ULF/ELF Electromagnetic Fields Produced in a Conducting Medium of Infinite Extent by a Linear Current Source of Finite Length

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Abstract—**A linear current source of finite length embedded in a conducting medium of infinite extent is considered. Assuming a sea-water medium, the components of the electric and magnetic fields are numerically evaluated for two frequencies in the ULF/ELF range (frequencies less than 3 kHz). Comparison is made between the electric field vectors produced at the two different frequencies, and curves are plotted for one of the frequencies showing the variation with distance of the amplitudes of the electric and magnetic field components. A parametric approach is outlined that generalizes the field data presented in the figures and which enables the data to be extended to conducting media other than sea water and to other frequencies in the ULF/ELF range. Some practical applications of the data are discussed.**

I. Introduction

WHILE IT IS well known that electromagnetic waves are strongly attenuated, at a rate of 55 dB/wavelength, as they propagate through a conducting medium, it does not appear to be as well recognized that the waves can still propagate to large distances if their frequency is low enough, i.e., if their wavelength is large. We are not of course concerned here with the free space wavelength, but with the wavelength in the conducting medium, which is normally very much smaller than the free space wavelength at any given frequency. This means that frequencies in the ultra low and extremely low ranges (ULF/ELF; frequencies less than 3 kHz) will almost inevitably be required for long-distance propagation. To illustrate the frequency constraint, consider 100 Hz and 1 Hz signals propagating in sea water: the wavelength at 100 Hz is close to 158 m and the rate of attenuation is about 347 dB/km, whereas at 1 Hz the wavelength is of the order of 1.6 km and the rate of attenuation is about 35 dB/km. Although the attenuation of these low frequency signals is certainly not negligible, it may be low enough for the signals to be used for low-data rate communication over distances of a few kilometers or for some active methods of prospecting. There are a variety of ways in which the low-frequency signals can be generated in a conducting medium; one of the simplest, and the method that is the subject of this paper, is to set up an alternating current in a length of insulated cable immersed in the medium and with electrodes at its ends. The primary purpose of this paper is to investigate the ULF/ELF fields that might be produced by such an "antenna." Since the emphasis of our work is on the fields that are produced, and not on practical details of the cable antenna, we consider the source in an abstract form which we refer to as a linear current source of finite length.

Comparatively simple general expressions for the time-harmonic electric field components produced by a linear current source of finite length in a conducting medium of infinite extent were derived some years ago by Wait [8]. The magnetic field components (or single magnetic field component, if an appropriate cylindrical coordinate system is chosen) are more difficult to treat theoretically and the integrals that occur in their expressions have not yet been evaluated in closed form: they must be evaluated by numerical methods. In this article, we extend Wait's work by evaluating both the electric and magnetic field components numerically at frequencies in the ULF/ELF range using a combination of tabulated numerical data and numerical integration. We also introduce a parametric approach that allows our numerical results (which are derived primarily at a frequency of 100 Hz) to be applied at other frequencies in the ULF/ELF range. Since no comparable numerical data are available in the literature, our results provide new information about the propagation of ULF/ELF electromagnetic fields in conducting media and they should be useful in studies of undersea communication and active methods of prospecting.

Following Wait [8], we assume an infinitely thin cross section for the linear current source throughout our analysis. As shown by Wait [8], this assumption is valid as long as the shortest distance from the observation point to the surface of the cylindrical current source is much greater than the radius of the source.

The surrounding conducting medium is taken to be isotropic, homogeneous, and time-invariant. It is also assumed that the source wire is insulated except at its ends and that it contains a uniform current. This latter assumption is valid provided certain conditions involving the length of the wire and the frequency of operation are satisfied (Wait [8]; Chang and Wait [1]). At 100 Hz, for example, the length of the source wire can be as great as a few tens of kilometers and the assumption is still valid (Inan *et al.* [4]). At lower frequencies the wire can be longer than this reference length and the assumption will remain valid; at higher frequencies the length will be less. We will generally restrict ourselves to a length of

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100 m in our derivations of numerical data and our results will be valid throughout the ULF/ELF range.

