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Surface-to-Surface and Subsurface-to-Air Propagation Of Electromagnetic Waves

THE DERIVATION OF ELECTRIC AND MAGNETIC FIELD COMPONENTS FOR THE QUASI-STATIC, QUASI-NEAR, AND NEAR-FIELD RANGES

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ABSTRACT

The electric and magnetic field components produced by vertical and horizontal dipoles (both electric and magnetic) are derived and presented for the quasi-static, quasi-near, and near-field ranges. The depth, h, of the transmitting dipole is less than or equal to zero; the height, z, of the receiving antenna above the plane, conducting, homogeneous earth varies from zero to some height, z, that is much less than the ionospheric reflecting height (ionospheric effects are neglected). The horizontal separation, ρ, between the transmitting and receiving antennas is comparable to the receiving antenna height, z. The derivations are based upon the quasi-static and near-field approximations to the vector potentials for the vertical and horizontal dipoles and upon application of the reciprocity theorem. The surface-to-surface propagation equations reduce to well-known expressions when $|\gamma_1 \rho| \gg 1$ and $|\gamma_1 \rho| \ll 1$, as do the subsurface-to-air equations when $\rho \gg z$.

ADMINISTRATIVE INFORMATION

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DEFINITIONS OF SYMBOLS AND ABBREVIATIONS

c	The velocity of propagation in the upper half-space (free space); $\cong 3 \times 10^8$ (meters/sec)
$d\ell$	The infinitesimal dipole length (meters)
dA	The infinitesimal dipole area (meters^2)
$e^{i\omega t}$	The time factor assumed
E_ρ	The horizontal electric field component in the ρ direction (volts/meter)
E_ϕ	The horizontal electric field component in the ϕ direction (volts/meter)
E_z	The vertical electric field component (volts/meter)
G_v	Wait's height gain factor for vertical polarization (valid for $\rho >> z$); $= 1 + \gamma_0^2 z/\gamma_1$
h	The depth of burial of the transmitting antenna ($h \leq 0^-$) (meters)
H	The height of the vertical loop antenna above the earth; $= 1/\gamma_1$
H_ρ	The horizontal magnetic field component in the ρ direction (amperes/meter)
H_ϕ	The horizontal magnetic field component in the ϕ direction (amperes/meter)
H_z	The vertical magnetic field component (amperes/meter)
HED	The horizontal electric dipole
HMD	The horizontal magnetic dipole
HGF	The height gain factor; equal to the field strength at height z divided by the field strength at height $z = 0^+$
$I_0(\gamma_1\rho/2)$	The modified Bessel function of the first kind, order zero, and argument $\gamma_1\rho/2$
$I_1(\gamma_1\rho/2)$	The modified Bessel function of the first kind, order one, and argument $\gamma_1\rho/2$
$J_0(\lambda\rho)$	The Bessel function of the first kind, order zero, and argument $\lambda\rho$
$K_0(\gamma_1\rho/2)$	The modified Bessel function of the second kind, order zero, and argument $\gamma_1\rho/2$
$K_1(\gamma_1\rho/2)$	The modified Bessel function of the second kind, order one, and argument $\gamma_1\rho/2$
mks	Meter-kilogram-seconds, the unit employed
R	The radial distance in a spherical coordinate system; $= (\rho^2 + z^2)^{1/2}$
T	$16 I_1 K_1 + 4\gamma_1\rho(I_1 K_0 - I_0 K_1) + \gamma_1^2\rho^2(I_1 K_1 - I_0 K_0)$
u_0	$(\lambda^2 + \gamma_0^2)^{1/2}$ (meters^{-1})
u_1	$(\lambda^2 + \gamma_1^2)^{1/2}$ (meters^{-1})
VED	The vertical electric dipole
VMD	The vertical magnetic dipole
W	$3 I_1 K_1 - (\gamma_1\rho/2)(I_0 K_1 - I_1 K_0)$
z	The height of the transmitting antenna above the plane conducting earth ($z \geq 0^+$) (meters)

γ_o	The upper half-space (free space) propagation constant (meters^{-1}); $= (-\epsilon_o \mu_o \omega^2)^{1/2}$
γ_1	The lower half-space (the earth) propagation constant (the displacement currents in the earth are assumed to be negligible); $\cong (i\,\omega\mu_o\sigma_1)^{1/2}$ (meters^{-1})
δ	The skin depth in the lower half-space (the earth); $= (2/\omega\mu\sigma_1)^{1/2}$
ϵ_o	The permittivity of free space; $\cong 10^{-9}/36\pi$ (farads/meter)
λ	The dummy integration variable
λ_{air}	The wavelength in the upper half-space (free space); $= c/f$
λ_{earth}	The wavelength in the lower half-space (the earth); $= 2\pi\delta$
$\mu \simeq \mu_o$	The permeability of free space; $= 4\pi \times 10^{-7}$ (henries/meter)
ρ	The radial distance in a cylindrical coordinate system; $= (x^2 + y^2)^{1/2}$
σ_1	The conductivity of the lower half-space (the earth) (mhos/meter)
ϕ	The azimuth angle in a cylindrical coordinate system; $= \tan^{-1}(y/x)$
ω	The angular frequency; $= 2\pi f$ (radians/sec)
0^+	The infinitesimal distance above the surface of the earth (meters)
0^-	The infinitesimal distance below the surface of the earth (meters)

SURFACE-TO-SURFACE AND SUBSURFACE-TO-AIR PROPAGATION OF ELECTROMAGNETIC WAVES

The Derivation of Electric and Magnetic Field Components for the Quasi-Static, Quasi-Near, and Near-Field Ranges

INTRODUCTION

Radiation from electric and magnetic dipole antennas in the air above a plane, conducting, homogeneous earth has been considered by many writers, beginning with Sommerfeld.[1] Unfortunately, relatively little attention has been paid to surface-to-surface propagation in the quasi-static range ($|\gamma_0 \rho| \ll 1$) when $\gamma_1 \rho$ is allowed to be any value. (Definitions of the symbols appear in the introductory pages at the front of the report.) In this report the theoretical work that has been accomplished for this range is summarized, and the electric and magnetic field components that have not been derived previously (to the author's knowledge) are derived for the case in which $z = h = 0$. Surface-to-air propagation in the near-field range has been considered by Norton,[2] who states, however, that some of his formulas are valid only for distances down to a free-space wavelength (i.e., $R > \lambda_{air}$). Subsurface-to-air propagation in the quasi-near and near-field ranges has been treated by Moore,[3] Wait,[4] Baños and Wesley,[5] and Baños[6] (among others) with the restriction that $\rho \gg z$. The field compo-

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[1] A. Sommerfeld, "On the Propagation of Waves in Wireless Telegraphy," *Annalen der Physik*, vol. 81, no. 25, 11 December 1926, pp. 1135-1153.

