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New Formulas That Extend Norton's Farfield Elementary Dipole Equations to the Quasi-Nearfield Range

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Preface

This report was prepared under NUSC Project No. A59007, "ELF Propagation RDT&E" (U), Principal Investigator, P. R. Bannister (Code 3411), Navy Program Element No. 11401N and Project No. X0792-SB, Naval Electronic Systems Command Communications Systems Project Office, D. Dyson (Code PME 110), Program Manager ELF Communications, Dr. B. Kruger (Code PME 110-XI).

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) → New formulas for the electric and magnetic fields produced by the four elementary dipole antennas have been derived for the air-to-air, subsurface-to air, air-to-subsurface, and surface-to-surface propagation cases. These formulas are of rather simple form and reduce to previously derived results when either (1) the measurement distance is much less than a free-space wavelength, (2) the Sommerfeld numerical distance is small, or (3) the measurement distance is much greater than a free-space wavelength. ~~They~~ These are valid at any frequency and at any range beyond a certain minimum distance → over		

20. (Cont'd)

for the flat-earth case. The main restrictions on these formulas are (1) $|n^2| \geq 10$, (2) the measurement distance is ≥ 10 skin depths from the source, and (3) the measurement distance is ≥ 5 times the depth of burial of the transmitting or receiving point sources.

In terms of computer time, these new formulas can be evaluated in fractions of a minute compared with hours for the complete numerical evaluation of the exact Sommerfeld integrals.

These formulas are intended to supplement the author's recently derived subsurface-to-subsurface, subsurface-to-surface, surface-to-subsurface, and surface-to-surface propagation formulas.

TABLE OF CONTENTS

	Page
LIST OF TABLES	ii
GLOSSARY OF SYMBOLS	iii
INTRODUCTION	1
AIR-TO-AIR PROPAGATION DERIVATION PROCEDURE	2
SUBSURFACE-TO-AIR PROPAGATION	9
AIR-TO-SUBSURFACE PROPAGATION	10
SURFACE-TO-SURFACE PROPAGATION	10
DISCUSSION	10
CONCLUSIONS	12
REFERENCES	43



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Justification	
By _____	
Distribution/ _____	
Availability Codes	
Dist	Avail and/or Special
A-1	

LIST OF TABLES

Table	Page
1 Electric-Field Air-to-Air Propagation Formulas ($ n^2 \geq 10$, $R_1 \geq 10\delta$)	15
2 Magnetic-Field Air-to-Air Propagation Formulas ($ n^2 \geq 10$, $R_1 \geq 10\delta$)	17
3 Electric-Field Air-to-Air Propagation Formulas for the Farfield Case ($ n^2 \geq 10$, $ \gamma_0 R_1 \gg 1$)	21
4 Magnetic-Field Air-to-Air Propagation Formulas for the Farfield Case ($ n^2 \geq 10$, $ \gamma_0 R \gg 1$)	23
5 Electric-Field Subsurface-to-Air Propagation Formulas ($ n^2 \geq 10$, $R \geq 10\delta$, $R \geq 5h$)	25
6 Magnetic-Field Subsurface-to-Air Propagation Formulas ($ n^2 \geq 10$, $R \geq 10\delta$, $R \geq 5h$)	27
7 Subsurface-to-Air Propagation Formulas When $\rho \gg z$ ($ n^2 \geq 10$, $\rho \geq 10\delta$, $\rho \geq 5h$)	29
8 Subsurface-to-Air Propagation Formulas When $z \gg \rho$ ($ n^2 \geq 10$, $z \geq 10\delta$, $z \geq 5h$)	31
9 Electric-Field Air-to-Subsurface Propagation Formulas ($ n^2 \geq 10$, $D \geq 10\delta$, $D \geq 5z$)	33
10 Magnetic-Field Air-to-Subsurface Propagation Formulas ($ n^2 \geq 10$, $D \geq 10\delta$, $D \geq 5z$)	35
11 Air-to-Subsurface Propagation Formulas When $\rho \gg h$ ($ n^2 \geq 10$, $\rho \geq 10\delta$, $\rho \geq 5z$)	37
12 Air-to-Subsurface Propagation Formulas When $h \gg \rho$ ($ n^2 \geq 10$, $h \geq 10\delta$, $h \geq 5z$)	39
13 Surface-to-Surface Propagation Formulas for $\rho \geq 10\delta$ ($ n^2 \geq 10$, $z = h = 0^+$)	41

GLOSSARY OF SYMBOLS

A	$\frac{\sin \psi_1 + \Delta_1 F(w)}{\sin \psi_1 + \Delta_1} = \left(\frac{1 + \Gamma_{11}}{2} \right) + \left(\frac{1 - \Gamma_{11}}{2} \right) F(w)$
B	$\frac{\sin^2 \psi_1 - \Delta_1^2 F(w)}{\sin \psi_1 + \Delta_1} = \left(\frac{1 + \Gamma_{11}}{2} \right) \sin \psi_1 - \left(\frac{1 - \Gamma_{11}}{2} \right) \Delta_1 F(w) = \sin \psi_1 - \Delta_1 A$
D	$(\rho^2 + h^2)^{1/2}$ (meters)
E_ρ	Horizontal electric-field component in the ρ direction (volts/meter)
E_ϕ	Horizontal electric-field component in the ϕ direction (volts/meter)
E_z	Vertical electric-field component (volts/meter)
F	$F(w)$ or $F(w_0)$, Sommerfeld surface-wave attenuation factors
h	Height ($h > 0$) of transmitting antenna with respect to earth's surface (meters)
HED	Horizontal electric dipole
HMD	Horizontal magnetic dipole
H_ρ	Horizontal magnetic-field component in the ρ direction (amperes/meter)
H_ϕ	Horizontal magnetic-field component in the ϕ direction (amperes/meter)
H_z	Vertical magnetic-field component (amperes/meter)
I	Current (amperes)
$J_0(\lambda\rho)$	Bessel function of the first kind, order zero, with argument $\lambda\rho$
m	Magnetic-dipole moment (ampere-meters ²)
n	γ_1/γ_0 , index of refraction
n_0	120π , free space impedance (ohms)
n_1	$n(1 - \Delta^2 \cos^2 \psi_1)^{1/2}$
p	Electric-current moment (ampere-meters)
P	Wait integral
R	$(\rho^2 + z^2)^{1/2}$ (meters)

R_0	$[\rho^2 + (z - h)^2]^{1/2}$ (meters)
R_1	$[\rho^2 + (z + h)^2]^{1/2}$ (meters)
S_1	$\text{Exp}(-\gamma_0 R_1)/R_1$, Sommerfeld integral
t	Time (seconds)
u_0	$(\lambda^2 + \gamma_0^2)^{1/2}$ (meters ⁻¹) (air)
u_1	$(\lambda^2 + \gamma_1^2)^{1/2}$ (meters ⁻¹) (earth)
VED	Vertical electric dipole
VMD	Vertical magnetic dipole
w	w_0 or w' , Sommerfeld numerical distances
X	$1 - \Delta^2 \cos^2 \psi_1$
z	Height ($z \geq 0$) of receiving antenna with respect to earth's surface (meters)
Γ_{11}	$\frac{\sin \psi_1 - \Delta_1}{\sin \psi_1 + \Delta_1}$, Fresnel reflection coefficient for vertical polarization
$\Gamma_{\perp}$	$\frac{\sin \psi_1 - n_1}{\sin \psi_1 + n_1}$, Fresnel reflection coefficient for horizontal polarization
γ_0	$(-\omega^2 \mu_0 \epsilon_0)^{1/2} = i2\pi/\lambda_0$, upper half-space (air) propagation constant (meters ⁻¹)
γ_1	$(i\omega \mu_1 \sigma_1 - \omega^2 \mu_1 \epsilon_1)^{1/2}$, lower half-space (earth) propagation constant (meters ⁻¹)
Δ	$\gamma_0/\gamma_1 = 1/n$
Δ_1	$\Delta(1 - \Delta^2 \cos^2 \psi_1)^{1/2}$
δ	$\left(\frac{2}{\omega \mu_0 \sigma_1}\right)^{1/2} \left[\left(\frac{\omega^2 \epsilon_1^2}{\sigma_1^2} + 1\right)^{1/2} - \frac{\omega \epsilon_1}{\sigma_1} \right]^{-1/2}$, skin depth in the water or earth (meters)
ϵ_0	$\approx 10^{-9}/36\pi$ farads/meter, permittivity of free space
ϵ_1	Permittivity of lower half-space (earth) (farads/meter)
λ	Dummy integration variable in the basic Sommerfeld integrals (meters ⁻¹)
λ_0	Wavelength in free space (meters)

ρ	$(x^2 + y^2)^{1/2}$ radial distance in a cylindrical coordinate system (meters)
σ_1	Conductivity of the lower half-space (earth) (Siemens/meter)
ϕ	$\tan^{-1} (y/x)$, azimuth angle in a cylindrical coordinate system
$\mu \sim \mu_0$	$= 4\pi \cdot 10^{-7}$ henries/meter, permeability of free space
ψ	$\tan^{-1} (z/\rho)$ or $\tan^{-1} (h/\rho)$, elevation angle
ψ_0	$\tan^{-1} [(z - h)/\rho]$, elevation angle
ψ_1	$\tan^{-1} [(z + h)/\rho]$, elevation angle
ω	$2\pi f$ radians/second, angular frequency

NEW FORMULAS THAT EXTEND NORTON'S FARFIELD ELEMENTARY DIPOLE EQUATIONS TO THE QUASI-NEARFIELD RANGE

INTRODUCTION

It is the purpose of this report to present new formulas for horizontal electric dipole (HED), horizontal magnetic dipole (HMD), vertical electric dipole (VED), and vertical magnetic dipole (VMD) air-to-air, subsurface-to-air, air-to-subsurface, and surface-to-surface propagation. The new air-to-air propagation formulas extend Norton's results,^{1,2,3} which are stated to be valid for measurement distances greater than a free-space wavelength (λ_0), down to the quasi-nearfield range, which is defined as the range where the measurement distance is much less than a free-space wavelength but much greater than an earth-skin depth (δ). The new subsurface-to-air and air-to-subsurface propagation formulas reduce to previously derived results⁴⁻¹⁰ when the measurement distance is much less than, or comparable to, λ_0 . Norton's^{1,2,3} (corrected) air-to-air propagation formulas are summarized by King,¹¹ while Kraichman¹² has tabulated the subsurface-to-air and air-to-subsurface propagation equations derived by various authors.⁴⁻¹⁰

In the past, many investigators erroneously have believed that the field-strength equations tabulated in Chapter 3 of Kraichman¹² are only valid when the conduction currents in the water or earth are much greater than the displacement currents (i.e., $\sigma_1 \gg \omega \epsilon_1$). Indeed, as long as $|n^2| = |\gamma_1^2 / \gamma_0^2| \gg 1$, the displacement currents can be included simply by replacing σ_1 by $\sigma_1 + i\omega \epsilon_1$ in the field-strength equations. Thus, Kraichman's tabulated results are considerably more general than they are stated to be.

The formulas presented in this report are intended to supplement the author's recently derived subsurface-to-subsurface, subsurface-to-surface, surface-to-subsurface, and surface-to-surface propagation formulas.¹³ They are valid at any frequency and any range beyond a certain minimum distance for the flat-earth case. The main restrictions on these formulas are (1) $|n^2| \geq 10$, (2) the measurement distance is $\geq 10\delta$ from the source, and (3) the measurement distance is ≥ 5 times the depth of burial of the transmitting or receiving point sources.

For the air-to-air propagation case, the four dipole antennas (VED, VMD, HED, and HMD) are situated at height h ($h \geq 0$) with respect to a cylindrical coordinate system (ρ, ϕ, z) and are assumed to carry a constant current, I . The axes of the VED and HED (of dipole moment p) are oriented in the z and x directions, respectively, while the axes of the VMD and HMD (of dipole moment m) are oriented in the z and y directions, respectively. The earth, which is assumed to be a homogeneous medium with conductivity σ_1 and dielectric constant ϵ_1 ($= \epsilon_r \epsilon_0$), occupies the lower half-space ($z < 0$) and the air occupies the upper half-space ($z > 0$). The magnetic permeability of the earth is assumed to equal μ_0 , the permeability of free space. Meter-kilogram-second (MKS) units are employed and a suppressed time factor of $\exp(i\omega t)$ is assumed.