We neglect displacement current in the medium. This is permissible for frequencies satisfying the condition $\sigma/\omega\epsilon \gg 1$, where σ and ϵ are the conductivity and the permittivity of the medium, and ω is the angular frequency of the source. In the case of sea water (for which we assume $\sigma = 4$ S/m and permeability $\mu = \mu_0 = 4\pi \times 10^{-7}$ H/m), which is the conducting medium of primary interest in this work, the displacement current can be neglected for frequencies less than about 100 MHz. For frequencies satisfying the condition $\sigma/\omega\epsilon \gg 1$, electromagnetic fields propagate in a conducting medium with wavelength given by $\lambda = 2\pi\delta$, where δ is the skin depth of the conducting medium defined as $\delta = (2/\omega\mu\sigma)^{1/2}$. It can be easily shown that the fields undergo an exponential attenuation at the rate of 55 dB/wavelength.

Although the numerical data presented in this work are for a conducting medium of infinite extent, they will also apply in a conducting medium of finite extent provided the boundaries of the medium are sufficiently distant from the source and receiver. Because of the rapid attenuation of the fields, the distance does not have to be large in terms of sea water wavelengths. In our case we have evaluated the field expressions for observation distances of about one wavelength or less and the results are likely to remain representative for a conducting medium of finite extent provided the boundaries of the medium are at a distance of at least a wavelength away from both the source and receiver.

II. The Field Components

The geometry of the line source, which is assumed to be carrying a current $Ie^{i\omega t}$ and to extend from l_1 to l_2 along the z-axis, is shown in Fig. 1. Cylindrical coordinates (ρ, ϕ, z) are used and the observer (i.e., the field point) is located at P.

The field components are obtained by following the approach used by Wait [8]. We start with the Hertz vector Π for the current element Idl located at $z = l$ in Fig. 1; in the assumed cylindrical coordinate system, this vector has only a single component, the z-component, which can be written

$$\Pi_z = \frac{Ie^{-\gamma r}}{4\pi\sigma r}\, dl, \tag{1}$$

where

$$r = [\rho^2 + (z-l)^2]^{1/2}, \quad \gamma = (i\omega\mu\sigma)^{1/2}.$$

The variable γ is the *propagation constant* for the conducting medium. Integrating (1) from l_1 to l_2, we obtain the Hertz vector for a finite linear current source

$$\Pi_z = \frac{I}{4\pi\sigma} \int_{l_1}^{l_2} \frac{e^{-\gamma r}}{r}\, dl. \tag{2}$$

The electric and the magnetic fields, $\mathbf{E}$ and $\mathbf{B}$, are related to the Hertz vector by

$$\mathbf{E} = -\gamma^2 \mathbf{\Pi} + \nabla\nabla \cdot \mathbf{\Pi}, \tag{3}$$

$$\mathbf{B} = \sigma\mu \nabla \times \mathbf{\Pi}, \tag{4}$$

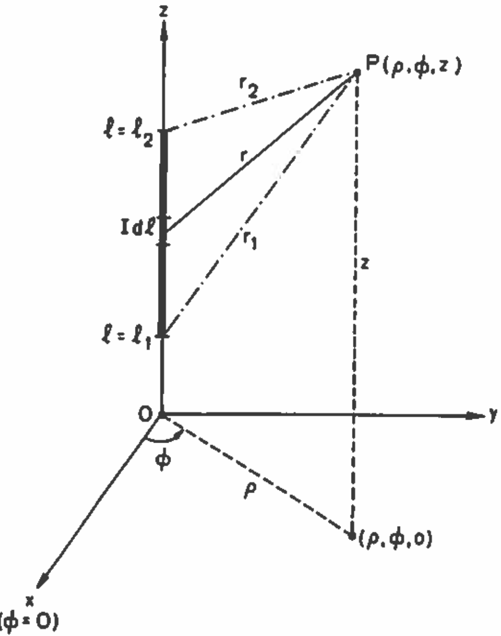

Fig. 1. Coordinate system and geometry used in the derivation of the electric and magnetic fields produced in a conducting medium of infinite extent by a linear current source of finite length.

from which, using the Hertz vector component given by (2), the fields components are obtained by performing the operations

$$E_\rho = \frac{\partial^2 \Pi_z}{\partial\rho\,\partial z}, \quad E_\phi = 0, \quad E_z = -\gamma^2 \Pi_z + \frac{\partial^2 \Pi_z}{\partial z^2}, \tag{5}$$

$$B_\rho = 0, \quad B_\phi = -\sigma\mu \frac{\partial \Pi_z}{\partial \rho}, \quad B_z = 0. \tag{6}$$