[2] K.A. Norton, "The Propagation of Radio Waves Over the Surface of the Earth and in the Upper Atmosphere," *Proceedings of the Institute of Radio Engineers*, vol. 25, no. 9, September 1937, pp. 1203-1236.

[3] R.K. Moore, "The Theory of Radio Communication between Submerged Submarines," Ph. D. Thesis, Cornell University, 1951. (Revised in 1961 by R.K. Moore and W.E. Blair, "Dipole Radiation in a Conducting Half-Space," *NBS Journal of Research—D. Radio Propagation*, vol. 65D, no. 6, November - December 1961, pp. 547-563.)

[4] J.R. Wait, "The Electromagnetic Fields of a Horizontal Dipole in the Presence of a Conducting Half-Space," *Canadian Journal of Physics*, vol. 39, 1961, pp. 1017-1028.

[5] A. Baños, Jr., and J.R. Wesley, *The Horizontal Electric Dipole in a Conducting Half-Space*, Parts I and II, Reports Nos. 53-33 and 54-31, Marine Physical Laboratory, University of California, 1953, 1954.

[6] A. Baños, Jr., *Dipole Radiation in the Presence of a Conducting Half-Space*, Pergamon Press, Oxford, England, 1966.

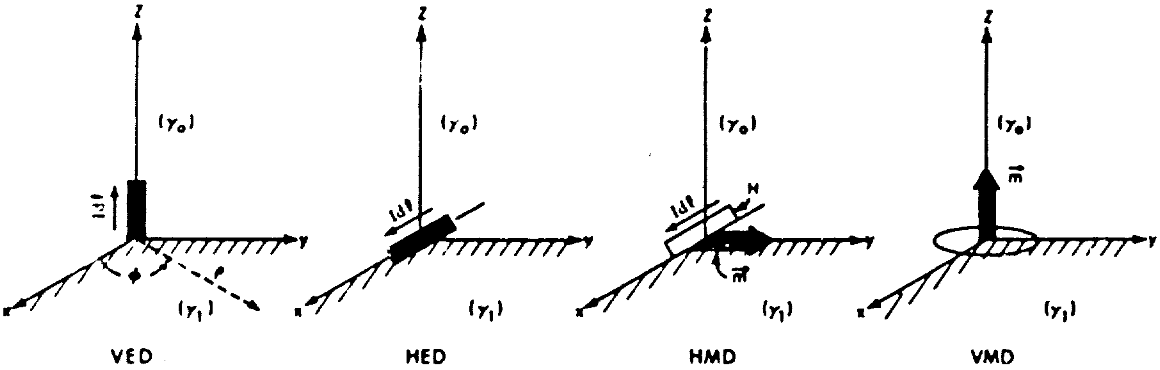

Fig. 1 - Dipole Orientations when $h = 0^+$

nents produced by subsurface dipole antennas that are valid for the quasi-near $(\lambda_{earth} \ll R \ll \lambda_{air})$ and near-field (R comparable to λ_{air}) ranges are presented in this report without the above restriction. Ionospheric effects are neglected.

Four types of dipole antennas will be examined: the vertical electric dipole (VED), vertical magnetic dipole (VMD), horizontal electric dipole (HED), and horizontal magnetic dipole (HMD). The four antennas are situated at the origin of a cylindrical coordinate system (ρ, ϕ, z) and are assumed to carry a constant current, I. The VED and HED are oriented in the z and x directions, respectively; the axes of the VMD and HMD are oriented in the z and y directions, respectively. The dipole orientations when $h = 0^+$ are shown in Fig. 1. The earth occupies the lower half-space $(z < 0)$; and the air, the upper half-space $(z > 0)$. The units employed are meter-kilogram-seconds (mks); a time factor of $e^{j\omega t}$ is assumed.

SURFACE-TO-SURFACE PROPAGATION IN THE QUASI-STATIC RANGE

THE GENERAL RANGE

For the general quasi-static range $(\rho << \lambda_{air})$ and $z = h = 0^+$, the approximation that the propagation constant in air (γ_0) is equal to zero can be utilized in the derivation of the field components. This is called the quasi-static approximation and was developed by Lien.[7] It is valid for observation distances that are very small with respect to an air wavelength (distances $< \lambda_{air}/20$) and for depths, h, much less than the observation distance.

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[7] R.H. Lien, "Radiation from a Horizontal Dipole in a Semi-Infinite Dissipative Medium," Journal of Applied Physics, vol. 24, January 1953, pp. 1-4.

Several electric and magnetic field-component expressions for the general quasi-static range have been determined previously. The E_z and H_ϕ components for the VED have been derived by Norton;[8] the E_ρ component has been derived by Wait and Campbell.[9] All electric and magnetic components for the VMD have been derived by Wait[10] and Gordon.[11] The HED E_ρ, E_ϕ, and H_z components also have been derived by Wait.[12] Martin has extended Wait's results and has evaluated the HED H_ρ, H_ϕ, and E_z components.[13] Furthermore, Wait has determined the HMD magnetic field components.[14] These expressions for the general quasi-static range are summarized in Table 1.

The reciprocity theorem (which applies to dipoles in the presence of any linear medium) states that the voltage, V_2, induced in antenna 2 by the current, I_1, of antenna 1 is the same as the voltage, V_1, induced in antenna 1 by an identical current, I_2, flowing in antenna 2. Applying the reciprocity theorem, we can then determine the remaining field components for the general quasi-static range. The HMD E_ρ and E_ϕ components can be determined from the HED H_ϕ and H_ρ components; and the HMD E_z component, from the VED H_ϕ component. Expressions for these field components also are included in Table 1. Note that $d\ell \sim \ell$ and $dA \sim A$ when ℓ and A are much smaller than λ_m and the measurement distance, ρ.

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[8] Norton, op. cit. (see footnote 2, above).

[9] J.R. Wait and L.L. Campbell, "The Fields of an Electric Dipole in a Semi-Infinite Conducting Medium," Journal of Geophysical Research, vol. 58, no. 1, 1953, pp. 21-28.

[10] J.R. Wait, "The Propagation of Electromagnetic Waves Along the Earth's Surface," Electromagnetic Waves, edited by R. Langer, University of Wisconsin Press, 1962, pp. 243-290.

[11] A.N. Gordon, "The Field Induced by an Oscillatory Magnetic Dipole Outside a Semi-Infinite Conductor," Quarterly Journal of Mechanical and Applied Mathematics, vol. 4, no. 1, 1951, pp. 105-115.

[12] Wait, op. cit. (see footnote 4, above).

[13] C.A. Martin, RCA Laboratories, Princeton, N.J., private communication, 1963.