AIR-TO-AIR PROPAGATION DERIVATION PROCEDURE

As an example of our derivation procedure, consider an HED source. When h and z are ≥ 0 , the Sommerfeld integral expressions for the HED Hertz vector are^{4,5,14}

$$\Pi_x = \frac{p}{4\pi i \omega \epsilon_0} \left[\frac{e^{-\gamma_0 R_0}}{R_0} - \frac{e^{-\gamma_0 R_1}}{R_1} + \int_0^\infty \left(\frac{2u_0}{u_1 + u_0} \right) e^{-u_0(z+h)} J_0(\lambda \rho) \frac{\lambda}{u_0} d\lambda \right] \quad (1)$$

and

$$\Pi_z = \frac{p \cos \phi}{4\pi i \omega \epsilon_0} \times \frac{\partial}{\partial \rho} \int_0^\infty \frac{2(u_1 - u_0)}{\gamma_1^2 u_0 + \gamma_0^2 u_1} e^{-u_0(z+h)} J_0(\lambda \rho) \lambda d\lambda, \quad (2)$$

where

$$R_0^2 = \rho^2 + (z - h)^2,$$

$$R_1^2 = \rho^2 + (z + h)^2,$$

$$u_0^2 = \lambda^2 + \gamma_0^2,$$

$$u_1^2 = \lambda^2 + \gamma_1^2,$$

$$\gamma_0^2 = -\omega^2 \mu_0 \epsilon_0, \text{ and}$$

$$\gamma_1^2 = i\omega \mu_0 (\sigma_1 + i\omega \epsilon_1).$$

From equations (1) and (2), and utilizing the identity $(u_1 - u_0)(u_1 + u_0) = \gamma_1^2 - \gamma_0^2$,

$$\vec{\nabla} \cdot \vec{\Pi} = \frac{p \cos \phi}{4\pi i \omega \epsilon_0} \times \frac{\partial}{\partial \rho} \left[\frac{e^{-\gamma_0 R_0}}{R_0} - \frac{e^{-\gamma_0 R_1}}{R_1} + \int_0^\infty \frac{2\gamma_0^2 e^{-u_0(z+h)}}{\gamma_1^2 u_0 + \gamma_0^2 u_1} J_0(\lambda \rho) \lambda d\lambda \right]. \quad (3)$$

When $|n^2| \gg 1$ and $\text{Re}(\gamma_1 R_1) \gg 1$, the function u_1 in the exact integral expressions can be replaced by γ_1 , the propagation constant in the earth.⁴ Therefore,

$$\Pi_x = \frac{p}{4\pi i \omega \epsilon_0} \left[\frac{e^{-\gamma_0 R_0}}{R_0} - \frac{e^{-\gamma_0 R_1}}{R_1} + \frac{2}{(\gamma_1^2 - \gamma_0^2)} \int_0^\infty (\gamma_1 - u_0) e^{-u_0(z+h)} J_0(\lambda \rho) \lambda d\lambda \right]. \quad (4)$$

Since Sommerfeld's integral, S_1 , is equal to

$$S_1 = \int_0^\infty e^{-u_0(z+h)} J_0(\lambda \rho) \frac{\lambda}{u_0} d\lambda = \frac{e^{-\gamma_0 R_1}}{R_1}, \quad (5)$$

then,

$$\int_0^\infty e^{-u_0(z+h)} J_0(\lambda \rho) \lambda d\lambda = - \frac{\partial S_1}{\partial (z+h)} = \frac{\sin \psi_1}{R_1^2} (1 + \gamma_0 R_1) e^{-\gamma_0 R_1} \quad (6)$$

and

$$\begin{aligned} \int_0^\infty u_0 e^{-u_0(z+h)} J_0(\lambda \rho) \lambda d\lambda &= \frac{\partial^2 S_1}{\partial (z+h)^2} \\ &= - \frac{e^{-\gamma_0 R_1}}{R_1^3} \left[(1 + \gamma_0 R_1) - \sin^2 \psi_1 (3 + 3\gamma_0 R_1 + \gamma_0^2 R_1^2) \right], \end{aligned} \quad (7)$$

where $\sin \psi_1 = (z+h)/R_1$. Therefore, from equations (4), (6), and (7),

$$\begin{aligned} \Pi_X \sim \frac{p}{4\pi i \omega \epsilon_0} \left\{ \frac{e^{-\gamma_0 R_0}}{R_0} - \frac{e^{-\gamma_0 R_1}}{R_1} + \frac{2e^{-\gamma_0 R_1}}{(\gamma_1^2 - \gamma_0^2) R_1^3} \right. \\ \left. \times \left[(1 + \gamma_1 R_1 \sin \psi_1) (1 + \gamma_0 R_1) - \sin^2 \psi_1 (3 + 3\gamma_0 R_1 + \gamma_0^2 R_1^2) \right] \right\}. \end{aligned} \quad (8a)$$

Alternatively, we could have replaced the quantity u_1 in the exact integral expressions by $\gamma_1 [1 - (\gamma_0^2/\gamma_1^2) \cos^2 \psi_1]^{1/2}$ instead of γ_1 .^{3,11,15} This change is equivalent to setting the normalized surface impedance, Δ_1 , equal to

$$\Delta_1 = \Delta (1 - \Delta^2 \cos^2 \psi_1)^{1/2}, \quad (9)$$

where $\Delta = \gamma_0/\gamma_1 = 1/n$ and $\cos \psi_1 = \rho/R_1$.

Since $|\gamma_1^2| \gg |\gamma_0^2|$, the factor in parentheses in equation (9) is very near unity (i.e., $\Delta_1 \sim \Delta$). Thus, the resultant modification is usually small. The retention of the parenthesized term is justified by the fact that the exact form of the Fresnel reflection coefficient is recovered from the asymptotic solution.^{3,15} For example, if we utilize the identity $(u_1 - u_0)(u_1 + u_0) = \gamma_1^2 - \gamma_0^2$, substituting $u_1 = \gamma_1 (1 - \Delta^2 \cos^2 \psi_1)^{1/2}$ into equation (1) and evaluating the Sommerfeld integrals results in

$$\Pi_X = \frac{p}{4\pi i \omega \epsilon_0} \left\{ \frac{e^{-\gamma_0 R_0}}{R_0} - \frac{e^{-\gamma_0 R_1}}{R_1} + \frac{2e^{-\gamma_0 R_1}}{(\gamma_1^2 - \gamma_0^2) R_1^3} \right. \\ \left. \times \left[(1 + \sqrt{X} \gamma_1 R_1 \sin \psi_1)(1 + \gamma_0 R_1) - \sin^2 \psi_1 (3 + 3\gamma_0 R_1 + \gamma_0^2 R_1^2) \right] \right\}, \quad (8b)$$

where $X = 1 - \Delta^2 \cos^2 \psi_1$.

When $|\gamma_0 R_1| \gg 1$, equation (8b) reduces to

$$\Pi_X = \frac{p}{4\pi i \omega \epsilon_0} \left\{ \frac{e^{-\gamma_0 R_0}}{R_0} + \frac{e^{-\gamma_0 R_1}}{R_1} \right. \\ \left. \times \left[\frac{2\gamma_0 \sin \psi_1}{(\gamma_1^2 - \gamma_0^2)} (\gamma_1 \sqrt{X} - \gamma_0 \sin \psi_1) - 1 \right] \right\}. \quad (10)$$

The quantity

$$\frac{2\gamma_0 \sin \psi_1 (\gamma_1 \sqrt{X} - \gamma_0 \sin \psi_1)}{\gamma_1^2 - \gamma_0^2} \times \frac{(\gamma_1 \sqrt{X} + \gamma_0 \sin \psi_1)}{(\gamma_1 \sqrt{X} + \gamma_0 \sin \psi_1)} \\ = \frac{2\gamma_0 \sin \psi_1}{\gamma_1 \sqrt{X} + \gamma_0 \sin \psi_1} = \frac{2 \sin \psi_1}{n_1 + \sin \psi_1} = 1 + \Gamma_1, \quad (11)$$

where

$$\Gamma_1 = \frac{\sin \psi_1 - n_1}{\sin \psi_1 + n_1} \quad (12)$$

is the Fresnel reflection coefficient for horizontal polarization and

$$n_1 = n(1 - \Delta^2 \cos^2 \psi_1)^{1/2} \quad (13)$$

when $|\gamma_1^2| \gg |\gamma_0^2|$, $n_1 \sim n$, and $\Delta_1 \sim \Delta = 1/n$.

Therefore, from equations (10) and (11), when $|\gamma_0 R_1| \gg 1$,

$$\Pi_X = \frac{p}{4\pi i \omega \epsilon_0} \left(\frac{e^{-\gamma_0 R_0}}{R_0} + \Gamma_1 \frac{e^{-\gamma_0 R_1}}{R_1} \right), \quad (14)$$

and the exact form of the Fresnel reflection coefficient is recovered.

When $|n^2| \gg 1$ and $\text{Re}(\gamma_1 R_1) \gg 1$, equation (2) reduces to

$$\Pi_z \sim \frac{p \cos \phi}{2\pi i \omega \epsilon_0 \gamma_1} \times \frac{\partial}{\partial \rho} \int_0^\infty \frac{(1 - u_0/\gamma_1)}{u_0 + \gamma_0 \Delta} e^{-u_0(z+h)} J_0(\lambda \rho) \lambda d\lambda. \quad (15)$$

Since

$$\frac{1}{u_0 + \gamma_0 \Delta} = \frac{1}{u_0} - \left(\frac{1}{u_0} - \frac{1}{u_0 + \gamma_0 \Delta} \right) = \frac{1}{u_0} - \frac{\gamma_0 \Delta}{u_0(u_0 + \gamma_0 \Delta)}, \quad (16)$$

then, for $|\Delta^2| \ll 1$,

$$\frac{(1 - u_0/\gamma_1)}{u_0 + \gamma_0 \Delta} \sim \frac{1}{u_0} - \frac{\gamma_0 \Delta}{u_0(u_0 + \gamma_0 \Delta)} - \frac{1}{\gamma_1}. \quad (17)$$

Therefore, equation (15) reduces to

$$\begin{aligned} \Pi_z \sim \frac{p \cos \phi}{2\pi i \omega \epsilon_0 \gamma_1} \times \frac{\partial}{\partial \rho} \left[\int_0^\infty e^{-u_0(z+h)} J_0(\lambda \rho) \frac{\lambda}{u_0} d\lambda \right. \\ \left. - P - \frac{1}{\gamma_1} \int_0^\infty e^{-u_0(z+h)} J_0(\lambda \rho) \lambda d\lambda \right], \end{aligned} \quad (18)$$

where

$$P = \int_0^\infty \frac{\gamma_0 \Delta e^{-u_0(z+h)}}{u_0(u_0 + \gamma_0 \Delta)} J_0(\lambda \rho) \lambda d\lambda. \quad (19)$$

From equations (5) and (6),

$$\Pi_z \sim \frac{p \cos \phi}{2\pi i \omega \epsilon_1 \gamma_1} \times \frac{\partial}{\partial \rho} \left[\frac{e^{-\gamma_0 R_1}}{R_1} - P - \frac{\sin \psi_1}{\gamma_1 R_1^2} (1 + \gamma_0 R_1) e^{-\gamma_0 R_1} \right]. \quad (20)$$

Because $|n^2| \gg 1$ and $\text{Re}(\gamma_1 R_1) \gg 1$, the third term in equation (20) will be of importance only near the source. Furthermore, since $|\gamma_0 \Delta| \ll 1$, the integral P will be of importance only when $|\gamma_0 R_1| \gg 1$. Wait^{4,15} has shown that, when $|\gamma_1^2| \gg |\gamma_0^2|$ and $|\gamma_0 R_1| \gg 1$,

$$P \sim \left(\frac{w'}{w} \right)^{1/2} i(\pi w)^{1/2} e^{-w} \text{erfc}(i w^{1/2}) \frac{e^{-\gamma_0 R_1}}{R_1}, \quad (21)$$

where

$$w' = -\gamma_0 R_1 \Delta^2 / 2 \quad (22)$$

and

$$w = -\frac{\gamma_0 R_1}{2}(\sin \psi_1 + \Delta)^2. \quad (23)$$

If we replace Δ by $\Delta_1^{3,11,15}$ (equation (9)),

$$\left(\frac{w'}{w}\right)^{1/2} = \left(\frac{1 - \Gamma_{11}}{2}\right) = \frac{\Delta_1}{\sin \psi_1 + \Delta_1}, \quad (24)$$

where

$$\Gamma_{11} = \frac{\sin \psi_1 - \Delta_1}{\sin \psi_1 + \Delta_1} \quad (25)$$

is the Fresnel reflection coefficient for vertical polarization. Therefore, equation (21) can be expressed as

$$P \sim \left(\frac{1 - \Gamma_{11}}{2}\right)[1 - F(w)] \frac{e^{-\gamma_0 R_1}}{R_1}, \quad (26)$$

where

$$F(w) \sim 1 - i(\pi w)^{1/2} e^{-w} \text{erfc}(i w^{1/2}) \quad (27)$$

is the Sommerfeld surface-wave attenuation function and

$$w = -\frac{\gamma_0 R_1}{2}(\sin \psi_1 + \Delta_1)^2 = \frac{4w'}{(1 - \Gamma_{11})^2} \quad (28)$$

is the Sommerfeld numerical distance. For small numerical distances $F(w) \sim 1$ and for large numerical distances and negative arguments $F(w) \sim -1/(2w)$.