The electric field components E_ρ and E_z have been derived by Wait [8]:

$$E_\rho = \frac{\rho I}{4\pi\sigma}\left[\frac{e^{-\gamma r_2}}{r_2^3}(\gamma r_2 + 1) - \frac{e^{-\gamma r_1}}{r_1^3}(\gamma r_1 + 1)\right], \tag{7}$$

$$\begin{aligned} E_z = \frac{i\omega\mu I}{4\pi}\Bigg[\bigg(&\sinh^{-1}\frac{x_2}{a} - \sinh^{-1}\frac{x_1}{a} - E_c(a, x_2) \\ &+ E_c(a, x_1)\bigg) - i(E_s(a, x_2) - E_s(a, x_1))\Bigg] \\ &+ \frac{I}{4\pi\sigma}\left[\frac{e^{-\gamma r_2}}{r_2^3}(\gamma r_2 + 1)(z - l_2) - \frac{e^{-\gamma r_1}}{r_1^3}(\gamma r_1 + 1)(z - l_1)\right], \end{aligned} \tag{8}$$

where

$$\gamma = (1+i)\beta, \quad a = \beta\rho, \quad \beta = (\omega\mu\sigma/2)^{1/2} = 1/\delta,$$

$$r_i(i = 1,\ 2) = [\rho^2 + (z - l_i)^2]^{1/2}, \quad x_i(i = 1,\ 2) = \beta(z - l_i),$$

and where $E_c(a, x_i)$ and $E_s(a, x_i)$ are the generalized cosine and sine integrals (Computation Laboratory of Harvard University

[2]), which are defined as follows:

$$E_c(a,\ x_i)=\int_0^{x_i}\frac{1-e^{-u}\cos u}{u}\,dx,$$

$$E_s(a,\ x_i)=\int_0^{x_i}\frac{e^{-u}\sin u}{u}\,dx,\tag{9}$$

with $u = (a^2 + x^2)^{1/2}$.

By carrying out the operation in (6), we obtain the following integral expression for the single magnetic field component:

$$B_\phi=-\frac{\mu I}{4\pi}\frac{\partial}{\partial\rho}\int_{l_1}^{l_2}\frac{e^{-\gamma r}}{r}\,dl,\tag{10}$$

which can also be written in the form

$$B_\phi=-\frac{\rho\mu I}{4\pi\delta^2}\int_{x_1}^{x_2}\left[\frac{(1+i)e^{-(1+i)u}}{u^2}+\frac{e^{-(1+i)u}}{u^3}\right]dx.$$

By defining four new integrals

$$M_c(a,\ x_i)=\int_0^{x_i}\frac{e^{-u}\cos u}{u^2}\,dx,$$

$$M_s(a,\ x_i)=\int_0^{x_i}\frac{e^{-u}\sin u}{u^2}\,dx,$$

$$N_c(a,\ x_i)=\int_0^{x_i}\frac{e^{-u}\cos u}{u^3}\,dx,$$

$$N_s(a,\ x_i)=\int_0^{x_i}\frac{e^{-u}\sin u}{u^3}\,dx,\tag{11}$$

the magnetic field expression can be written in the following form, which is convenient for numerical evaluation:

$$\begin{aligned}B_\phi=&-\frac{\rho\mu I}{4\pi\delta^2}\,[(M_c(a,\ x_2)+M_s(a,\ x_2)+N_c(a,\ x_2)\\&-M_c(a,\ x_1)-M_s(a,\ x_1)-N_c(a,\ x_1))\\&+i(M_c(a,\ x_2)-M_s(a,\ x_2)-N_s(a,\ x_2)\\&-M_c(a,\ x_1)+M_s(a,\ x_1)+N_s(a,\ x_1))].\end{aligned}\tag{12}$$

III. Computed Fields

The expressions given above for the field components E_z and B_ϕ contain integrals that can only be evaluated in general by numerical integration, but which are comparatively easy to evaluate by such methods. We evaluated the expressions numerically by means of Weddle's rule (Scarborough, [7]). The numerical integration method, and the computed values for the integrals, were checked in several different ways. One obvious way was to compare computed results for the generalized cosine and sine integrals, $E_c(a,\ x_i)$ and $E_s(a,\ x_i)$, with the available tabulated values (Computation Laboratory of Harvard University [2]). Another way was to see if the values of the integrals converged to the values tabulated for Kelvin functions and their derivatives (Lowell [5]; Young and Kirk [9]; see Appendix B in Inan *et al.* [4]) for large values of the upper limit of these integrals.