[14] J.R. Wait, "Induction in a Horizontal Oscillating Magnetic Dipole Over a Conducting Homogeneous Earth," Transactions of the American Geophysical Union, vol. 34, no. 2, April 1953, pp. 185-188; and "The Fields of an Oscillating Magnetic Dipole Immersed in a Semi-Infinite Conducting Medium," Journal of Geophysical Research, vol. 58, no. 2, June 1953, pp. 167-178.

SUBRANGE $|\gamma_0\rho| << 1 << |\gamma_1\rho|$

For the quasi-static subrange in which $|\gamma_0\rho| << 1 << |\gamma_1\rho|$ (i.e., $\lambda_{earth} << \rho << \lambda_{air}$), which is actually the quasi-near range, the modified Bessel functions of Table 1 can be replaced by the first one or two terms of their asymptotic expansions and the $e^{-\gamma_1\rho}$ terms approach zero. The resulting field-component expressions are presented in Table 2.

For an HED antenna there is a diffused return current in the earth corresponding to the current in the horizontal wire. For this reason a horizontal wire above the earth with the ends of the wire grounded is called a "ground return antenna." The current in the horizontal wire of length ℓ and the ground return current act as an HMD (vertical loop) antenna of height $H = 1/\gamma_1$ above the earth. This can be observed easily by comparing the HED and HMD field-component equations in Table 2. That is, the magnitude of the effective area, A, of this equivalent loop antenna is

$$A = \ell H = \frac{\ell}{|\gamma_1|} = \frac{\ell\delta}{\sqrt{2}}, \tag{1}$$

where δ is the skin depth in the earth. As a matter of interest, a "ground return antenna," either buried or on the surface of a semi-infinite conducting medium, is equivalent to a rectangular one-turn loop of length ℓ and height $H = 1/\gamma_1$ as long as $\rho >> \delta$.

SUBRANGE $|\gamma_0\rho| << 1 >> |\gamma_1\rho|$

For the quasi-static subrange in which $|\gamma_0\rho| << 1 >> |\gamma_1\rho|$ (i.e., $\lambda_{earth} >> \rho << \lambda_{air}$), the exponential and modified Bessel functions in Table 1 can be replaced by the first two or three terms of their series expansions. The resulting field-component expressions are given in Table 3.

SOME VALUES OF THE FIELD-COMPONENT FUNCTIONS

Many of the equations in Table 1 contain modified Bessel functions of order zero or one and argument $\gamma_1\rho/2$. The magnitude of the function I_1K_1 versus $|\gamma_1\rho/2|$ is plotted in Fig. 2. For small values of the argument the function approaches the value of 1/2; for large values I_1K_1 is approximately equal to $1/\gamma_1\rho$. This asymptotic expansion may be employed for values of $|\gamma_1\rho/2| > 5$ The magnitude of the function W versus $|\gamma_1\rho/2|$ is plotted in Fig. 3. For