Since

$$\begin{aligned} 1 - \left(\frac{1 - \Gamma_{11}}{2}\right)[1 - F(w)] &= \left(\frac{1 + \Gamma_{11}}{2}\right) + \left(\frac{1 - \Gamma_{11}}{2}\right)F(w) \\ &= \frac{\sin \psi_1 + \Delta_1 F(w)}{\sin \psi_1 + \Delta_1} = A, \end{aligned} \quad (29)$$

equation (20) reduces to

$$\Pi_z \sim \frac{p \cos \phi}{2\pi i \omega \epsilon_0 \gamma_1} \times \frac{\partial}{\partial \rho} \left[\frac{A e^{-\gamma_0 R_1}}{R_1} - \frac{\sin \psi_1}{\gamma_1 R_1^2} (1 + \gamma_0 R_1) e^{-\gamma_0 R_1} \right]. \quad (30)$$

Another factor that we will encounter in the derivation of the field-strength components is the factor B, which is equal to

$$B = \sin \psi_1 - \Delta_1 A = \left(\frac{1 + \Gamma_{11}}{2} \right) \sin \psi_1 - \left(\frac{1 - \Gamma_{11}}{2} \right) \Delta_1 F(w) \quad (31)$$

$$= \frac{\sin^2 \psi_1 - \Delta_1^2 F(w)}{\sin \psi_1 + \Delta_1}.$$

For small numerical distances (i.e., $F(w) \sim 1$), $A \sim 1$, and $B \sim \sin \psi_1 - \Delta_1$. Furthermore, for $\sin \psi_1 \gg |\Delta_1|$, $A \sim 1$ and $B \sim \sin \psi_1$. For $\sin \psi_1$ comparable to or less than Δ_1 , the horizontal distance ρ will be much greater than the sum of the transmitting and receiving heights ($z + h$). In the limit as ψ_1 approaches 0, $A \sim F(w_0)$ and $B \sim -\Delta_1 F(w_0)$, where

$$F(w_0) \sim 1 - i(\pi w_0)^{1/2} e^{-w_0} \operatorname{erfc}(i w_0^{1/2}) \quad (32)$$

and

$$w_0 = -\frac{\gamma_0 \rho}{2} \Delta_1^2. \quad (33)$$

When $\rho^2 \gg (z + h)^2$, Wait^{4,15} has shown that

$$F(w) \sim [1 + \gamma_0 \Delta_1 (z + h)] F(w_0) = [1 + \gamma_0 R_1 \Delta_1 \sin \psi_1] F(w_0) \quad (34)$$

and

$$\frac{\partial F(w)}{\partial z} \sim \gamma_0 \Delta_1 F(w_0). \quad (35)$$

Extensive numerical results for the function $F(w_0)$ have been provided by Wait¹⁵ and King and Schlak.¹⁶

Since the factor A (equation (29)) is different from unity only when (1) the angle ψ_1 is very small and (2) the Sommerfeld attenuation function $F(w)$ is different from unity, A is only a farfield surface-wave term. Therefore, we can discard all derivatives of A that are not farfield terms. For example, when $|\gamma_1^2| \gg |\gamma_0^2|$ and $|\Delta_1| \sin \psi_1 \ll 1$,

$$\begin{aligned} \frac{\partial}{\partial \rho} \left(\frac{A e^{-\gamma_0 R_1}}{R_1} \right) &= -A(1 + \gamma_0 R_1) \cos \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1^2} + \frac{e^{-\gamma_0 R_1}}{R_1} \left(\frac{\partial A}{\partial \rho} \right) \\ &\sim -A(1 + \gamma_0 R_1) \cos \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1^2} \\ &\sim -(1 + \gamma_0 R_1 A) \cos \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1^2}. \end{aligned} \quad (36)$$

Therefore, from equations (30) and (36),

$$\Pi_z = - \frac{p \cos \phi \cos \psi_1 e^{-\gamma_0 R_1}}{2\pi i \omega \epsilon_0 \gamma_1 R_1^2} \left[(1 + \gamma_0 R_1 A) - \frac{\sin \psi_1}{\gamma_1 R_1} (3 + 3\gamma_0 R_1 + \gamma_0^2 R_1^2) \right] . \quad (37)$$

When $|n^2| \gg 1$ and $\text{Re}(\gamma_1 R_1) \gg 1$, equation (3) reduces to

$$\vec{\nabla} \cdot \vec{\Pi} = \frac{p \cos \phi}{4\pi i \omega \epsilon_0} \times \frac{\partial}{\partial \rho} \left[\frac{e^{-\gamma_0 R_0}}{R_0} - \frac{e^{-\gamma_0 R_1}}{R_1} \right. \\ \left. + \frac{2}{n^2} \int_0^\infty \frac{e^{-u_0(z+h)}}{u_0 + \gamma_0 \Delta} J_0(\lambda \rho) \lambda d\lambda \right] . \quad (38)$$

Since

$$\frac{1}{u_0 + \gamma_0 \Delta} = \frac{1}{u_0} - \left(\frac{1}{u_0} - \frac{1}{u_0 + \gamma_0 \Delta} \right) = \frac{1}{u_0} - \frac{\gamma_0 \Delta}{u_0(u_0 + \gamma_0 \Delta)} , \quad (16)$$

then, following the same procedure as in the derivation of the HED Π_z component results in

$$\vec{\nabla} \cdot \vec{\Pi} = \frac{p \cos \phi}{4\pi i \omega \epsilon_0} \times \frac{\partial}{\partial \rho} \left[\frac{e^{-\gamma_0 R_0}}{R_0} - \frac{e^{-\gamma_0 R_1}}{R_1} + \frac{2}{n^2} \left(\frac{e^{-\gamma_0 R_1}}{R_1} - p \right) \right] \\ = \frac{p \cos \phi}{4\pi i \omega \epsilon_0} \times \frac{\partial}{\partial \rho} \left[\frac{e^{-\gamma_0 R_0}}{R_0} - \frac{e^{-\gamma_0 R_1}}{R_1} + \frac{2Ae^{-\gamma_0 R_1}}{n^2 R_1} \right] \\ = - \frac{p \cos \phi}{4\pi i \omega \epsilon_0} \left[(1 + \gamma_0 R_0) \cos \psi_0 \frac{e^{-\gamma_0 R_0}}{R_0^2} - (1 + \gamma_0 R_1) \cos \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1^2} \right. \\ \left. + \frac{2}{n^2} (1 + \gamma_0 R_1 A) \cos \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1^2} \right] . \quad (39)$$

Since we have now derived expressions for the HED Hertz vector (equations (8), (37), and (39)), the fields in air can be obtained from

$$\vec{E} = -\gamma_0^2 \vec{\Pi} + \vec{\nabla}(\vec{\nabla} \cdot \vec{\Pi}) \\ \vec{H} = i\omega \epsilon_0 (\vec{\nabla} \times \vec{\Pi}) . \quad (40)$$

By following the same procedure as outlined above, we can also obtain suitable expressions for the HMD, VED, and VMD Hertz vectors. The resulting HED, HMD, VED, and VMD field-component expressions for the air-to-air

propagation case are presented in tables 1 and 2.* They are strictly valid for $|n^2| \gg 1$ and $\text{Re}(\gamma_1 R_1) \gg 1$. However, for most cases, the requirement that $|n^2| \geq 10$ and $R_1 \geq 10\delta$ is sufficient. When $|\gamma_0 R_1| \ll 1$, they reduce to Bannister's quasi-near range results.^{7,10}

When $|\gamma_0 R_1| \gg 1$, they reduce to Norton's farfield range results^{1,2,3,11} (for $|n^2| \gg 1$). For convenience, the farfield expressions ($|\gamma_0 R_1| \gg 1$) are listed in tables 3 and 4. In these tables, $\sin \psi_0 = (z - h)/R_0$, $\cos \psi_0 = \rho/R_0$, $\sin \psi_1 = (z + h)/R_1$, and $\cos \psi_1 = \rho/R_1$.

The air-to-air propagation results presented in this report can be extended to a multilayered earth simply by substituting γ_1/Q for γ_1 , where Q is the familiar plane-wave correction factor employed to account for the presence of stratification in the earth.¹⁵ For a homogeneous ground, the argument of the Sommerfeld numerical distance w_0 (equation (33)) is always between 0 and -90 deg, resulting in the transverse magnetic (TM) surface-wave fields varying as $1/\rho^2$ as $\rho \rightarrow \infty$. For a stratified ground, the argument of w_0 can be positive, resulting in the TM surface-wave fields varying as $1/\sqrt{\rho}$. This fact is discussed in further detail by Wait¹⁵ and King and Schlak.¹⁶

SUBSURFACE-TO-AIR PROPAGATION

The HED, HMD, VED, and VMD field-component expressions for the subsurface-to-air propagation case ($h \leq 0$, $z \geq 0$) can be obtained from the air-to-air propagation equations (tables 1 and 2) simply by setting $h = 0$ and multiplying each resulting expression by $\exp(\gamma_1 h)$. (All VED components must also be multiplied by $1/n^2$ to satisfy the boundary conditions.) The resulting equations are presented in tables 5 and 6 for the general case, in table 7 for $\rho \gg z$, and in table 8 for $z \gg \rho$. In these tables, $R = \rho^2 + z^2$, $\sin \psi = z/R$, and $\cos \psi = \rho/R$.

The expressions presented in tables 5 through 8 are strictly valid for $|n^2| \gg 1$, $\text{Re}(\gamma_1 R) \gg 1$, and $R \gg |h|$. However, for most cases, the requirement that $|n^2| \geq 10$, $R \geq 10\delta$, and $R \geq 5|h|$ is sufficient.

When $|\gamma_0 R| \ll 1$, they reduce to Bannister's quasi-near range formulas,^{7,10} which are tabulated in Kraichman¹² (with σ_1 replaced by $\sigma_1 + i\omega\epsilon_1$). When $F(w) = 1$ (i.e., small numerical distances), they reduce to Bannister's nearfield range formulas,^{9,10} which are also tabulated in Kraichman¹² (with σ_1 replaced by $\sigma_1 + i\omega\epsilon_1$). Furthermore, when $h = 0$ and $|\gamma_0 R| \gg 1$, they are consistent with Norton's farfield surface-to-air results.^{1,2,3,11}

*All tables have been placed together at the end of this report.

AIR-TO-SUBSURFACE PROPAGATION

The HED, HMD, VED, and VMD field-component expressions for the air-to-subsurface propagation case ($h \geq 0$, $z \leq 0$) can be obtained from the air-to-air propagation equations (tables 1 and 2) simply by setting $z = 0$ and multiplying each resulting expression by $\exp(\gamma_1 z)$. (All E_z components must also be multiplied by $1/n^2$ to satisfy the boundary conditions.) The resulting equations are presented in tables 9 and 10 for the general case, in table 11 for $\rho \gg h$, and in table 12 for $h \gg \rho$. In these tables, $D = \rho^2 + h^2$, $\sin \psi = h/D$, and $\cos \psi = \rho/D$.