All our numerical data apply to a sea water medium (σ = 4 S/m). Shown in Figs. 2-7 are computed values of the electric and magnetic fields produced at frequencies of 100 Hz (Figs. 2, 4-7) and 1 Hz (Fig. 3) by a linear current source of 100 m length carrying an alternating current of 1000 A amplitude. The fields are shown in two dimensions; in all cases the fields are cylindrically symmetric about the axis defined by the source. Figs. 2 and 3 show the spatial variations of the total electric field vector at the instant when there is maximum current (1000 A) in the source flowing from B to A. The shorter wavelength at 100 Hz can be clearly seen when comparison is made of the two figures. Fig. 4 shows equal amplitude contours of the magnetic field component B_ϕ for a frequency of 100 Hz at the time instant of maximum current flow from B to A. Figs. 5 and 6 show contours of the maximum values reached by the two components of the electric field, E_z and E_ρ, during one cycle of the source current. The dashed contours indicated zero amplitude; thus in Fig. 6 the E_ρ component is zero along the axis of the source and along the perpendicular line through the center of the source. Comparing these two electric field figures, it can be seen how the two separate components E_z and E_ρ contribute to the total electric field. In Fig. 7, we have drawn contours indicating the maximum values reached by the 100 Hz total magnetic field variation at each point during one cycle. Thus, at all points inside the contour labeled 10^4 pT, our data show that the total magnetic field (or, equivalently, the magnetic field component B_ϕ) will reach a value of 10^4 pT or more during one cycle of the source current.

The large maximum source current chosen for the computations that resulted in the above displays is not wholly without significance: the field components are directly proportional to the current, as shown by (7), (8), and (12), and the generation of measurable fields at usefully large distances from a linear source will require very substantial currents, as our field data show. For other values of the maximum current, say I A, the corresponding field values can be obtained from those in the figures by multiplying by $I/1000$.

IV. Parametric Approach

Fraser-Smith and Bubenik [3] used a parametric approach to minimize the computation required to obtain field data and to generalize the data obtained from particular computations. The same parametric approach can be used here simply by measuring all distances in units of the skin depth δ of the conducting medium and by converting the electric and magnetic field components, E_ρ, E_z, and B_ϕ, as given by (7), (8), and (12), to the following parametric form:

$$E_\rho^p=\sigma\delta^2E_\rho,\tag{13}$$

$$E_z^p=\sigma\delta^2E_z,\tag{14}$$

$$B_\phi^p=\delta B_\phi,\tag{15}$$

where the superscript p on the left sides of the above equations means the field components are in parametric form. To show