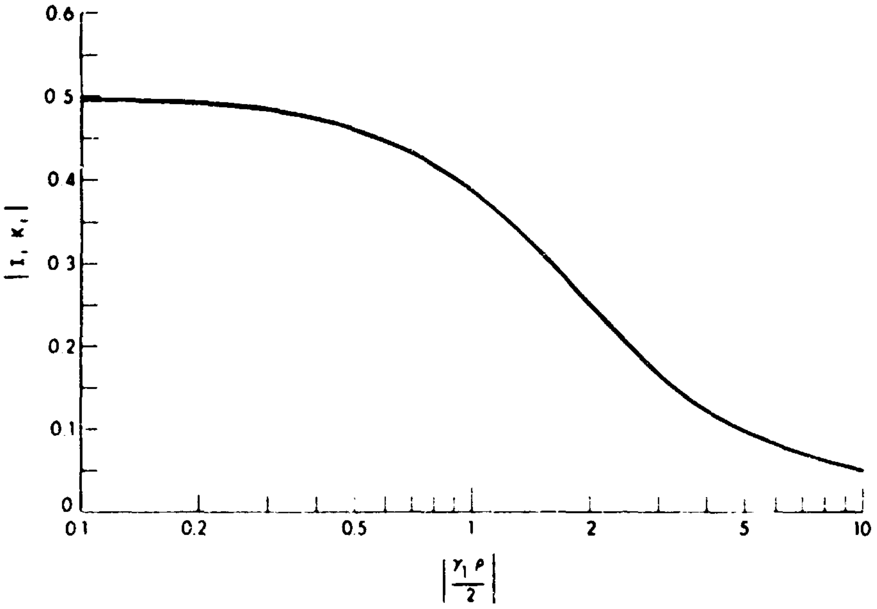

Fig. 2 - $|I_1 K_1|$ versus $|\gamma_1 \rho/2|$

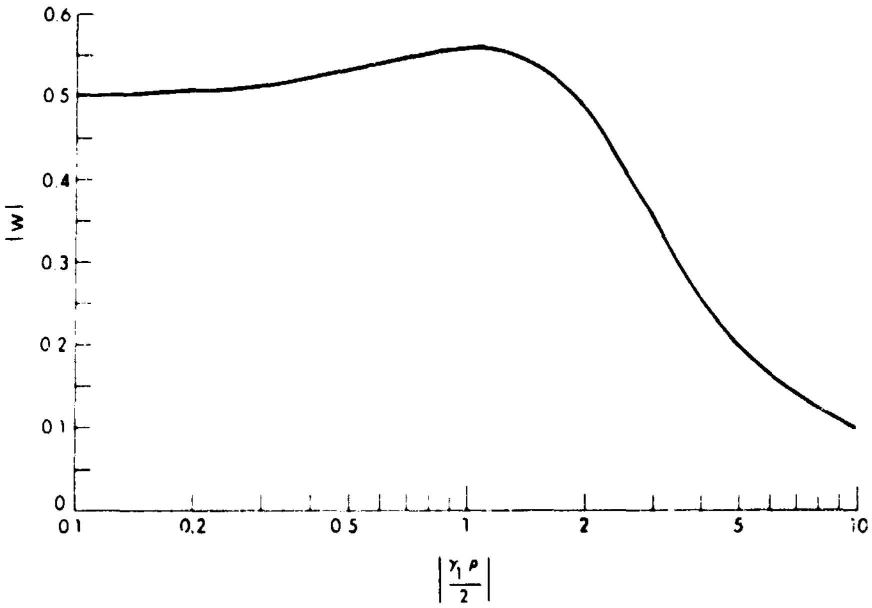

Fig. 3 - $|W|$ versus $|\gamma_1 \rho/2|$

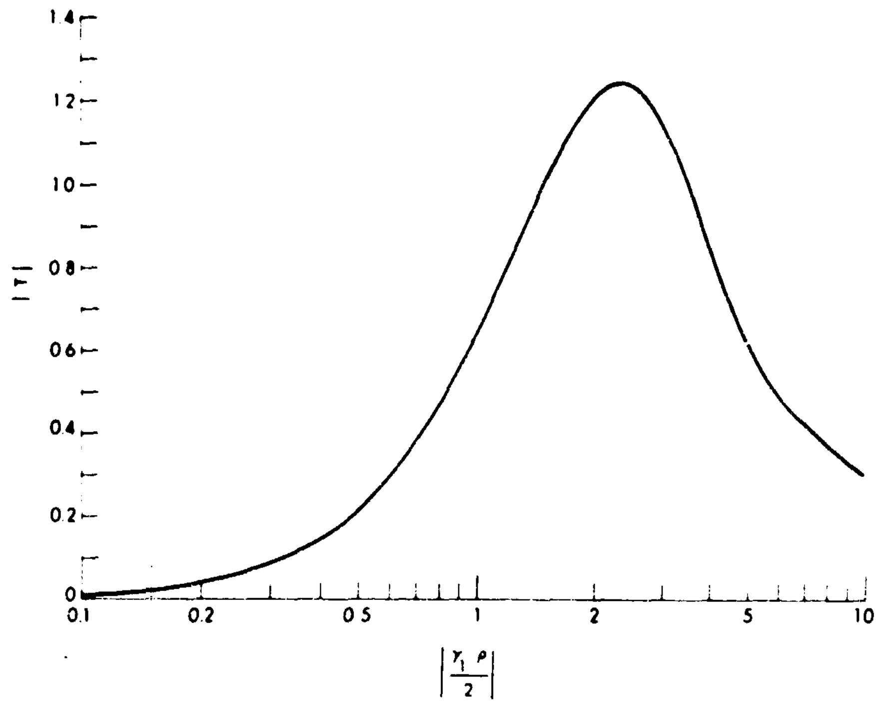

Fig. 4 - $|T|$ versus $|\gamma_1 \rho/2|$

small arguments this function also approaches 1/2; for large arguments it is approximately equal to $2/\gamma_1\rho$. The magnitude of the function T versus $|\gamma_1\rho/2|$ is plotted in Fig. 4. For small arguments T equals approximately $\gamma_1^2\rho^2/4$; for large arguments ($\rho > 7\delta$) the asymptotic expansion $T \simeq 6/\gamma_1\rho$ may be employed.

SUBSURFACE-TO-AIR PROPAGATION

THE QUASI-NEAR RANGE

For the quasi-near range (i.e., $\lambda_{earth} << R << \lambda_{air}$) with $h \leq 0^-$ and $z \geq 0^+$, the Lien quasi-static approximation applies as long as the observation distance, R, is less than $\lambda_{air}/20$ and the depth, h, of the transmitting dipole is much less than R. If the earth is a conductor and $|\gamma_1 R| >> 1$ ($R >> \delta$), then $u_1 = (\lambda^2 + \gamma_1^2)^{1/2} \sim \gamma_1$, in the exact integral expressions, since the important values of λ are of the order of γ_0 . Therefore, the exponential attenuation-with-depth term, $e^{\gamma_1 h}$, may be removed from under the integral sign (in the exact formulas for the field-component functions). By utilizing the above approximations and the integral[15]

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[15] A. Erdélyi (editor), Tables of Integral Transforms, McGraw-Hill Book Company, Inc., New York, N.Y., vol. 2, 1954, p. 9.

$$\int_0^\infty \lambda^n e^{-\lambda z} J_0(\lambda\rho)\, d\lambda = \frac{n!}{R^{n+1}} P_n\left(\frac{z}{R}\right) \tag{2}$$

(where the P_n (z/R) are the Legendre polynomials), we have calculated the VED, VMD, and HED field components for subsurface-to-air propagation in the quasi-static range. They are listed in Table 4.

The HMD field components can be obtained with the reciprocity theorem or by a synthesis of the HED field components. They can be found simply by differentiating the HED field components with respect to the depth, h. For $|\gamma_1 R| >> 1$ ($R >> \delta$) the depth factor is simply $e^{\gamma_1 h}$. Therefore, the HMD components can be obtained by replacing $d\ell$ with $\gamma_1 dA$ in the HED equations. The results of this method agree with those obtained with the somewhat different explanation presented for surface-to-surface propagation in the quasi-static subrange $|\gamma_0\rho| << 1 << \gamma_1\rho$. The HMD field components also are listed in Table 4.

An examination of the equations presented in Table 4 reveals that the E_ρ, E_ϕ, and H_z components have substantial height gain factors. The height gain factor is defined as the field strength at height z divided by the field strength at height $z = 0^+$. However, the E_z, H_ρ, and H_ϕ components are decreased in magnitude when $z > 0$. In fact, when $z/\rho = 1/\sqrt{2}$, the VED E_z component is essentially zero (to a first-order approximation). Similarly, when $z/\rho = \sqrt{2}$, the HED and HMD H_ρ components approach zero; and, when $z/\rho = 1/2$, the VMD H_ρ component is essentially zero (to a first-order approximation).

We note also that when $h = 0^-$ and $z = 0^+$, the VMD, HED, and HMD field-component expressions in Table 4 reduce to the expressions given in Table 3 (which are valid for the quasi-near range with $z = h = 0^+$). The VED components in Table 4 will be compatible also with those in Table 3 if they are multiplied by the factor γ_1^2/γ_0^2 (this is due to the shift from $h = 0^-$ to $h = 0^+$).

THE NEAR-FIELD RANGE

For the near-field range (R comparable to λ_{air}) with $h \leq 0^-$ and $z \geq 0^+$, the assumptions that the earth is a conductor ($\sigma_1 >> \omega\epsilon_1$), that $\gamma_1 R >> 1$ ($R >> \delta$), and that $R >> h$ still apply. The restriction that $(\gamma_0^2/\gamma_1)\rho << 1$ has been assumed also. This limits the range to small "numerical distances,"[16] although $\gamma_0\rho$ may exceed unity. Also, the radiation field ($\gamma_0\rho >> 1$) height gain factor for vertical polarization,

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[16] Norton, op. cit. (see footnote 2, above).

$$G_v = 1 + (\gamma_0^2 / \gamma_1) z , \tag{3}$$

is approximately equal to 1. The VED, VMD, and HED field components for this range were evaluated on the basis of the above approximations and with Sommerfeld's integral:[17]

$$\int_0^\infty \frac{e^{-u_0 z} J_0 (\lambda \rho) \lambda \, d\lambda}{u_0} = \frac{e^{-\gamma_0 R}}{R} . \tag{4}$$

The components are listed in Table 5. The HMD field components (see Table 5) were obtained from the HED field components by setting $d\ell = \gamma_1 \, dA$ (as was done for the quasi-near range).