The expressions presented in tables 9 through 12 are strictly valid for $|n^2| \gg 1$, $\text{Re}(\gamma_1 D) \gg 1$, and $D \gg |z|$. However, for most cases, the requirement that $|n^2| \geq 10$, $D \geq 10\delta$, and $D \geq 5|z|$ is sufficient.

When $|\gamma_0 D| \ll 1$, they reduce to Bannister's quasi-near range formulas,^{7,10} which are tabulated in Kraichman¹² (with σ_1 replaced by $\sigma_1 + i\omega\epsilon_1$). When the numerical distance is small (i.e., $F(w) \sim 1$), they reduce to Bannister's near-field range formulas,⁸ which are also tabulated in Kraichman¹² (with σ_1 replaced by $\sigma_1 + i\omega\epsilon_1$). Furthermore, when $z = 0$ and $|\gamma_0 D| \gg 1$, they are consistent with Norton's farfield air-to-surface results.^{1,2,3,11}

SURFACE-TO-SURFACE PROPAGATION

The simple-form HED, HMD, VED, and VMD field-component expressions for the surface-to-surface propagation case can be obtained from the air-to-air propagation equations (tables 1 and 2) simply by setting both z and h equal to zero. The resulting equations are listed in table 13. They are strictly valid for $|n^2| \gg 1$ and $\text{Re}(\gamma_1 \rho) \gg 1$. However, the requirement that $|n^2| \geq 10$ and $\rho \geq 10\delta$ is sufficient. When either (1) $|\gamma_0 \rho| \ll 1$, (2) $F(w_0) \sim 1$, or (3) $|\gamma_0 \rho| \gg 1$, they reduce to previously derived results.⁴⁻¹² Note that the function F in this table is equal to $F(w_0)$.

DISCUSSION

Since $|n^2| \gg 1$ (i.e., $|\Delta^2| \ll 1$), the factor $n_1 \sim n$ and $\Delta_1 \sim \Delta$. Furthermore,

$$\Gamma_{11} = \frac{\sin \psi_1 - \Delta}{\sin \psi_1 + \Delta} \quad (41)$$

and

$$\Gamma_{\perp} = \frac{\sin \psi_1 - n}{\sin \psi_1 + n} = -1 + \frac{2 \sin \psi_1}{n} \quad (42)$$

For small numerical distances (i.e., $F(w) \sim 1$), $A \sim 1$ and $B \sim \sin \psi_1 - \Delta$. Furthermore, for $\sin \psi_1 \gg |\Delta|$, $A \sim 1$ and $B \sim \sin \psi_1$. When $\sin \psi_1$ is comparable to or less than Δ , the horizontal distance ρ will be much greater than the sum of the transmitting and receiving antenna heights ($z + h$). In the limit as ψ_1 approaches zero, $A \sim F(w_0)$ and $B \sim -\Delta F(w_0)$, where

$$F(w_0) \sim 1 - i(\pi w_0)^{1/2} e^{-w_0} \operatorname{erfc}(i w_0^{1/2}) \quad (43)$$

and

$$w_0 = -\frac{\gamma_0 \rho^2}{2} \Delta^2. \quad (44)$$

For this case (i.e., $\rho^2 \gg (z + h)^2$), Wait^{4,15} has shown that $F(w)$ can be replaced by

$$F(w) \sim [1 + \gamma_0 \Delta (z + h)] F(w_0), \quad (45)$$

and we can make use of his tabulated results¹⁵ of the function $F(w_0)$.

When we were confirming the validity for the subsurface-to-air and air-to-subsurface propagation equations derived in this report (which were derived from the air-to-air propagation equations), we discovered that they could also have been obtained by combining previously derived results. The derivation procedure can best be shown by example.

From table 3.3 of Kraichman,¹² the nearfield range subsurface-to-air HED H_ϕ component is

$$H_\phi^{HE} \sim -\frac{\rho \cos \phi e^{\gamma_1 h} e^{-\gamma_0 R}}{2\pi \gamma_1 R^3} (1 + \gamma_0 R + \gamma_0^2 R^2). \quad (46)$$

When $|\gamma_0 R| \gg 1$, equation (46) reduces to

$$H_\phi^{HE} \sim -\frac{\gamma_0 \rho \cos \phi e^{\gamma_1 h} e^{-\gamma_0 R}}{2\pi R} (\Delta). \quad (47)$$

If we take Norton's farfield H_ϕ equation (table 4), set $h = 0$, and multiply by $\exp(\gamma_1 h)$, we obtain (for $|\gamma_0 R| \gg 1$)

$$H_\phi^{HE} \sim -\frac{\gamma_0 \rho \cos \phi e^{\gamma_1 h} e^{-\gamma_0 R}}{2\pi R} \left(\frac{1 - \Gamma_{11}}{2} \right) [\sin \psi + \Delta F(w)]. \quad (48)$$

Since

$$\left(\frac{1 - \Gamma_{11}}{2} \right) = \frac{\Delta}{\sin \psi + \Delta}, \quad (49)$$

then,

$$\left(\frac{1 - \Gamma_{11}}{2}\right) [\sin \psi + \Delta F(w)] = \Delta \left[\frac{\sin \psi + \Delta F(w)}{\sin \psi + \Delta} \right] = \Delta A. \quad (50)$$

Therefore, equation (48) reduces to

$$H_{\phi}^{HE} = - \frac{\gamma_0 p \cos \phi e^{\gamma_1 h} e^{-\gamma_0 R}}{2\pi R} - (\Delta A), \quad (51)$$

which is equivalent to equation (47) except for the factor A. When either $\sin \psi_1 \gg |\Delta|$ or the Sommerfeld numerical distance (w) is small, $A \sim 1$. For $|n^2| \gg 1$, the range of validity of equations (46) and (51) overlap when $|w| \ll 1$ and $|\gamma_0 R| \gg 1$ simultaneously. Therefore, we can simply combine equations (46) and (51) to obtain an expression for the HED H_{ϕ} component valid from the quasi-nearfield to the farfield ranges. Therefore, for $|n^2| \gg 1$, $\text{Re}(\gamma_1 R) \gg 1$, and $R \gg |h|$,

$$H_{\phi}^{HE} = - \frac{p \cos \phi e^{\gamma_1 h} e^{-\gamma_0 R}}{2\pi \gamma_1 R^3} (1 + \gamma_0 R + \gamma_0^2 R^2 A), \quad (52)$$

which is the result listed in table 6.

In following this procedure, we discovered a small error in the HED and HMD E_{ϕ} and H_{ρ} farfield subsurface-to-air and subsurface-to-subsurface propagation equations tabulated in tables 3.1 and 3.2 of Kraichman¹² (and also in equation (14) of Wait⁴). These equations should be multiplied by the factor $[1 + F(w_0)]/2$. They will then agree with Norton's farfield surface-to-surface propagation results. This correction is unimportant for small numerical distances, since, for this case, $F(w_0) \sim 1$ and $[1 + F(w_0)]/2 = 1$. For large numerical distances, the difference is a factor of 1/2. However, for this case, $E_{\rho} \gg E_{\phi}$ and $H_{\phi} \gg H_{\rho}$.

CONCLUSIONS

New formulas that extend Norton's farfield elementary dipole equations to the quasi-nearfield range have been developed for the air-to-air, subsurface-to-air, air-to-subsurface, and surface-to-surface propagation cases. They are valid at any frequency and at any range beyond a certain minimum distance for the flat-earth case. The main restrictions on these formulas are (1) $|n^2| > 10$, (2) the measurement distance is ≥ 10 skin depths from the source, and (3) the measurement distance is ≥ 5 times the depth of burial of the transmitting or receiving point sources.

These new formulas reduce to previously derived results when either (1) the measurement distance is much less than a free-space wavelength, (2) the Sommerfeld numerical distance is small, or (3) the measurement distance is much greater than a free-space wavelength.

It should be noted that the two media can be inverted and the air replaced by the earth's crust (of conductivity σ_2 and dielectric constant ϵ_2). The same equations (tables 1 through 13) can be utilized as long as $|n_2^2| = |\gamma_1^2/\gamma_2^2| \geq 10$, $R_1 \geq 10\delta_2$, and $R \geq 5|h|$ (or $D \geq 5|z|$) simply by replacing $i\omega\epsilon_0$ by $\sigma_2 + i\omega\epsilon_2$.

We have recently employed finitely conducting earth-image theory techniques to derive field-component expressions valid at any range from the source for the air-to-air propagation case. The only restriction on these new image-theory formulas is that $|n^2| \gg 1$. When the measurement distance is ≥ 10 skin depths from the source, they reduce to the air-to-air equations derived in this report. These new image-theory results will be the subject of a future report.¹⁷

Table 1. Electric-Field Air-to-Air Propagation For

Dipole Type	E_ρ	E_ϕ
VED	$\frac{p}{4\pi i \omega \epsilon_0} \left\{ (3 + 3\gamma_0 R_0 + \gamma_0^2 R_0^2) \sin \psi_0 \cos \psi_0 \frac{e^{-\gamma_0 R_0}}{R_0^3} \right.$ $+ (3 + 3\gamma_0 R_1 + \gamma_0^2 R_1^2) \sin \psi_1 \cos \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1^3}$ $\left. - \frac{2\gamma_1 \cos \psi_1 e^{-\gamma_0 R_1}}{n^2 R_1^2} \left[1 + \left(\frac{1 - \Gamma_{11}}{2} \right) F(w) \gamma_0 R_1 \right] \right\}$	0
VMD	0	$- \frac{i \omega \mu_0 m}{4\pi} \left\{ (1 + \gamma_0 R_0) \cos \psi_0 \frac{e^{-\gamma_0 R_0}}{R_0^2} - (1 + \right.$ $\left. \frac{2 \cos \psi_1 e^{-\gamma_0 R_1}}{(\gamma_1^2 - \gamma_0^2) R_1^4} [(1 + \gamma_1 R_1 \sin \psi_1) (3 + \right.$ $\left. - \sin^2 \psi_1 (15 + 15\gamma_0 R_1 + 6\gamma_0^2 R_1^2 + \gamma_0^3 R_1^3)) \right\}$
HED	$\frac{p \cos \phi}{4\pi i \omega \epsilon_0} \left\{ [(3 \cos^2 \psi_0 - 1)(1 + \gamma_0 R_0) - \gamma_0^2 R_0^2 \sin^2 \psi_0] \frac{e^{-\gamma_0 R_0}}{R_0^3} \right.$ $- [(3 \cos^2 \psi_1 - 1)(1 + \gamma_0 R_1) - \gamma_0^2 R_1^2 \sin^2 \psi_1] \frac{e^{-\gamma_0 R_1}}{R_1^3}$ $\left. + \frac{2e^{-\gamma_0 R_1}}{n^2 R_1^3} \left[1 - \gamma_1 R_1 \sin \psi_1 + \gamma_0 R_1 + \left(\frac{1 - \Gamma_{11}}{2} \right) F(w) \gamma_0^2 R_1^2 \right] \right\}$	$\frac{p \sin \psi}{4\pi i \omega \epsilon_0} \left\{ (1 + \gamma_0 R_0 + \gamma_0^2 R_0^2) \frac{e^{-\gamma_0 R_0}}{R_0^3} - (1 + \right.$ $\left. + \frac{2e^{-\gamma_0 R_1}}{n^2 R_1^3} [(2 + \gamma_1 R_1 \sin \psi_1) + \gamma_0 R_1 (1 + \right.$ $\left. - \sin^2 \psi_1 (3 + 3\gamma_0 R_1 + \gamma_0^2 R_1^2)) \right\}$
HMD	$- \frac{i \omega \mu_0 m \cos \phi}{4\pi} \left\{ (1 + \gamma_0 R_0) \sin \psi_0 \frac{e^{-\gamma_0 R_0}}{R_0^2} \right.$ $+ (1 + \gamma_0 R_1) \sin \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1^2}$ $\left. - \frac{2e^{-\gamma_0 R_1}}{\gamma_1 R_1^3} \left[1 + \gamma_0 R_1 + \left(\frac{1 - \Gamma_{11}}{2} \right) F(w) \gamma_0^2 R_1^2 \right] \right\}$	$\frac{i \omega \mu_0 m \sin \phi}{4\pi} \left\{ (1 + \gamma_0 R_0) \sin \psi_0 \frac{e^{-\gamma_0 R_0}}{R_0^2} + \right.$ $\left. + \frac{2e^{-\gamma_0 R_1}}{\gamma_1 R_1^3} [2 + \gamma_0 R_1 (1 + A) - \sin^2 \psi_1 (3 + \right.$