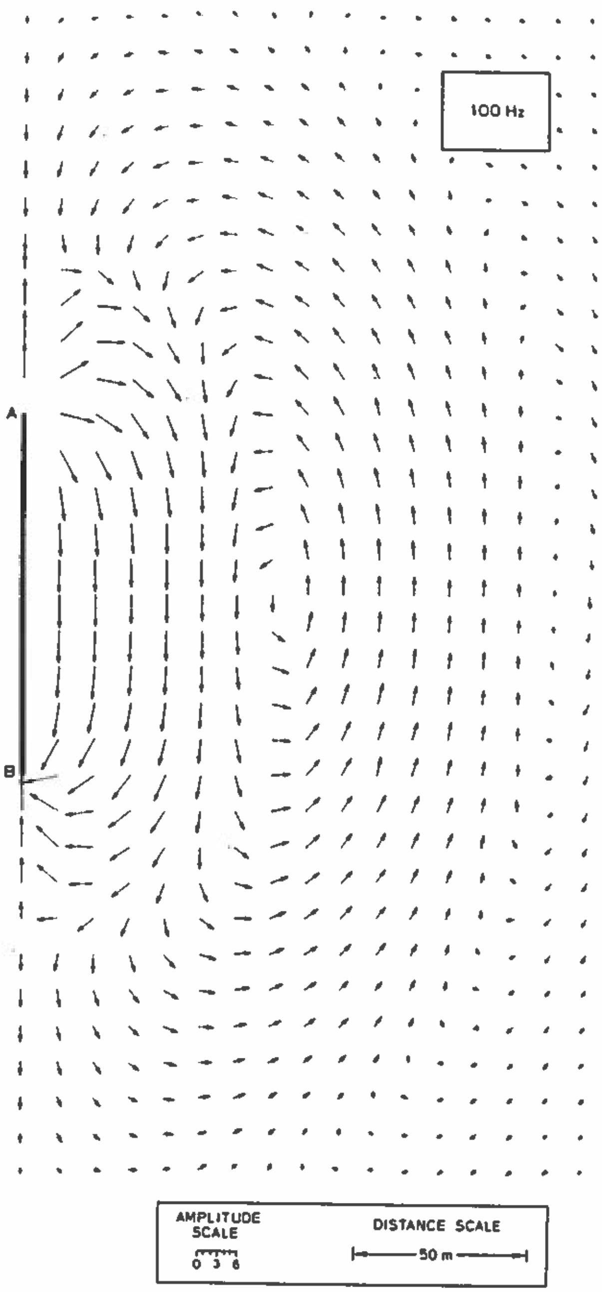

Fig. 2. Variation of the total electric field vector produced in sea water by a linear current source of finite length (100 m) carrying an alternating current of amplitude 1000 A and frequency 100 Hz at the time instant when there is maximum current flowing in the direction B to A. The magnitude of the electric field vector is 10^n μV/m, where n can be read from the amplitude scale shown at the bottom. The field pattern in this and all succeeding figures is cylindrically symmetric around the axis of the source.