When $|\gamma_0 R| << 1$, the near-field components (Table 5) reduce to the quasi-static field components (Table 4). If the VED antenna is placed at the earth's surface ($h = 0^+$), the field components will be identical with those previously derived by Norton.[18] When $\rho >> z$, the near-field components reduce to well-known expressions; these are listed in Table 6. For example, the HED equations are identical with those previously derived by Wait[19] except for the following differences:

a. Wait assumed that $z = 0$ when he derived the E_ρ and E_ϕ components.

b. Wait's height gain factor for the E_z component $[1 + (\gamma_0^2/\gamma_1) z]$ is negligible for the near-field range (ρ comparable to λ_{air}); therefore, it was not included in Table 6.

When $|\gamma_0 \rho| << 1$, the horizontally polarized components (E_ϕ, H_ρ, and H_z) also are identical with Wait's. Therefore, the restriction that $|(\gamma_0^2/\gamma_1) \rho| << 1$ is not required for these components.

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[17] Sommerfeld, op. cit. (see footnote 1, above); and Erdélyi, op. cit. (see footnote 14, above).

[18] Norton, op. cit. (see footnote 2, above).

[19] Wait, op. cit. (see footnote 4, above).

SUMMARY

The electric and magnetic field components produced by vertical and horizontal dipoles (both electric and magnetic types) were derived and presented for:

a. Surface-to-surface propagation in the quasi-static range,

b. Subsurface-to-air propagation in the quasi-near range, and

c. Subsurface-to-air propagation in the near-field range.

When $|\gamma_1\rho| >> 1$ or $|\gamma_1\rho| << 1$, the surface-to-surface propagation equations reduce to previously derived expressions, as do the subsurface-to-air equations when $\rho >> z$. Also, when $|\gamma_0 R| << 1$, the near-field equations reduce to the quasi-near field formulas. For additional information on the derivation of the field components, see USL Reports Nos. 698, 701, 719, 720, and 729.[20]

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[20] P.R. Bannister, The Quasi-Static Fields of a Horizontal Magnetic Dipole, USL Report No. 698, 1 November 1965; P.R. Bannister, The Quasi-Static Fields of Dipole Antennas, Part I, USL Report No. 701, 3 January 1966; P.R. Bannister and W.C. Hart, The Quasi-Static Fields of Dipole Antennas, Parts II and III, USL Reports Nos. 719 and 720, 8 February 1966 and 23 February 1966; P.R. Bannister and W.C. Hart, The Near Fields of Subsurface Electric Dipole Antennas, USL Report No. 728, 4 March 1966; and W.C. Hart and P.R. Bannister, The Near Fields of Subsurface Magnetic Dipole Antennas, USL Report No. 729, 7 March 1966.

Table 1

SURFACE-TO-SURFACE PROPAGATION FORMULAS FOR THE GENERAL QUASI-STATIC RANGE

Dipole Type	E_ρ	E_ϕ	E_z
VED	$-\frac{i\mu_o \omega I d\ell}{2\pi\rho} I_1\left(\frac{\gamma_1\rho}{2}\right) K_1\left(\frac{\gamma_1\rho}{2}\right)$	0	$-\frac{I d\ell}{2\pi i \omega \epsilon_o \rho^3}$
VMD	0	$-\frac{i\mu_o \omega IdA}{2\pi\gamma_1^2\rho^4}\left[3-(3+3\gamma_1\rho+\gamma_1^2\rho^2)\, e^{-\gamma_1\rho}\right]$	0
HED	$\frac{I d\ell}{2\pi\sigma_1\rho^3}\,[1+(1+\gamma_1\rho)\, e^{-\gamma_1\rho}]\cos\phi$	$\frac{I d\ell}{2\pi\sigma_1\rho^3}\,[2-(1+\gamma_1\rho)\, e^{-\gamma_1\rho}]\sin\phi$	$\frac{i\mu_o \omega I d\ell}{2\pi\rho} I_1 K_1 \cos\phi$
HMD	$\frac{i\omega\mu_o IdA}{2\pi\rho^2} I_1\left(\frac{\gamma_1\rho}{2}\right) K_1\left(\frac{\gamma_1\rho}{2}\right)\cos\phi$	$\frac{i\omega\mu_o IdA}{2\pi\rho^2}\sin\phi\,[3 I_1 K_1 - \frac{\gamma_1\rho}{2}(I_o K_1 - I_1 K_o)]$	$\frac{i\omega\mu_o IdA}{2\pi\rho^2}\cos\phi$

Table 1 (Cont'd)

SURFACE-TO-SURFACE PROPAGATION FORMULAS FOR THE GENERAL QUASI-STATIC RANGE

Dipole Type	H_ρ	H_ϕ	H_z
VED	0	$\frac{Id\ell}{2\pi\rho^2}$	0
VMD	$-\frac{IdA}{4\pi\rho^3}\{16I_1K_1+\gamma_1^2\rho^2[I_1K_1-I_oK_o]$ $+4\gamma_1\rho[I_1K_o-i_oK_1]\}$	0	$-\frac{IdA}{2\pi\gamma_1^2\rho^5}\Big[9$ $-(9+9\gamma_1\rho+4\gamma_1^2\rho^2+\gamma_1^3\rho^3)e^{-\gamma_1\rho}\Big]$
HED	$\frac{Id\ell\sin\phi}{2\pi\rho^2}\{3I_1K_1$ $-\frac{\gamma_1\rho}{2}(I_oK_1-I_1K_o)\}$	$-\frac{Id\ell\cos\phi}{2\pi\rho^2}I_1K_1$	$\frac{Id\ell}{2\pi\gamma_1^2\rho^4}\{3$ $-(3+3\gamma_1\rho+\gamma_1^2\rho^2)e^{-\gamma_1\rho}\}\sin\phi$
HMD	$\frac{IdA}{2\pi\gamma_1^2}\frac{\sin\phi}{\rho^5}[(\gamma_1^3\rho^3+5\gamma_1^2\rho^2$ $+12\gamma_1\rho+12)e^{-\gamma_1\rho}-12+2\gamma_1^2\rho^2]$	$-\frac{IdA\cos\phi}{2\pi\gamma_1^2\rho^5}[(\gamma_1^2\rho^2$ $+3\gamma_1\rho+3)e^{-\gamma_1\rho}+\gamma_1^2\rho^2-3]$	$\frac{IdA\sin\phi}{4\pi\rho^3}\{\gamma_1^2\rho^2(I_1K_1-I_oK_o)$ $+4\gamma_1\rho(I_1K_o-I_oK_1)+16I_1K_1\}$

Table 2

SURFACE-TO-SURFACE PROPAGATION FORMULAS FOR THE QUASI-STATIC SUBRANGE $|\gamma_o \rho| << 1 << |\gamma_1 \rho|$