Air Propagation Formulas ($|n^2| \geq 10$, $R_1 \geq 106$)

E_ϕ	E_z
0	$-\frac{p}{4\pi i \omega \epsilon_0} \left\{ [(1 - 3 \sin^2 \psi_0)(1 + \gamma_0 R_0) + \gamma_0^2 R_0^2 \cos^2 \psi_0] \frac{e^{-\gamma_0 R_0}}{R_0^3} \right.$ $+ [(1 - 3 \sin^2 \psi_1)(1 + \gamma_0 R_1) + \Gamma_{11} \gamma_0^2 R_1^2 \cos^2 \psi_1] \frac{e^{-\gamma_0 R_1}}{R_1^3}$ $+ (1 - \Gamma_{11}) F(w) \gamma_0^2 R_1^2 \cos^2 \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1^3} \Bigg\}$
$p \sin \psi_0 \frac{e^{-\gamma_0 R_0}}{R_0^2} - (1 + \gamma_0 R_1) \cos \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1^2}$ $+ \gamma_1 R_1 \sin \psi_1 (3 + 3\gamma_0 R_1 + \gamma_0^2 R_1^2)$ $+ \gamma_1^2 R_1^2 + 6\gamma_0^2 R_1^2 + \gamma_0^3 R_1^3 \Bigg\}$	0
$\gamma_0^2 R_0^2 \frac{e^{-\gamma_0 R_0}}{R_0^3} - (1 + \gamma_0 R_1 + \gamma_0^2 R_1^2) \frac{e^{-\gamma_0 R_1}}{R_1^3}$ $\sin \psi_1 + \gamma_0 R_1 (1 + A + \gamma_1 R_1 \sin \psi_1)$ $+ \gamma_0^2 R_1^2 \Bigg\}$	$\frac{p \cos \phi}{4\pi i \omega \epsilon_0} \left\{ (3 + 3\gamma_0 R_0 + \gamma_0^2 R_0^2) \sin \psi_0 \cos \psi_0 \frac{e^{-\gamma_0 R_0}}{R_0^3} \right.$ $- (3 + 3\gamma_0 R_1 + \Gamma_{11} \gamma_0^2 R_1^2) \sin \psi_1 \cos \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1^3}$ $+ \frac{2\gamma_1 \cos \psi_1 e^{-\gamma_0 R_1}}{n^2 R_1^2} \left[1 + \left(\frac{1 - \Gamma_{11}}{2} \right) F(w) \gamma_0 R_1 \right] \Bigg\}$
$p_0 \sin \psi_0 \frac{e^{-\gamma_0 R_0}}{R_0^2} + (1 + \gamma_0 R_1) \sin \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1^2}$ $+ A - \sin^2 \psi_1 (3 + 3\gamma_0 R_1 + \gamma_0^2 R_1^2) \Bigg\}$	$\frac{i \omega \mu_0 m \cos \phi}{4\pi} \left\{ (1 + \gamma_0 R_0) \cos \psi_0 \frac{e^{-\gamma_0 R_0}}{R_0^2} \right.$ $+ (1 + \Gamma_{11} \gamma_0 R_1) \cos \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1^2}$ $+ (1 - \Gamma_{11}) F(w) \gamma_0 R_1 \cos \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1^2} \Bigg\}$

Table 2. Magnetic-Field Air-to-Air Propagation

Dipole Type	H_p	H_ϕ
VED	0	$\frac{p}{4\pi} \left[(1 + \gamma_0 R_0) \cos \psi_0 \frac{e^{-\gamma_0 R_0}}{R_0^2} + (1 + (1 - \Gamma_{11}) F(w) \gamma_0 R_1 \cos \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1^2} \right]$
VMD	$\frac{p}{4\pi} \left\{ (3 + 3\gamma_0 R_0 + \gamma_0^2 R_0^2) \sin \psi_0 \cos \psi_0 \frac{e^{-\gamma_0 R_0}}{R_0^3} \right. \\ - (3 + 3\gamma_0 R_1 + \gamma_0^2 R_1^2) \sin \psi_1 \cos \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1^3} \\ - \frac{2 \cos \psi_1 e^{-\gamma_0 R_1}}{\gamma_1 R_1^4} [(3 + 3\gamma_0 R_1 + \gamma_0^2 R_1^2) \\ \left. - \sin^2 \psi_1 (15 + 15\gamma_0 R_1 + 6\gamma_0^2 R_1^2 + \gamma_0^3 R_1^3)] \right\}$	0

Air Propagation Formulas ($|n^2| \geq 10$, $R_1 \geq 10\delta$)

H_ϕ	H_z
$\cos \psi_0 \frac{e^{-\gamma_0 R_0}}{R_0^2} + (1 + \Gamma_{11} \gamma_0 R_1) \cos \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1^2}$ $\left[\gamma_0 R_1 \cos \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1^2} \right]$	0
0	$ \begin{aligned} & - \frac{m}{4\pi} [(1 - 3 \sin^2 \psi_0)(1 + \gamma_0 R_0) + \gamma_0^2 R_0^2 \cos^2 \psi_0] \frac{e^{-\gamma_0 R_0}}{R_0^3} \\ & - [(1 - 3 \sin^2 \psi_1)(1 + \gamma_0 R_1) + \gamma_0^2 R_1^2 \cos^2 \psi_1] \frac{e^{-\gamma_0 R_1}}{R_1^3} \\ & + \frac{2e^{-\gamma_0 R_1}}{(\gamma_1^2 - \gamma_0^2)R_1^5} \left\{ (1 + \gamma_1 R_1 \sin \psi_1) [(9 + 9\gamma_0 R_1 + 4\gamma_0^2 R_1^2 + \gamma_0^3 R_1^3) \right. \\ & \quad - \sin^2 \psi_1 (15 + 15\gamma_0 R_1 + 6\gamma_0^2 R_1^2 + \gamma_0^3 R_1^3)] \\ & \quad - \sin^2 \psi_1 (75 + 75\gamma_0 R_1 + 33\gamma_0^2 R_1^2 + 6\gamma_0^3 R_1^3) \\ & \quad \left. + \sin^4 \psi_1 (105 + 105\gamma_0 R_1 + 45\gamma_0^2 R_1^2 + 6\gamma_0^3 R_1^3) \right\} \end{aligned} $

Table 2. (Cont'd) Magnetic-Field Air-to-Air Prop

Dipole Type	H_p	H_ϕ
HED	$-\frac{p \sin \phi}{4\pi} \left\{ (1 + \gamma_0 R_0) \sin \psi_0 \frac{e^{-\gamma_0 R_0}}{R_0^2} - (1 + \gamma_0 R_1) \sin \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1^2} \right. \\ \left. - \frac{2e^{-\gamma_0 R_1}}{\gamma_1 R_1^3} [2 + \gamma_0 R_1 (1 + A) - \sin^2 \psi_1 (3 + 3\gamma_0 R_1 + \gamma_0^2 R_1^2)] \right\}$	$-\frac{p \cos \phi}{4\pi} \left\{ (1 + \gamma_0 R_0) \sin \psi_0 \frac{e^{-\gamma_0 R_0}}{R_0^2} \right. \\ \left. + (1 + \Gamma_{11} \gamma_0 R_1) \sin \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1^2} \right. \\ \left. + \frac{2e^{-\gamma_0 R_1}}{\gamma_1 R_1^3} \left[1 + \gamma_0 R_1 + \left(\frac{1 - \Gamma_{11}}{2} \right) F(w) \right] \right\}$
HMD	$\frac{m \sin \phi}{4\pi} \left\{ [2(1 + \gamma_0 R_0) - \sin^2 \psi_0 (3 + 3\gamma_0 R_0 + \gamma_0^2 R_0^2)] \frac{e^{-\gamma_0 R_0}}{R_0^3} \right. \\ \left. + [2(1 + \gamma_0 R_1 A) - \sin^2 \psi_1 (3 + 3\gamma_0 R_1 + \gamma_0^2 R_1^2)] \frac{e^{-\gamma_0 R_1}}{R_1^3} \right\}$	$-\frac{m \cos \phi}{4\pi} \left\{ (1 + \gamma_0 R_0 + \gamma_0^2 R_0^2) \frac{e^{-\gamma_0 R_0}}{R_0^3} \right. \\ \left. + (1 + \gamma_0 R_1 + \Gamma_{11} \gamma_0^2 R_1^2) \frac{e^{-\gamma_0 R_1}}{R_1^3} \right. \\ \left. + (1 - \Gamma_{11}) F(w) \gamma_0^2 R_1^2 \frac{e^{-\gamma_0 R_1}}{R_1^3} \right\}$

and Air-to-Air Propagation Formulas ($|n^2| \geq 10$, $R_1 \geq 10\delta$)

H_ϕ	H_z
$+ \gamma_0 R_0) \sin \psi_0 \frac{e^{-\gamma_0 R_0}}{R_0^2}$ $+ \gamma_1 R_1) \sin \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1^2}$ $+ \gamma_0 R_1 + \left(\frac{1 - \Gamma_1}{2} \right) F(w) \gamma_0^2 R_1^2 \Bigg\}$	$\frac{p \sin \phi}{4\pi} \left\{ (1 + \gamma_0 R_0) \cos \psi_0 \frac{e^{-\gamma_0 R_0}}{R_0^2} - (1 + \gamma_0 R_1) \cos \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1^2} \right.$ $+ \frac{2 \cos \psi_1 e^{-\gamma_0 R_1}}{(\gamma_1^2 - \gamma_0^2) R_1^4} [(1 + \gamma_1 R_1 \sin \psi_1) (3 + 3\gamma_0 R_1 + \gamma_0^2 R_1^2)$ $- \sin^2 \psi_1 (15 + 15\gamma_0 R_1 + 6\gamma_0^2 R_1^2 + \gamma_0^3 R_1^3)] \Bigg\}$
$+ \gamma_0 R_0 + \gamma_0^2 R_0^2) \frac{e^{-\gamma_0 R_0}}{R_0^3}$ $+ \gamma_1^2 R_1^2) \frac{e^{-\gamma_0 R_1}}{R_1^3}$ $+ \gamma_0^2 R_1^2) \frac{e^{-\gamma_0 R_1}}{R_1^3} \Bigg\}$	$\frac{m \sin \phi}{4\pi} \left\{ (3 + 3\gamma_0 R_0 + \gamma_0^2 R_0^2) \sin \psi_0 \cos \psi_0 \frac{e^{-\gamma_0 R_0}}{R_0^3} \right.$ $+ (3 + 3\gamma_0 R_1 + \gamma_0^2 R_1^2) \sin \psi_1 \cos \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1^3}$ $+ \frac{2 \cos \psi_1 e^{-\gamma_0 R_1}}{\gamma_1 R_1^4} [(3 + 3\gamma_0 R_1 + \gamma_0^2 R_1^2)$ $- \sin^2 \psi_1 (15 + 15\gamma_0 R_1 + 6\gamma_0^2 R_1^2 + \gamma_0^3 R_1^3)] \Bigg\}$