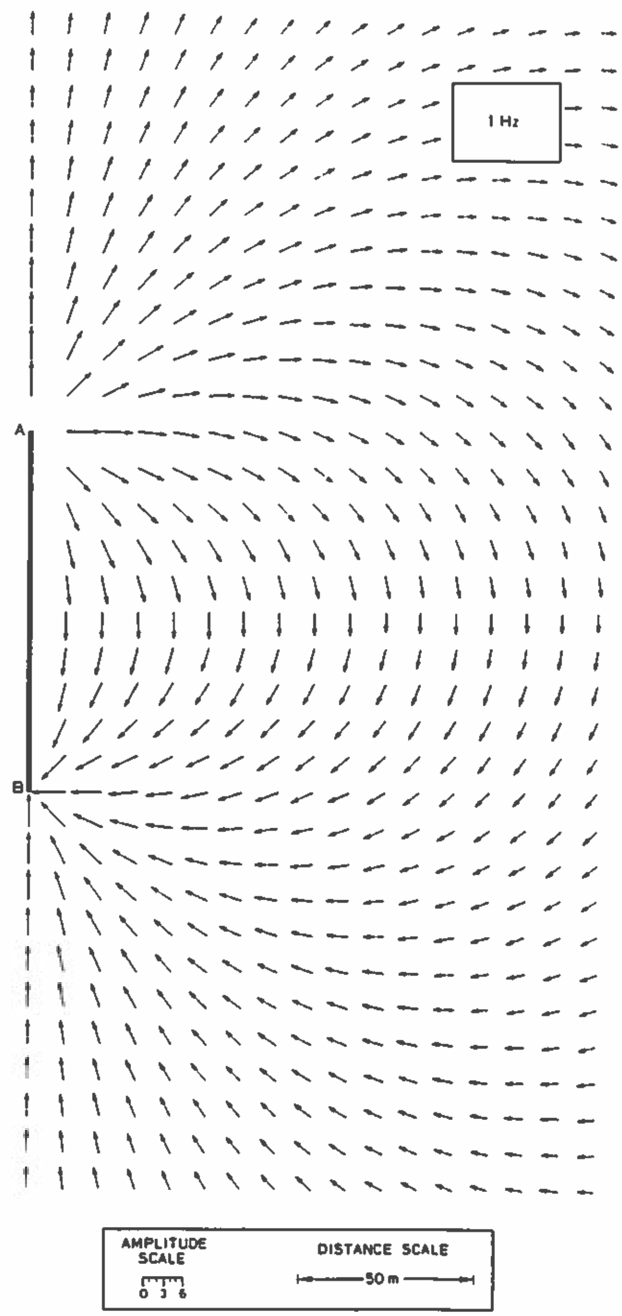

Fig. 3. Variation of the total electric field vector produced in sea water by a linear current source of finite length (100 m) carrying an alternating current of amplitude 1000 A and frequency 1 Hz at the time instant when there is maximum current flowing in the direction B to A. The magnitude of the electric field vector is 10^n μV/m, where n can be read from the amplitude scale shown at the bottom.

the significance of these changes, consider their effect on (7). Multiplying both sides of this equation by $\sigma\delta^2$, and normalizing the distance quantities by δ, we obtain

$$\sigma\delta^2 E_\rho = E_\rho^p = \frac{\rho I}{4\pi}\left[\frac{e^{-(2i)^{1/2}r_2}}{r_2^3}((2i)^{1/2}r_2+1) - \frac{e^{-(2i)^{1/2}r_1}}{r_1^3}((2i)^{1/2}r_1+1)\right]. \tag{16}$$

The right side of this equation, and thus E_ρ^p, can now be evaluated without reference to any particular frequency or conductivity. The more complicated equations for E_z and B_ϕ can also be reduced to parametric form by making the appropriate changes: normalizing the distance quantities by δ and multiplying through either by $\sigma\delta^2$, to obtain the parametric expression for E_z^p, or by δ, to obtain the parametric expression for B_ϕ^p. It is clear that use of these parametric equations can greatly reduce the numerical computation required to obtain field values.

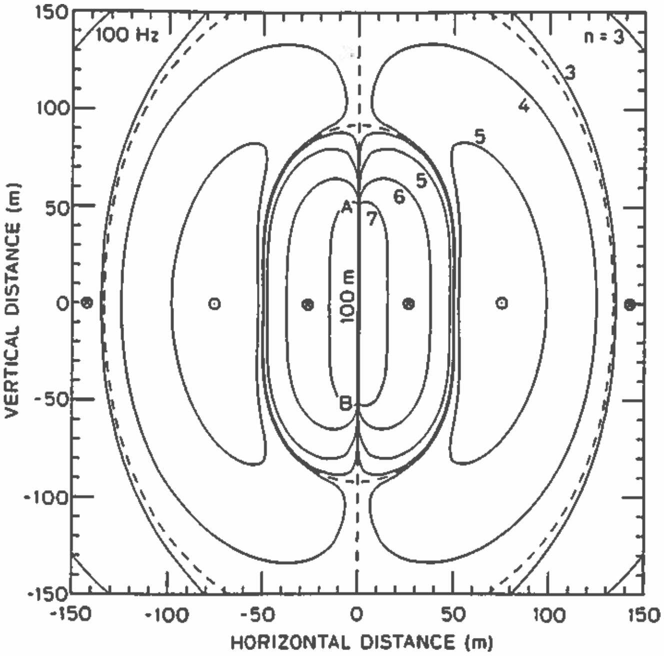

Fig. 4. Variation of the total magnetic field (i.e., the component B_ϕ) produced in sea water by a linear current source of finite length (100 m) carrying an alternating current of amplitude 1000 A and frequency 100 Hz at the time instant when there is maximum current flowing in the direction B to A. The magnitude of B_ϕ is given by 10^n pT, where n is given for each contour in the figure ($B_\phi = 0$ on the dashed contours). As indicated, the direction of B_ϕ is either into the page or out depending on the region between the dashed lines.

