMENTAL ANALOGUE MODEL MEASUREMENTS AND NUMERICAL CALCULATIONS OF THE COASTLINE EFFECT FOR TWO BOTTOM CONFIGURATIONS (H_{1X} NORMALIZED TO 10^5 GAMMAS AT X = 10 km). PERIOD = 17 SECONDS ,σ_1 = 4 mho/m ,$\sigma_2 = 1.1 \times 10^{-3}$ mho/m

solutions lends credence to their validity. Although the results in figure 8 are shown for a single pulsation period and conductivity contrast, it may be stated in general that for a given bottom configuration, the distance from shore over which field deviations occur is greater for longer period pulsations and larger conductivity contrasts. This is true for the deviations in the subsurface fields as well.

To the author's knowledge, there is only one study of the subsurface field perturbations due to a coastline. The theoretical numerical results are reported in reference (j). Because of the unrealistic coastal boundary used and the manner in which the numerical data are presented, only qualitative results can be extracted from the above reference that are of interest here. Thus, as the coastline is approached from the open ocean at a given depth Z, there is a significant enhancement of both the surface and subsurface vertical magnetic field, $H_{1Z}(Z \gtrsim 0)$, for the case where $E_{1Y}(Z)$ is parallel to the coastline. For $E_{1Y}(Z)$ normal to the coastline, there is the appearance and significant enhancement of the subsurface vertical electric field, $E_{1Z}(Z>0)$.

(j) Jones, F.W., and Price, A.T., The Perturbations of Alternating Geomagnetic Fields by Conductivity Anomalies, Geophysical Journal of the Royal Astronomical Society, Vol. 20, (1970), pp. 317-34.

CONCLUSIONS

Power spectra of geomagnetic variations measured at various surface land stations in the period range 0.5 to 1000 sec are available in either component or total field form. If such measurements are reasonably free from the effects of the discontinuity of conductivity at a coast, then it is possible to obtain estimates of the open ocean component values of both the surface and subsurface electric and magnetic fields. The expressions for calculating such open ocean field components are given in this report.

The presence of a conductivity discontinuity at a coastline results in perturbations in both the surface and subsurface open ocean field values. Quantitative results for realistic bottom configurations and a pulsation period of 17 sec are available for the surface electric and magnetic fields in the case where the ionospheric currents are parallel to the coastline. These results show that there is an enhancement in the electric and magnetic field values as the coastline is approached. At the shoreline, the vertical magnetic field exceeds the horizontal magnetic field in magnitude. Only qualitative results are available for the subsurface field perturbations. As the coastline is approached at a constant depth, there is a significant enhancement of the vertical magnetic field for the case where the horizontal electric field is parallel to the coastline. For the horizontal electric field normal to the coastline, there is the appearance and significant enhancement of the vertical electric field.

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