Table 3. Electric-Field Air-to-Air Propagation Formulas for the

Dipole Type	E_p	E_ϕ
VED	$\frac{\gamma_0 n_0 p}{4\pi} \left[\sin \psi_0 \cos \psi_0 \frac{e^{-\gamma_0 R_0}}{R_0} + \Gamma_{11} \sin \psi_1 \cos \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1} - (1 - \Gamma_{11}) \Delta F(w) \cos \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1} \right]$	0
VMD	0	$-\frac{i\omega\mu_0\gamma_0 m}{4\pi} \left[\cos \psi_0 \frac{e^{-\gamma_0 R_0}}{R_0} - \cos \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1} \right] + \frac{2 \cos \psi_1 e^{-\gamma_0 R_1}}{\gamma_0 n^2 R_1^2} (1 + \gamma_1 R_1 \sin \psi_1)$
HED	$-\frac{\gamma_0 n_0 p \cos \phi}{4\pi} \left[\sin^2 \psi_0 \frac{e^{-\gamma_0 R_0}}{R_0} - \Gamma_{11} \sin^2 \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1} - (1 - \Gamma_{11}) \Delta^2 F(w) \frac{e^{-\gamma_0 R_1}}{R_1} \right]$	$\frac{\gamma_0 n_0 p \sin \phi}{4\pi} \left[\frac{e^{-\gamma_0 R_0}}{R_0} - \frac{e^{-\gamma_0 R_1}}{R_1} \right] + \frac{2e^{-\gamma_0 R_1}}{\gamma_0 n^2 R_1^2} (1 + A + \gamma_1 R_1 \sin \psi_1)$
HMD	$-\frac{i\omega\mu_0\gamma_0 m \cos \phi}{4\pi} \left[\sin \psi_0 \frac{e^{-\gamma_0 R_0}}{R_0} + \Gamma_{11} \sin \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1} - (1 - \Gamma_{11}) \Delta F(w) \frac{e^{-\gamma_0 R_1}}{R_1} \right]$	$\frac{i\omega\mu_0\gamma_0 m \sin \phi}{4\pi} \left[\sin \psi_0 \frac{e^{-\gamma_0 R_0}}{R_0} + \sin \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1} \right] - \frac{2e^{-\gamma_0 R_1}}{n R_1} \left[\sin^2 \psi_1 - \frac{1}{\gamma_0 R_1} (1 + A) \right]$

Propagation Formulas for the Farfield Case ($|n^2| \geq 10$, $|\gamma_0 R_1| \gg 1$)

E_ϕ	E_z
0	$-\frac{\gamma_0 n_0 p}{4\pi} \left[\cos^2 \psi_0 \frac{e^{-\gamma_0 R_0}}{R_0} + \Gamma_{11} \cos^2 \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1} \right. \\ \left. + (1 - \Gamma_{11}) F(w) \cos^2 \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1} \right]$
$\frac{i\omega\mu_0\gamma_0 m}{4\pi} \left[\cos \psi_0 \frac{e^{-\gamma_0 R_0}}{R_0} - \cos \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1} \right. \\ \left. - \frac{\cos \psi_1 e^{-\gamma_0 R_1}}{\gamma_0 n^2 R_1^2} (1 + \gamma_1 R_1 \sin \psi_1) \right]$	0
$\frac{n_0 p \sin \phi}{4\pi} \left[\frac{e^{-\gamma_0 R_0}}{R_0} - \frac{e^{-\gamma_0 R_1}}{R_1} \right. \\ \left. - \frac{e^{-\gamma_0 R_1}}{\gamma_0 n^2 R_1^2} (1 + A + \gamma_1 R_1 \sin \psi_1) \right]$	$\frac{\gamma_0 n_0 p \cos \phi}{4\pi} \left[\sin \psi_0 \cos \psi_0 \frac{e^{-\gamma_0 R_0}}{R_0} \right. \\ \left. - \Gamma_{11} \sin \psi_1 \cos \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1} \right. \\ \left. + (1 - \Gamma_{11}) \Delta F(w) \cos \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1} \right]$
$\frac{i\omega\mu_0\gamma_0 m \sin \phi}{4\pi} \left[\sin \psi_0 \frac{e^{-\gamma_0 R_0}}{R_0} + \sin \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1} \right. \\ \left. - \frac{e^{-\gamma_0 R_1}}{\gamma_0 n R_1} \left[\sin^2 \psi_1 - \frac{1}{\gamma_0 R_1} (1 + A - 3 \sin^2 \psi_1) \right] \right]$	$\frac{i\omega\mu_0\gamma_0 m \cos \phi}{4\pi} \left[\cos \psi_0 \frac{e^{-\gamma_0 R_0}}{R_0} + \Gamma_{11} \cos \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1} \right. \\ \left. + (1 - \Gamma_{11}) F(w) \cos \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1} \right]$

Table 4. Magnetic-Field Air-to-Air Propagation Formulas for the Farfield Case

Dipole Type	H_0	H_ϕ
VED	0	$\frac{p}{4\pi} \left[\cos \psi_0 \frac{e^{-\gamma_0 R_0}}{R_0} + \Gamma_{11} \cos \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1} + (1 - \Gamma_{11}) F(w) \cos \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1} \right]$
VMD	$\frac{\gamma_0^2 m}{4\pi} \left[\sin \psi_0 \cos \psi_0 \frac{e^{-\gamma_0 R_0}}{R_0} - \sin \psi_1 \cos \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1} + \frac{2 \cos \psi_1 e^{-\gamma_0 R_1}}{n R_1} \left(\sin^2 \psi_1 - \frac{1}{\gamma_0 R_1} \right) \right]$	0
HED	$-\frac{\gamma_0 p \sin \phi}{4\pi} \left[\sin \psi_0 \frac{e^{-\gamma_0 R_0}}{R_0} - \sin \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1} + \frac{2 e^{-\gamma_0 R_1}}{n R_1} \left[\sin^2 \psi_1 - \frac{1}{\gamma_0 R_1} (1 + A - 3 \sin^2 \psi_1) \right] \right]$	$-\frac{\gamma_0 p \cos \phi}{4\pi} \left[\sin \psi_0 \frac{e^{-\gamma_0 R_0}}{R_0} - \Gamma_{11} \sin \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1} + (1 - \Gamma_{11}) \Delta F(w) \frac{e^{-\gamma_0 R_1}}{R_1} \right]$
HMD	$-\frac{\gamma_0^2 m \sin \phi}{4\pi} \left[\left[\sin^2 \psi_0 - \frac{1}{\gamma_0 R_0} (2 - 3 \sin^2 \psi_0) \right] \frac{e^{-\gamma_0 R_0}}{R_0} + \left[\sin^2 \psi_1 - \frac{1}{\gamma_0 R_1} (2A - 3 \sin^2 \psi_1) \right] \frac{e^{-\gamma_0 R_1}}{R_1} \right]$	$-\frac{\gamma_0^2 m \cos \phi}{4\pi} \left[\frac{e^{-\gamma_0 R_0}}{R_0} + (\Gamma_{11}) \frac{e^{-\gamma_0 R_1}}{R_1} + (1 - \Gamma_{11}) F(w) \frac{e^{-\gamma_0 R_1}}{R_1} \right]$

Far Propagation Formulas for the Farfield Case ($|n^2| \geq 10$, $|\gamma_0 R| \gg 1$)

H_ϕ	H_z
$\frac{p}{4\pi} \left[\cos \psi_0 \frac{e^{-\gamma_0 R_0}}{R_0} + \Gamma_{11} \cos \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1} \right. \\ \left. + (1 - \Gamma_{11}) F(w) \cos \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1} \right]$	0
0	$-\frac{\gamma_0^2 m}{4\pi} \left[\cos^2 \psi_0 \frac{e^{-\gamma_0 R_0}}{R_0} - \cos^2 \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1} \right. \\ \left. + \frac{2 \cos^2 \psi_1 e^{-\gamma_0 R_1}}{\gamma_0 n^2 R_1^2} (1 + \gamma_1 R_1 \sin \psi_1) \right]$
$-\frac{\gamma_0 p \cos \phi}{4\pi} \left[\sin \psi_0 \frac{e^{-\gamma_0 R_0}}{R_0} - \Gamma_{11} \sin \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1} \right. \\ \left. + (1 - \Gamma_{11}) \Delta F(w) \frac{e^{-\gamma_0 R_1}}{R_1} \right]$	$\frac{\gamma_0 p \sin \phi}{4\pi} \left[\cos \psi_0 \frac{e^{-\gamma_0 R_0}}{R_0} - \cos \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1} \right. \\ \left. + \frac{2 \cos \psi_1 e^{-\gamma_0 R_1}}{\gamma_0 n^2 R_1^2} (1 + \gamma_1 R_1 \sin \psi_1) \right]$
$-\frac{\gamma_0^2 m \cos \phi}{4\pi} \left[\frac{e^{-\gamma_0 R_0}}{R_0} + (\Gamma_{11}) \frac{e^{-\gamma_0 R_1}}{R_1} \right. \\ \left. + (1 - \Gamma_{11}) F(w) \frac{e^{-\gamma_0 R_1}}{R_1} \right]$	$\frac{\gamma_0^2 m \sin \phi}{4\pi} \left[\sin \psi_0 \cos \psi_0 \frac{e^{-\gamma_0 R_0}}{R_0} \right. \\ \left. + \sin \psi_1 \cos \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1} \right. \\ \left. - \frac{2 \cos \psi_1 e^{-\gamma_0 R_1}}{n R_1} \left(\sin^2 \psi_1 - \frac{1}{\gamma_0 R_1} \right) \right]$

Table 5. Electric-Field Subsurface-to-Air Propagation Formulas

Dipole Type	E_ρ	E_ϕ
VED	$\frac{p \cos \psi e^{-\gamma_1 h} e^{-\gamma_0 R}}{2\pi(\sigma_1 + i\omega\epsilon_1)R^3} [(3 + 3\gamma_0 R) \sin \psi - \Delta\gamma_0 R + \gamma_0^2 R^2 B]$	0
VMD	0	$-\frac{m \cos \psi e^{-\gamma_1 h} e^{-\gamma_0 R}}{2\pi(\sigma_1 + i\omega\epsilon_1)R^4} [(1 + \gamma_1 R \sin \psi)(3 + \gamma_0^2 R^2) - \sin^2 \psi(15 + 15\gamma_0 R + 6\gamma_0^2 R^2 +$
HED	$\frac{p \cos \phi e^{-\gamma_1 h} e^{-\gamma_0 R}}{2\pi(\sigma_1 + i\omega\epsilon_1)R^3} (1 - \gamma_1 R \sin \psi + \gamma_0 R - \gamma_0^2 R^2 nB)$	$\frac{p \sin \phi e^{-\gamma_1 h} e^{-\gamma_0 R}}{2\pi(\sigma_1 + i\omega\epsilon_1)R^3} [2 + \gamma_1 R \sin \psi + \gamma_0 R(1 + \gamma_1 R \sin \psi) - \sin^2 \psi(3 + 3\gamma_0 R + \gamma_0^2 R^2)]$
HMD	$\frac{\gamma_1 m \cos \phi e^{-\gamma_1 h} e^{-\gamma_0 R}}{2\pi(\sigma_1 + i\omega\epsilon_1)R^3} (1 - \gamma_1 R \sin \psi + \gamma_0 R - \gamma_0^2 R^2 nB)$	$\frac{\gamma_1 m \sin \phi e^{-\gamma_1 h} e^{-\gamma_0 R}}{2\pi(\sigma_1 + i\omega\epsilon_1)R^3} [2 + \gamma_1 R \sin \psi + \gamma_0 R(1 + \gamma_1 R \sin \psi) - \sin^2 \psi(3 + 3\gamma_0 R + \gamma_0^2 R^2)]$

to-Air Propagation Formulas ($|n^2| \geq 10$, $R \geq 10\delta$, $R \geq 5h$)

E_ϕ	E_z
0	$-\frac{pe^{-\gamma_1 h} e^{-\gamma_0 R}}{2\pi(\sigma_1 + i\omega\epsilon_1)R^3}[(1 - 3 \sin^2 \psi)(1 + \gamma_0 R)$ $+ \gamma_0^2 R^2 A \cos^2 \psi]$
$\frac{pe^{-\gamma_1 h} e^{-\gamma_0 R}}{2\pi(\sigma_1 + i\omega\epsilon_1)R^4}[(1 + \gamma_1 R \sin \psi)(3 + 3\gamma_0 R$ $\sin^2 \psi(15 + 15\gamma_0 R + 6\gamma_0^2 R^2 + \gamma_0^3 R^3)]$	0
$\frac{pe^{-\gamma_1 h} e^{-\gamma_0 R}}{2\pi(\sigma_1 + i\omega\epsilon_1)R^3}[2 + \gamma_1 R \sin \psi + \gamma_0 R(1 + A$ $\sin^2 \psi(3 + 3\gamma_0 R + \gamma_0^2 R^2)]$	$\frac{\gamma_1 p \cos \phi \cos \psi e^{-\gamma_1 h} e^{-\gamma_0 R}}{2\pi(\sigma_1 + i\omega\epsilon_1)R^2}(1 + \gamma_0 R A)$
$\frac{pe^{-\gamma_1 h} e^{-\gamma_0 R}}{2\pi(\sigma_1 + i\omega\epsilon_1)R^3}[2 + \gamma_1 R \sin \psi + \gamma_0 R(1 + A$ $\sin^2 \psi(3 + 3\gamma_0 R + \gamma_0^2 R^2)]$	$\frac{\gamma_1^2 m \cos \phi \cos \psi e^{-\gamma_1 h} e^{-\gamma_0 R}}{2\pi(\sigma_1 + i\omega\epsilon_1)R^2}(1 + \gamma_0 R A)$