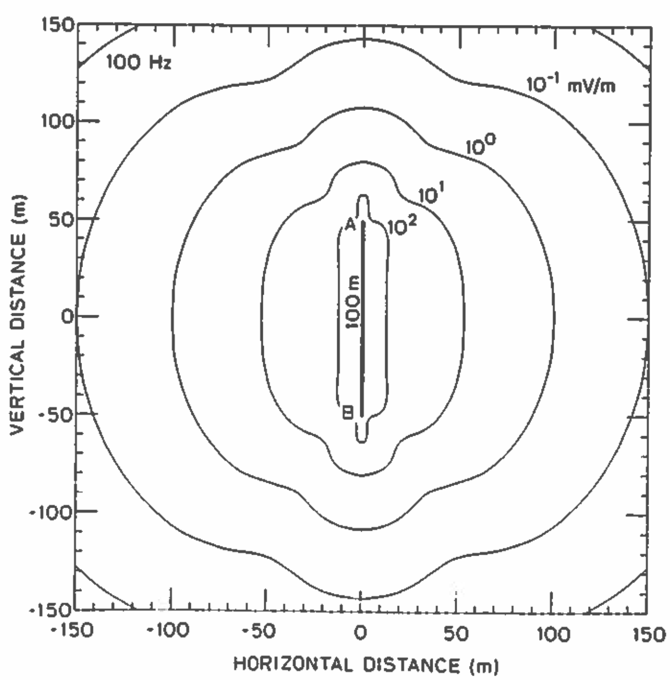

Fig. 5. Variation of the amplitude of the parallel component of the electric field E_z, produced in sea water by a linear current source of finite length (100 m) carrying an alternating current of amplitude 1000 A and frequency 100 Hz. The amplitude of E_z is constant along each contour.

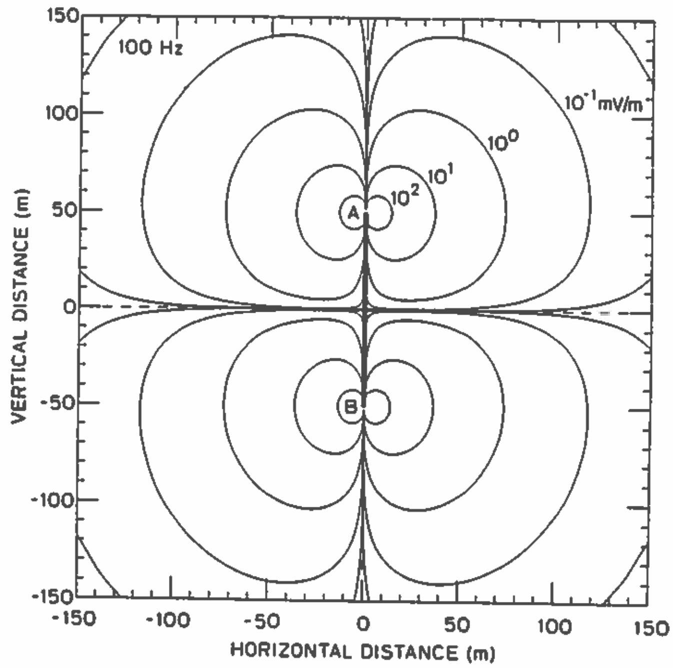

Fig. 6. Variation of the amplitude of the perpendicular component of the electric field, E_ρ, produced in sea water by a linear current source of finite length (100 m) carrying an alternating current of amplitude 1000 A and frequency 100 Hz. The amplitude of E_ρ is constant along each contour and is zero along the dashed lines.

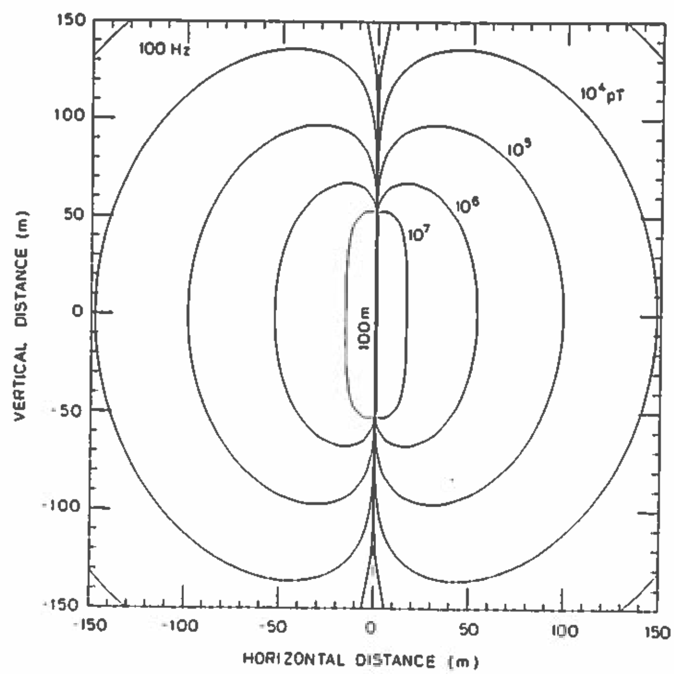

Fig. 7. Variation of the amplitude of the total magnetic field (i.e., the component B_ϕ) produced in sea water by a linear current source of finite length (100 m) carrying an alternating current of amplitude 1000 A and frequency 100 Hz.