Dipole Type	E_ρ	E_ϕ	E_z	H_ρ	H_ϕ	H_z
VED	$-\frac{i\mu_o \omega I d\ell}{2\pi\gamma_1\rho^2}$	0	$-\frac{I d\ell}{2\pi i\omega\epsilon_o\rho^3}$	0	$\frac{I d\ell}{2\pi\rho^2}$	0
VMD	0	$-\frac{3IdA}{2\pi\sigma_1\rho^4}$	0	$-\frac{3IdA}{2\pi\gamma_1\rho^4}$	0	$-\frac{9IdA}{2\pi\gamma_1^2\rho^5}$
HED	$\frac{I d\ell}{2\pi\sigma_1\rho^3}\cos\phi$	$\frac{I d\ell}{\pi\sigma_1\rho^3}\sin\phi$	$\frac{i\mu_o\omega I d\ell\cos\phi}{2\pi\gamma_1\rho^2}$	$\frac{I d\ell\sin\phi}{\pi\gamma_1\rho^3}$	$-\frac{I d\ell\cos\phi}{2\pi\gamma_1\rho^3}$	$\frac{3I d\ell}{2\pi\gamma_1^2\rho^4}\sin\phi$
HMD	$\frac{i\omega\mu_o IdA}{2\pi\gamma_1\rho^3}\cos\phi$	$\frac{i\omega\mu_o IdA}{\pi\gamma_1\rho^3}\sin\phi$	$\frac{i\omega\mu_o IdA}{2\pi\rho^2}\cos\phi$	$\frac{IdA\sin\phi}{\pi\rho^3}$	$-\frac{IdA\cos\phi}{2\pi\rho^3}$	$\frac{3IdA\sin\phi}{2\pi\gamma_1\rho^4}$

Table 3

SURFACE-TO-SURFACE PROPAGATION FORMULAS FOR THE QUASI-STATIC SUBRANGE $|\gamma_o \rho| << 1 >> |\gamma_1 \rho|$

Dipole Type	E_ρ	E_ϕ	E_z	H_ρ	H_ϕ	H_z
VED	$-\frac{i\mu_o \omega I d\ell}{4\pi\rho}$	0	$-\frac{I d\ell}{2\pi i \omega \epsilon_o \rho^3}$	0	$\frac{I d\ell}{2\pi\rho^2}$	0
VMD	0	$-\frac{IdAi\mu_o\omega}{4\pi\rho^3}$	0	$-\frac{IdA\gamma_1^2}{16\pi\rho}$	0	$-\frac{IdA}{4\pi\rho^3}$
HED	$\frac{I d\ell}{\pi\sigma_1\rho^3}\cos\phi$	$\frac{I d\ell}{2\pi\sigma_1\rho^3}\sin\phi$	$\frac{i\mu_o\omega I d\ell \cos\phi}{4\pi\rho}$	$\frac{I d\ell}{4\pi\rho^2}\sin\phi$	$-\frac{I d\ell \cos\phi}{4\pi\rho^2}$	$\frac{I d\ell}{4\pi\rho^2}\sin\phi$
HMD	$\frac{i\omega\mu_o IdA}{4\pi\rho^2}\cos\phi$	$\frac{i\omega\mu_o IdA \sin\phi}{4\pi\rho^2}$	$\frac{i\omega\mu_o IdA\cos\phi}{2\pi\rho^2}$	$\frac{IdA}{2\pi\rho^3}\sin\phi$	$-\frac{IdA}{4\pi\rho^3}\cos\phi$	$\frac{IdA\gamma_1^2\sin\phi}{16\pi\rho}$

Table 4
SUBSURFACE-TO-AIR PROPAGATION FORMULAS FOR THE QUASI-NEAR RANGE

Dipole Type	E_ρ	E_ϕ	E_z
VED	$\frac{I d\ell\, e^{\gamma_1 h}}{2\pi\sigma_1}\,\frac{\rho}{R^5}\left[3z - \frac{\gamma_0^2}{\gamma_1} R^2\right]$	0	$-\frac{I d\ell}{2\pi\sigma_1}\,\frac{e^{\gamma_1 h}}{R^3}\left(1 - \frac{3z^2}{R^2}\right)$
VMD	0	$-\frac{3 I dA\, e^{\gamma_1 h}}{2\pi\sigma_1}\,\frac{\rho}{R^5}\left(1 + \gamma_1 z - \frac{5z^2}{R^2}\right)$	0
HED	$\frac{I d\ell \cos\phi}{2\pi\sigma_1}\,\frac{e^{\gamma_1 h}}{R^3}\left[1 - \gamma_1 z\right]$	$\frac{I d\ell \sin\phi}{2\pi\sigma_1}\,\frac{e^{\gamma_1 h}}{R^3}\left(2 + \gamma_1 z - \frac{3z^2}{R^2}\right)$	$\frac{i\mu_0 \omega I d\ell \cos\phi}{2\pi\gamma_1}\,\frac{\rho e^{\gamma_1 h}}{R^3}$
HMD	$\frac{i\mu_0 \omega I dA \cos\phi\, e^{\gamma_1 h}}{2\pi\gamma_1 R^3}\left(1 - \gamma_1 z\right)$	$\frac{i\mu_0 \omega I dA \sin\phi\, e^{\gamma_1 h}}{2\pi\gamma_1 R^3}\left(2 + \gamma_1 z - \frac{3z^2}{R^2}\right)$	$\frac{i\mu_0 \omega I dA \cos\phi\, \rho e^{\gamma_1 h}}{2\pi R^3}$

Table 4 (Cont'd)

SUBSURFACE-TO-AIR PROPAGATION FORMULAS FOR THE QUASI-NEAR RANGE

Dipole Type	H_ρ	H_ϕ	H_z
VED	0	$\frac{I d\ell}{2\pi} \frac{\gamma_0^2}{\gamma_1^3} e^{\gamma_1 h} \frac{\rho}{R^3}$	0
VMD	$-\frac{3IdA\, e^{\gamma_1 h}}{2\pi\gamma_1} \frac{\rho}{R^5}\left(1-\frac{5z^2}{R^2}\right)$	0	$-\frac{3IdA}{2\pi\gamma_1^2} \frac{e^{\gamma_1 h}}{R^5}\left[3(1+\gamma_1 z) - \frac{5z^2}{R^2}(6+\gamma_1 z) + \frac{35z^4}{R^4}\right]$
HED	$\frac{I d\ell \sin\phi}{2\pi\gamma_1} \frac{e^{\gamma_1 h}}{R^3}\left[2 - \frac{3z^2}{R^2}\right]$	$-\frac{I d\ell \cos\phi}{2\pi\gamma_1} \frac{e^{\gamma_1 h}}{R^3}$	$\frac{3I d\ell \sin\phi}{2\pi\gamma_1^2} \frac{\rho e^{\gamma_1 h}}{R^5}\left[1+\gamma_1 z - \frac{5z^2}{R^2}\right]$
HMD	$\frac{IdA \sin\phi\, e^{\gamma_1 h}}{2\pi R^3}\left[2 - \frac{3z^2}{R^2}\right]$	$-\frac{IdA \cos\phi\, e^{\gamma_1 h}}{2\pi R^3}$	$\frac{3IdA \sin\phi\, \rho e^{\gamma_1 h}}{2\pi\gamma_1 R^5}\left(1+\gamma_1 z - \frac{5z^2}{R^2}\right)$