Table 6. Magnetic-Field Subsurface-to-Air Propagation Formulas ($|n^2$

Dipole Type	H_p	H_ϕ	
VED	0	$\frac{p \cos \psi e^{-\gamma_1 h} e^{-\gamma_0 R}}{2\pi n^2 R^2} (1 + \gamma_0 R A)$	
VMD	$-\frac{m \cos \psi e^{-\gamma_1 h} e^{-\gamma_0 R}}{2\pi \gamma_1 R^4} [(3 + 3\gamma_0 R + \gamma_0^2 R^2) - \sin^2 \psi (15 + 15\gamma_0 R + 6\gamma_0^2 R^2 + \gamma_0^3 R^3)]$	0	$-\frac{m \cos \psi e^{-\gamma_1 h} e^{-\gamma_0 R}}{2\pi \gamma_1 R^4} [(3 + 3\gamma_0 R + \gamma_0^2 R^2) - \sin^2 \psi (15 + 15\gamma_0 R + 6\gamma_0^2 R^2 + \gamma_0^3 R^3)]$
HED	$\frac{p \sin \phi e^{-\gamma_1 h} e^{-\gamma_0 R}}{2\pi \gamma_1 R^3} [2 + \gamma_0 R (1 + A) - \sin^2 \psi (3 + 3\gamma_0 R + \gamma_0^2 R^2)]$	$-\frac{p \cos \phi e^{-\gamma_1 h} e^{-\gamma_0 R}}{2\pi \gamma_1 R^3} (1 + \gamma_0 R + \gamma_0^2 R^2 A)$	$\frac{p \sin \phi e^{-\gamma_1 h} e^{-\gamma_0 R}}{2\pi \gamma_1 R^3} [2 + \gamma_0 R (1 + A) - \sin^2 \psi (3 + 3\gamma_0 R + \gamma_0^2 R^2)]$
HMD	$\frac{m \sin \phi e^{-\gamma_1 h} e^{-\gamma_0 R}}{2\pi R^3} [2 + \gamma_0 R (1 + A) - \sin^2 \psi (3 + 3\gamma_0 R + \gamma_0^2 R^2)]$	$-\frac{m \cos \phi e^{-\gamma_1 h} e^{-\gamma_0 R}}{2\pi R^3} (1 + \gamma_0 R + \gamma_0^2 R^2 A)$	$\frac{m \sin \phi e^{-\gamma_1 h} e^{-\gamma_0 R}}{2\pi R^3} [2 + \gamma_0 R (1 + A) - \sin^2 \psi (3 + 3\gamma_0 R + \gamma_0^2 R^2)]$

Surface-to-Air Propagation Formulas ($|n^2| \geq 10$, $R \geq 106$, $R \geq 5h$)

H_ϕ	H_z
$\frac{e^{-\gamma_1 h} e^{-\gamma_0 R}}{2\pi R^2} (1 + \gamma_0 R A)$	0
0	$- \frac{m e^{-\gamma_1 h} e^{-\gamma_0 R}}{2\pi(\gamma_1^2 - \gamma_0^2)R^5} \left\{ (1 + \gamma_1 R \sin \psi) [(9 + 9\gamma_0 R + 4\gamma_0^2 R^2 + \gamma_0^3 R^3) \right.$ $- \sin^2 \psi (15 + 15\gamma_0 R + 6\gamma_0^2 R^2 + \gamma_0^3 R^3)]$ $- \sin^2 \psi (75 + 75\gamma_0 R + 33\gamma_0^2 R^2 + 6\gamma_0^3 R^3)$ $\left. + \sin^4 \psi (105 + 105\gamma_0 R + 45\gamma_0^2 R^2 + 6\gamma_0^3 R^3) \right\}$
$\frac{p e^{-\gamma_1 h} e^{-\gamma_0 R}}{2\pi \gamma_1 R^3} (1 + \gamma_0 R + \gamma_0^2 R^2 A)$	$\frac{p \sin \phi \cos \psi e^{-\gamma_1 h} e^{-\gamma_0 R}}{2\pi(\gamma_1^2 - \gamma_0^2)R^4} [(1 + \gamma_1 R \sin \psi) (3 + 3\gamma_0 R$ $+ \gamma_0^2 R^2) - \sin^2 \psi (15 + 15\gamma_0 R + 6\gamma_0^2 R^2 + \gamma_0^3 R^3)]$
$\frac{m e^{-\gamma_1 h} e^{-\gamma_0 R}}{2\pi R^3} (1 + \gamma_0 R + \gamma_0^2 R^2 A)$	$\frac{m \sin \phi \cos \psi e^{-\gamma_1 h} e^{-\gamma_0 R}}{2\pi \gamma_1 R^4} [(1 + \gamma_1 R \sin \psi) (3 + 3\gamma_0 R$ $+ \gamma_0^2 R^2) - \sin^2 \psi (15 + 15\gamma_0 R + 6\gamma_0^2 R^2 + \gamma_0^3 R^3)]$

Table 7. Subsurface-to-Air Propagation Formulas When $\rho \gg$

Dipole Type	E_ρ	E_ϕ	E_z	
VED	$\frac{pe^{-\gamma_1 h} e^{-\gamma_0 \rho}}{2\pi(\sigma_1 + i\omega\epsilon_1)\rho^3} [(3 + 3\gamma_0 \rho) \sin \psi$ $- \Delta\gamma_0 \rho + \gamma_0^2 \rho^2 B]$	0	$- \frac{pe^{-\gamma_1 h} e^{-\gamma_0 \rho}}{2\pi(\sigma_1 + i\omega\epsilon_1)\rho^3}$ $\times (1 + \gamma_0 \rho + \gamma_0^2 \rho^2 A)$	
VMD	0	$- \frac{me^{-\gamma_1 h} e^{-\gamma_0 \rho}}{2\pi(\sigma_1 + i\omega\epsilon_1)\rho^4} (1 + \gamma_1 z)$ $\times (3 + 3\gamma_0 \rho + \gamma_0^2 \rho^2)$	0	
HED	$\frac{p \cos \phi e^{-\gamma_1 h} e^{-\gamma_0 \rho}}{2\pi(\sigma_1 + i\omega\epsilon_1)\rho^3} (1 - \gamma_1 z$ $+ \gamma_0 \rho - \gamma_0^2 \rho^2 nB)$	$\frac{p \sin \phi e^{-\gamma_1 h} e^{-\gamma_0 \rho}}{2\pi(\sigma_1 + i\omega\epsilon_1)\rho^3} [2 + \gamma_1 z$ $+ \gamma_0 \rho (1 + A + \gamma_1 z)]$	$\frac{\gamma_1 p \cos \phi e^{-\gamma_1 h} e^{-\gamma_0 \rho}}{2\pi(\sigma_1 + i\omega\epsilon_1)\rho^2}$ $\times (1 + \gamma_0 \rho A)$	$\frac{p}{\rho}$
HMD	$\frac{\gamma_1 m \cos \phi e^{-\gamma_1 h} e^{-\gamma_0 \rho}}{2\pi(\sigma_1 + i\omega\epsilon_1)\rho^3} (1 - \gamma_1 z$ $+ \gamma_0 \rho - \gamma_0^2 \rho^2 nB)$	$\frac{\gamma_1 m \sin \phi e^{-\gamma_1 h} e^{-\gamma_0 \rho}}{2\pi(\sigma_1 + i\omega\epsilon_1)\rho^3} [2 + \gamma_1 z$ $+ \gamma_0 \rho (1 + A + \gamma_1 z)]$	$\frac{\gamma_1^2 m \cos \phi e^{-\gamma_1 h} e^{-\gamma_0 \rho}}{2\pi(\sigma_1 + i\omega\epsilon_1)\rho^2}$ $\times (1 + \gamma_0 \rho A)$	$\frac{m}{\rho}$

Formulas When $\rho \gg z$ ($|n^2| \geq 10$, $\rho \geq 10\delta$, $\rho \geq 5h$)

E_z	H_ρ	H_ϕ	H_z
$\frac{-\gamma_1 h e^{-\gamma_0 \rho}}{1 + i\omega\epsilon_1 \rho^3}$ $(\gamma_0 \rho + \gamma_0^2 \rho^2 A)$	0	$\frac{p e^{-\gamma_1 h} e^{-\gamma_0 \rho}}{2\pi n^2 \rho^2} (1 + \gamma_0 \rho A)$	0
0	$-\frac{m e^{-\gamma_1 h} e^{-\gamma_0 \rho}}{2\pi \gamma_1 \rho^4}$ $\times (3 + 3\gamma_0 \rho + \gamma_0^2 \rho^2)$	0	$-\frac{m e^{-\gamma_1 h} e^{-\gamma_0 \rho}}{2\pi (\gamma_1^2 - \gamma_0^2) \rho^5} (1 + \gamma_1 z)$ $\times (9 + 9\gamma_0 \rho + 4\gamma_0^2 \rho^2 + \gamma_0^3 \rho^3)$
$\frac{p e^{-\gamma_1 h} e^{-\gamma_0 \rho}}{1 + i\omega\epsilon_1 \rho^2}$ $(\gamma_0 \rho A)$	$\frac{p \sin \phi e^{-\gamma_1 h} e^{-\gamma_0 \rho}}{2\pi \gamma_1 \rho^3}$ $\times [2 + \gamma_0 \rho (1 + A)]$	$-\frac{p \cos \phi e^{-\gamma_1 h} e^{-\gamma_0 \rho}}{2\pi \gamma_1 \rho^3}$ $\times (1 + \gamma_0 \rho + \gamma_0^2 \rho^2 A)$	$\frac{p \sin \phi e^{-\gamma_1 h} e^{-\gamma_0 \rho}}{2\pi (\gamma_1^2 - \gamma_0^2) \rho^4} (1 + \gamma_1 z)$ $\times (3 + 3\gamma_0 \rho + \gamma_0^2 \rho^2)$
$\frac{p e^{-\gamma_1 h} e^{-\gamma_0 \rho}}{1 + i\omega\epsilon_1 \rho^2}$ $(\gamma_0 \rho A)$	$\frac{m \sin \phi e^{-\gamma_1 h} e^{-\gamma_0 \rho}}{2\pi \rho^3}$ $\times [2 + \gamma_0 \rho (1 + A)]$	$-\frac{m \cos \phi e^{-\gamma_1 h} e^{-\gamma_0 \rho}}{2\pi \rho^3}$ $\times (1 + \gamma_0 \rho + \gamma_0^2 \rho^2 A)$	$\frac{m \sin \phi e^{-\gamma_1 h} e^{-\gamma_0 \rho}}{2\pi \gamma_1 \rho^4} (1 + \gamma_1 z)$ $\times (3 + 3\gamma_0 \rho + \gamma_0^2 \rho^2)$