In addition to simplifying the computation required to obtain the field components, the parametric approach outlined above also provides a simple procedure for converting the field values calculated for one particular frequency to another set of field values at some other frequency with little additional computation. To illustrate, assume the values of the electric and the magnetic fields produced by the linear current source at the observation point $P(\rho, \phi, z)$ in Fig. 1 are known for a certain frequency f_1. Let these field values be $E_\rho = E_{\rho 1}$, $E_z = E_{z1}$, and $B_\phi = B_{\phi 1}$. If we now change the frequency by a factor $1/A^2$ to $f_2 = f_1/A^2$, the new skin depth will be $\delta_2 = A\delta_1$. If we multiply all the distance coordinates in Fig. 1 by A, i.e., change l_1, l_2, ρ, and z to Al_1, Al_2, $A\rho$, and Az, it follows that all the normalized distances in the parametric equations will remain unchanged and thus the parametric fields E_ρ^p, E_z^p, and B_ϕ^p will also remain the same. The electric and magnetic field components $E_{\rho 2}$, E_{z2}, and $B_{\phi 2}$, at the new observation point $P(A\rho, \phi, Az)$, produced by the linear current source extending from $l = Al_1$ to $l = Al_2$ and operating at the new frequency $f_2 = f_1/A^2$, are now simply obtained by computing $E_{\rho 2} = E_{\rho 1}/A^2$, $E_{z2} = E_{z1}/A^2$, and $B_{\phi 1} = B_{\phi 2}/A$. These new field values can obviously be calculated more easily from the field values for frequency f_1 than they can from the original integral expressions.

V. Summary and Conclusion

With the theoretical work of Wait [8] as a starting point, we have derived a representative collection of numerical values for the ULF/ELF electromagnetic fields produced in a conducting medium of infinite extent by a linear current source of finite length. The numerical results apply specifically to a sea-water medium, but the basic theory is given in a form that is independent of the specific conducting medium and the numerical results we have presented can be converted simply to the values appropriate for other conducting media either 1) by changing the distances that are used (while keeping the frequency constant), or 2) by changing the frequency and field amplitudes (while keeping the distances the same). The changes are analogous to those described above in the section detailing our parametric approach.

To illustrate, consider the data in Fig. 5. These data can be converted to the appropriate data for a medium with $\sigma = 0.04$ S/m (100 times less than the conductivity of our assumed sea-water medium, representing the conductivity of fresh water) by making the following changes. First, if the source length is changed from 100 m to 1 km and the distance scale is multiplied by 10, the field data will apply at the same frequency (100 Hz) in the lower conductivity medium. Second, if all the field amplitudes are multiplied by 100, but no other changes made, the data will apply at a frequency of 10 kHz in the lower conductivity medium.

As expected, our numerical results show evidence of significant exponential attenuation as the fields propagate in the conducting medium. However, it is evident that reasonably large communication ranges should be achievable in sea water for frequencies in the lower part of the ULF/ELF range, and larger ranges are likely in the lower conductivity materials comprising the earth's crust. An obvious disadvantage of this method of communication is its low data rate, but it may be adequate for messages of short length.

Other possible applications of the ULF/ELF fields produced by linear current sources of finite length are in geophysical exploration and in short-range undersea communication. Indeed, insofar as the latter application is concerned, a commercial unit has been described that uses the electric fields from a comparatively small length (about 30 m) of submerged cable to provide short-range communication between divers at frequencies in the lower part (300–5000 Hz) of the voice frequency range (MacLeod [6]). Because of the wide frequency range involved, dispersion effects will have to be taken into account in this application, and they will be an important factor in determining the maximum range the signals can travel without serious loss of intelligibility.

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