Table 5

SUBSURFACE-TO-AIR PROPAGATION FORMULAS FOR THE NEAR-FIELD RANGE

Dipole Type	E_ρ	E_ϕ	E_z
VED	$\frac{I d\ell\, e^{\gamma_1 h}}{2\pi\sigma_1}\,\frac{\rho e^{-\gamma_0 R}}{R^5}\left[z\left(3+3\gamma_0 R + \gamma_0^2 R^2\right) - \frac{\gamma_0^2}{\gamma_1} R^2 (1+\gamma_0 R)\right]$	0	$-\frac{I d\ell\, e^{\gamma_1 h}}{2\pi\sigma_1}\,\frac{e^{-\gamma_0 R}}{R^3}\left[1+\gamma_0 R+\gamma_0^2\rho^2 - \frac{3z^2}{R^2}(1+\gamma_0 R)\right]$
VMD	0	$-\frac{I dA\, e^{\gamma_1 h}}{2\pi\sigma_1}\,\frac{\rho e^{-\gamma_0 R}}{R^5}\left[\left(3+3\gamma_1 z-\frac{15z^2}{R^2}\right)(1+\gamma_0 R)+\left(1+\gamma_1 z-\frac{6z^2}{R^2}\right)(\gamma_0 R)^2\right]$	0
HED	$\frac{I d\ell \cos\phi\, e^{\gamma_1 h}}{2\pi\sigma_1}\,\frac{e^{-\gamma_0 R}}{R^3}\left[\left(1-\gamma_1 z\right)(1+\gamma_0 R)+\gamma_0^2 R^2\right]$	$\frac{I d\ell \sin\phi\, e^{\gamma_1 h}}{2\pi\sigma_1}\,\frac{e^{-\gamma_0 R}}{R^3}\left[\left(2+\gamma_1 z-\frac{3z^2}{R^2}\right)(1+\gamma_0 R)\right]$	$\frac{i\mu_0\omega I d\ell \cos\phi\, e^{\gamma_1 h}}{2\pi\gamma_1}\,\frac{\rho e^{-\gamma_0 R}}{R^3}(1+\gamma_0 R)$
HMD	$\frac{i\mu_0\omega I dA \cos\phi\, e^{\gamma_1 h}}{2\pi\gamma_1}\,\frac{e^{-\gamma_0 R}}{R^3}\left[\left(1-\gamma_1 z\right)(1+\gamma_0 R)+\gamma_0^2 R^2\right]$	$\frac{i\mu_0\omega I dA \sin\phi\, e^{\gamma_1 h}}{2\pi\gamma_1}\,\frac{e^{-\gamma_0 R}}{R^3}\left[\left(2+\gamma_1 z-\frac{3z^2}{R^2}\right)(1+\gamma_0 R)\right]$	$\frac{i\mu_0\omega I dA \cos\phi\, e^{\gamma_1 h}}{2\pi}\,\frac{e^{-\gamma_0 R}}{R^3}\,\rho(1+\gamma_0 R)$

Table 5 (Cont'd)

SUBSURFACE-TO-AIR PROPAGATION FORMULAS FOR THE NEAR-FIELD RANGE

Dipole Type	H_ρ	H_ϕ	H_z
VED	0	$\frac{Id\ell}{2\pi} \frac{\gamma_o^2}{\gamma_1^2} e^{\gamma_1 h} \frac{\rho}{R^3} (1 + \gamma_o R) e^{-\gamma_o R}$	0
VMD	$-\frac{IdA\, e^{\gamma_1 h}}{2\pi\gamma_1} \frac{\rho e^{-\gamma_o R}}{R^5}$ $\left[\left(3 - \frac{15z^2}{R^2}\right)(1 + \gamma_o R)\right.$ $\left. + \left(1 - \frac{6z^2}{R^2}\right)(\gamma_o R)^2 - \frac{z^2}{R^2}(\gamma_o R)^3\right]$	0	$-\frac{IdA\, e^{\gamma_1 h}}{2\pi\gamma_1^2} \frac{e^{-\gamma_o R}}{R^5} \left\{\left[9(1 + \gamma_1 z)\right.\right.$ $\left. - \frac{15z^2}{R^2}(6 + \gamma_1 z) + \frac{105z^4}{R^4}\right](1 + \gamma_o R)$ $+ \left[4(1 + \gamma_1 z) - \frac{6z^2}{R^2}\left(\frac{39}{6} + \gamma_1 z\right) + \frac{45z^4}{R^4}\right](\gamma_o R)^2$ $\left. + \left[(1 + \gamma_1 z) - \frac{z^2}{R^2}(9 + \gamma_1 z) + \frac{10z^4}{R^4}\right](\gamma_o R)^3\right\}$
HED	$\frac{Id\ell \sin\phi\, e^{\gamma_1 h}}{2\pi\gamma_1} \frac{e^{-\gamma_o R}}{R^3}$ $\left[\left(2 - \frac{3z^2}{R^2}\right)(1 + \gamma_o R) - \gamma_o^2 z^2\right]$	$-\frac{Id\ell \cos\phi\, e^{\gamma_1 h}}{2\pi\gamma_1} \frac{e^{-\gamma_o R}}{R^3}$ $\left[1 + \gamma_o R + \gamma_o^2 R^2\right]$	$\frac{Id\ell \sin\phi\, e^{\gamma_1 h}}{2\pi\gamma_1^2} \frac{e^{-\gamma_o R}}{R^4} \left(\frac{\rho}{R}\right) \left[\left(3 + 3\gamma_1 z\right.\right.$ $\left.\left. - \frac{15z^2}{R^2}\right)(1 + \gamma_o R) + \left(1 + \gamma_1 z - \frac{6z^2}{R^2}\right)(\gamma_o R)^2\right]$
HMD	$\frac{IdA \sin\phi\, e^{\gamma_1 h}}{2\pi} \frac{e^{-\gamma_o R}}{R^3}$ $\left\{\left(2 - \frac{3z^2}{R^2}\right)(1 + \gamma_o R) - \gamma_o^2 z^2\right\}$	$-\frac{IdA \cos\phi\, e^{\gamma_1 h}}{2\pi} \frac{e^{-\gamma_o R}}{R^3}$ $\left(1 + \gamma_o R + \gamma_o^2 R^2\right)$	$\frac{IdA \sin\phi\, \rho e^{\gamma_1 h}}{2\pi\gamma_1} \frac{e^{-\gamma_o R}}{R^5}$ $\left[(3 + 3\gamma_1 z - 15z^2/R^2)(1 + \gamma_o R)\right.$ $\left. + (1 + \gamma_1 z - 6z^2/R^2)(\gamma_o R)^2\right]$

Table 6

SUBSURFACE-TO-AIR PROPAGATION FORMULAS FOR THE NEAR-FIELD RANGE WITH $\rho >> z$

Dipole Type	E_ρ	E_ϕ	E_z
VED	$-\frac{I\,d\ell}{2\pi\sigma_1}\frac{e^{\gamma_1 h}}{\rho^4}\left[\left(\frac{\gamma_o^2}{\gamma_1}\right)(1+\gamma_o\rho)\rho^2 - z(3+3\gamma_o\rho+\gamma_o^2\rho^2)\right]e^{-\gamma_o\rho}$	0	$-\frac{I\,d\ell}{2\pi\sigma_1}e^{\gamma_1 h}\frac{e^{-\gamma_o\rho}}{\rho^3}(1+\gamma_o\rho+\gamma_o^2\rho^2)$
VMD	0	$-\frac{I\,dA\,e^{\gamma_1 h}}{2\pi\sigma_1}\frac{e^{-\gamma_o\rho}}{\rho^4}$ $(3+3\gamma_o\rho+\gamma_o^2\rho^2)(1+\gamma_1 z)$	0
HED	$\frac{I\,d\ell\cos\phi\,e^{\gamma_1 h}}{2\pi\sigma_1}\frac{e^{-\gamma_o\rho}}{\rho^3}$ $[(1-\gamma_1 z)(1+\gamma_o\rho)+\gamma_o^2\rho^2]$	$\frac{I\,d\ell\sin\phi\,e^{\gamma_1 h}}{2\pi\sigma_1}\frac{e^{-\gamma_o\rho}}{\rho^3}$ $[(2+\gamma_1 z)(1+\gamma_o\rho)]$	$\frac{i\mu_o\omega I\,d\ell\cos\phi\,e^{\gamma_1 h}}{2\pi\gamma_1}\frac{e^{-\gamma_o\rho}}{\rho^2}[1+\gamma_o\rho]$
HMD	$\frac{i\mu_o\omega I\,dA\cos\phi\,e^{\gamma_1 h}}{2\pi\gamma_1}\frac{e^{-\gamma_o\rho}}{\rho^3}$ $[(1-\gamma_1 z)(1+\gamma_o\rho)+\gamma_o^2\rho^2]$	$\frac{i\mu_o\omega I\,dA\sin\phi\,e^{\gamma_1 h}}{2\pi\gamma_1}\frac{e^{-\gamma_o\rho}}{\rho^3}$ $[(2+\gamma_1 z)(1+\gamma_o\rho)]$	$\frac{i\mu_o\omega I\,dA\cos\phi\,e^{\gamma_1 h}}{2\pi}\frac{e^{-\gamma_o\rho}}{\rho^2}(1+\gamma_o\rho)$

Table 6 (Cont'd)

SUBSURFACE-TO-AIR PROPAGATION FORMULAS FOR THE NEAR-FIELD RANGE WITH $\rho >> z$

Dipole Type	H_ρ	H_ϕ	H_z
VED	0	$\frac{I d\ell}{2\pi\rho^2} \frac{\gamma_o^2}{\gamma_1^2} (1 + \gamma_o \rho) e^{\gamma_1 h} e^{-\gamma_o \rho}$	0
VMD	$-\frac{I dA\, e^{\gamma_1 h}}{2\pi\gamma_1} \frac{e^{-\gamma_o \rho}}{\rho^4} (3 + 3\gamma_o \rho + \gamma_o^2 \rho^2)$	0	$-\frac{I dA\, e^{\gamma_1 h}}{2\pi\gamma_1^2} \frac{e^{-\gamma_o \rho}}{\rho^3}$ $(9 + 9\gamma_o \rho + 4\gamma_o^2 \rho^2 + \gamma_o^3 \rho^3)(1 + \gamma_1 z)$
HED	$\frac{I d\ell \sin\phi\, e^{\gamma_1 h}}{\pi\gamma_1} \frac{e^{-\gamma_o \rho}}{\rho^3} [1 + \gamma_o \rho]$	$-\frac{I d\ell \cos\phi\, e^{\gamma_1 h}}{2\pi\gamma_1} \frac{e^{-\gamma_o \rho}}{\rho^3}$ $[1 + \gamma_o \rho + \gamma_o^2 \rho^2]$	$\frac{I d\ell \sin\phi\, e^{\gamma_1 h}}{2\pi\gamma_1^2} \frac{e^{-\gamma_o \rho}}{\rho^4}$ $[(1 + \gamma_1 z)(3 + 3\gamma_o \rho + \gamma_o^2 \rho^2)]$
HMD	$\frac{I dA \sin\phi\, e^{\gamma_1 h}}{2\pi} \frac{e^{-\gamma_o \rho}}{\rho^3} [2(1 + \gamma_o \rho)]$	$-\frac{I dA \cos\phi\, e^{\gamma_1 h}}{2\pi} \frac{e^{-\gamma_o \rho}}{\rho^3}$ $[1 + \gamma_o \rho + \gamma_o^2 \rho^2]$	$\frac{I dA \sin\phi\, e^{\gamma_1 h}}{2\pi\gamma_1} \frac{e^{-\gamma_o \rho}}{\rho^4}$ $[(3 + 3\gamma_o \rho + \gamma_o^2 \rho^2)(1 + \gamma_1 z)]$

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13. ABSTRACT

The electric and magnetic field components produced by vertical and horizontal dipoles (both electric and magnetic) are derived and presented for the quasi-static, quasi-near, and near-field ranges. The depth, h, of the transmitting dipole is less than or equal to zero; the height, z, of the receiving antenna above the plane, conducting, homogeneous earth varies from zero to some height, z, that is much less than the ionospheric reflecting height (ionospheric effects are neglected). The horizontal separation, ρ, between the transmitting and receiving antennas is comparable to the receiving antenna height, z. The derivations are based upon the quasi-static and near-field approximations to the vector potentials for the vertical and horizontal dipoles and upon application of the reciprocity theorem. The surface-to-surface propagation equations reduce to well-known expressions when $|\gamma_1 \rho| >> 1$ and $|\gamma_1 \rho| << 1$, as do the subsurface-to-air equations when $\rho >> z$.

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