Table 8. Subsurface-to-Air Propagation Formulas

Dipole Type	E_ρ	E_ϕ	E_z
VED	$\frac{p \sin \psi \cos \psi e^{-\gamma_1 h} e^{-\gamma_0 z}}{2\pi(\sigma_1 + i\omega\epsilon_1)z^3}$ $\times (3 + 3\gamma_0 z + \gamma_0^2 z^2)$	0	$-\frac{p e^{-\gamma_1 h} e^{-\gamma_0 z}}{2\pi(\sigma_1 + i\omega\epsilon_1)z^3}[(1 - 3 \sin^2 \psi)]$ $\times (1 + \gamma_0 z) + \gamma_0^2 z^2 \cos^2 \psi]$
VMD	0	$-\frac{\gamma_1 m \sin \psi \cos \psi e^{-\gamma_1 h} e^{-\gamma_0 z}}{2\pi(\sigma_1 + i\omega\epsilon_1)z^3}$ $\times (3 + 3\gamma_0 z + \gamma_0^2 z^2)$	0
HED	$-\frac{\gamma_1 p \cos \phi \sin \psi e^{-\gamma_1 h} e^{-\gamma_0 z}}{2\pi(\sigma_1 + i\omega\epsilon_1)z^2}$ $\times (1 + \gamma_0 z)$	$\frac{\gamma_1 p \sin \phi \sin \psi e^{-\gamma_1 h} e^{-\gamma_0 z}}{2\pi(\sigma_1 + i\omega\epsilon_1)z^2}$ $\times (1 + \gamma_0 z)$	$\frac{\gamma_1 p \cos \phi \cos \psi e^{-\gamma_1 h} e^{-\gamma_0 z}}{2\pi(\sigma_1 + i\omega\epsilon_1)z^2}$ $\times (1 + \gamma_0 z)$
HMD	$-\frac{\gamma_1^2 m \cos \phi \sin \psi e^{-\gamma_1 h} e^{-\gamma_0 z}}{2\pi(\sigma_1 + i\omega\epsilon_1)z^2}$ $\times (1 + \gamma_0 z)$	$\frac{\gamma_1^2 m \sin \phi \sin \psi e^{-\gamma_1 h} e^{-\gamma_0 z}}{2\pi(\sigma_1 + i\omega\epsilon_1)z^2}$ $\times (1 + \gamma_0 z)$	$\frac{\gamma_1^2 m \cos \phi \cos \psi e^{-\gamma_1 h} e^{-\gamma_0 z}}{2\pi(\sigma_1 + i\omega\epsilon_1)z^2}$ $\times (1 + \gamma_0 z)$

on Formulas When $z \gg \rho$ ($|n^2| \geq 10$, $z \geq 10\delta$, $z \geq 5h$)

	H_p	H_ϕ	H_z
$(1 - 3 \sin^2 \psi)$ $\cos^2 \psi]$	0	$\frac{p \cos \psi e^{-\gamma_1 h} e^{-\gamma_0 z}}{2\pi n^2 z^2}$ $\times (1 + \gamma_0 z)$	0
	$\frac{m \cos \psi e^{-\gamma_1 h} e^{-\gamma_0 z}}{2\pi \gamma_1 z^4} (12 + 12\gamma_0 z$ $+ 5\gamma_0^2 z^2 + \gamma_0^3 z^3)$	0	$\frac{m \sin \psi e^{-\gamma_1 h} e^{-\gamma_0 z}}{\pi \gamma_1 z^4}$ $\times (3 + 3\gamma_0 z + \gamma_0^2 z^2)$
$\frac{h e^{-\gamma_0 z}}{z^2}$	$-\frac{p \sin \phi e^{-\gamma_1 h} e^{-\gamma_0 z}}{2\pi \gamma_1 z^3}$ $\times (1 + \gamma_0 z + \gamma_0^2 z^2)$	$-\frac{p \cos \phi e^{-\gamma_1 h} e^{-\gamma_0 z}}{2\pi \gamma_1 z^3}$ $\times (1 + \gamma_0 z + \gamma_0^2 z^2)$	$\frac{p \sin \phi \sin \psi \cos \psi e^{-\gamma_1 h} e^{-\gamma_0 z}}{2\pi \gamma_1 z^3}$ $\times (3 + 3\gamma_0 z + \gamma_0^2 z^2)$
$\frac{h e^{-\gamma_0 z}}{z^2}$	$-\frac{m \sin \phi e^{-\gamma_1 h} e^{-\gamma_0 z}}{2\pi z^3}$ $\times (1 + \gamma_0 z + \gamma_0^2 z^2)$	$-\frac{m \cos \phi e^{-\gamma_1 h} e^{-\gamma_0 z}}{2\pi z^3}$ $\times (1 + \gamma_0 z + \gamma_0^2 z^2)$	$\frac{m \sin \phi \sin \psi \cos \psi e^{-\gamma_1 h} e^{-\gamma_0 z}}{2\pi z^3}$ $\times (3 + 3\gamma_0 z + \gamma_0^2 z^2)$

Table 9. Electric-Field Air-to-Subsurface Propagation

Dipole Type	E_ρ	E_ϕ
VED	$-\frac{\gamma_1 p \cos \psi e^{-\gamma_1 z} e^{-\gamma_0 D}}{2\pi(\sigma_1 + i\omega\epsilon_1)D^2}(1 + \gamma_0 D A)$	0
VMD	0	$-\frac{m \cos \psi e^{-\gamma_1 z} e^{-\gamma_0 D}}{2\pi(\sigma_1 + i\omega\epsilon_1)D^4}[(1 + \gamma_1 D \sin \psi)(3 + \sin^2 \psi(15 + 15\gamma_0 D + 6\gamma_0^2 D^2 + \gamma_0^3 D^3))]$
HED	$\frac{p \cos \phi e^{-\gamma_1 z} e^{-\gamma_0 D}}{2\pi(\sigma_1 + i\omega\epsilon_1)D^3}(1 - \gamma_1 D \sin \psi + \gamma_0 D - \gamma_0^2 D^2 n B)$	$\frac{p \sin \phi e^{-\gamma_1 z} e^{-\gamma_0 D}}{2\pi(\sigma_1 + i\omega\epsilon_1)D^3}[2 + \gamma_1 D \sin \psi + \gamma_0 D(1 + A + \gamma_1 D \sin \psi) - \sin^2 \psi(3 + \gamma_0 D(1 + A + \gamma_1 D \sin \psi) - \sin^2 \psi(3 + 3\gamma_0 D + \gamma_0^2 D^2))]$
HMD	$\frac{\gamma_1 m \cos \phi e^{-\gamma_1 z} e^{-\gamma_0 D}}{2\pi(\sigma_1 + i\omega\epsilon_1)D^3}(1 + \gamma_0 D + \gamma_0^2 D^2 A)$	$\frac{\gamma_1 m \sin \phi e^{-\gamma_1 z} e^{-\gamma_0 D}}{2\pi(\sigma_1 + i\omega\epsilon_1)D^3}[2 + \gamma_0 D(1 + A) - \sin^2 \psi(3 + 3\gamma_0 D + \gamma_0^2 D^2)]$

Subsurface Propagation Formulas ($|n^2| \geq 10$, $D \geq 10\delta$, $D \geq 5z$)

E_ϕ	E_z
0	$-\frac{pe^{-\gamma_1 z} e^{-\gamma_0 D}}{2\pi(\sigma_1 + i\omega\epsilon_1)D^3}[(1 - 3 \sin^2 \psi)(1 + \gamma_0 D)$ $+ \gamma_0^2 D^2 A \cos^2 \psi]$
$\frac{-\gamma_1 z e^{-\gamma_0 D}}{i\omega\epsilon_1 D^4}[(1 + \gamma_1 D \sin \psi)(3 + 3\gamma_0 D + \gamma_0^2 D^2)$ $+ 15\gamma_0 D + 6\gamma_0^2 D^2 + \gamma_0^3 D^3]$	0
$\frac{-\gamma_1 z e^{-\gamma_0 D}}{i\omega\epsilon_1 D^3}[2 + \gamma_1 D \sin \psi$ $(A + \gamma_1 D \sin \psi) - \sin^2 \psi(3 + 3\gamma_0 D + \gamma_0^2 D^2)]$	$-\frac{p \cos \phi \cos \psi e^{-\gamma_1 z} e^{-\gamma_0 D}}{2\pi(\sigma_1 + i\omega\epsilon_1)D^3}[(3 + 3\gamma_0 D) \sin \psi$ $- \gamma_0 \Delta D + \gamma_0^2 D^2 B]$
$\frac{-\gamma_1 z e^{-\gamma_0 D}}{i\omega\epsilon_1 D^3}[2 + \gamma_0 D(1 + A)$ $+ 3\gamma_0 D + \gamma_0^2 D^2]$	$\frac{m \cos \phi \cos \psi e^{-\gamma_1 z} e^{-\gamma_0 D}}{2\pi(\sigma_1 + i\omega\epsilon_1)D^2}(\gamma_0^2)(1 + \gamma_0 \Delta A)$

Table 10. Magnetic-Field Air-to-Subsurface Propagation Formulas

Dipole Type	H_p	H_ϕ
VED	0	$\frac{p \cos \psi e^{-\gamma_1 z} e^{-\gamma_0 D}}{2\pi D^2} (1 + \gamma_0 D A)$
VMD	$-\frac{m \cos \psi e^{-\gamma_1 z} e^{-\gamma_0 D}}{2\pi \gamma_1 D^4} [(1 + \gamma_1 D \sin \psi)(3 + 3\gamma_0 D + \gamma_0^2 D^2) - \sin^2 \psi (15 + 15\gamma_0 D + 6\gamma_0^2 D^2 + \gamma_0^3 D^3)]$	0
HED	$\frac{p \sin \phi e^{-\gamma_1 z} e^{-\gamma_0 D}}{2\pi \gamma_1 D^3} [2 + \gamma_1 D \sin \psi + \gamma_0 D (1 + A + \gamma_1 D \sin \psi) - \sin^2 \psi (3 + 3\gamma_0 D + \gamma_0^2 D^2)]$	$-\frac{p \cos \phi e^{-\gamma_1 z} e^{-\gamma_0 D}}{2\pi \gamma_1 D^3} (1 - \gamma_1 D \sin \psi + \gamma_0 D)$
HMD	$\frac{m \sin \phi e^{-\gamma_1 z} e^{-\gamma_0 D}}{2\pi D^3} [2 + \gamma_0 D (1 + A) - \sin^2 \psi (3 + 3\gamma_0 D + \gamma_0^2 D^2)]$	$-\frac{m \cos \phi e^{-\gamma_1 z} e^{-\gamma_0 D}}{2\pi D^3} (1 + \gamma_0 D + \gamma_0^2 D^2 A)$

Subsurface Propagation Formulas ($|n^2| \geq 10$, $D \geq 10\delta$, $D \geq 5z$)

H_ϕ	H_z
$\frac{e^{-\gamma_1 z - \gamma_0 D}}{(1 + \gamma_0 D A)}$	0
0	$- \frac{m e^{-\gamma_1 z - \gamma_0 D}}{2\pi(\gamma_1^2 - \gamma_0^2) D^5} \left\{ (1 + \gamma_1 D \sin \psi) (9 + 9\gamma_0 D + 4\gamma_0^2 D^2 + \gamma_0^3 D^3) \right.$ $- \sin^2 \psi (15 + 15\gamma_0 D + 6\gamma_0^2 D^2 + \gamma_0^3 D^3) - \sin^2 \psi (75 + 75\gamma_0 D$ $+ 33\gamma_0^2 D^2 + 6\gamma_0^3 D^3) + \sin^4 \psi (105 + 105\gamma_0 D + 45\gamma_0^2 D^2 + 6\gamma_0^3 D^3) \left. \right\}$
$\frac{\gamma_1 z - \gamma_0 D}{D^3} (1 - \gamma_1 D \sin \psi + \gamma_0 D - \gamma_0^2 D^2 n B)$	$\frac{p \sin \phi \cos \psi e^{-\gamma_1 z - \gamma_0 D}}{2\pi(\gamma_1^2 - \gamma_0^2) D^4} [(1 + \gamma_1 D \sin \psi) (3 + 3\gamma_0 D + \gamma_0^2 D^2)$ $- \sin^2 \psi (15 + 15\gamma_0 D + 6\gamma_0^2 D^2 + \gamma_0^3 D^3)]$
$\frac{\gamma_1 z - \gamma_0 D}{D^3} (1 + \gamma_0 D + \gamma_0^2 D^2 A)$	$\frac{m \sin \phi \cos \psi e^{-\gamma_1 z - \gamma_0 D}}{2\pi\gamma_1 D^4} [(3 + 3\gamma_0 D + \gamma_0^2 D^2)$ $- \sin^2 \psi (15 + 15\gamma_0 D + 6\gamma_0^2 D^2 + \gamma_0^3 D^3)]$

1 2

Table 11. Air-to-Subsurface Propagation Formulas When

Dipole Type	E_ρ	E_ϕ	E_z
VED	$-\frac{\gamma_1 p e^{-\gamma_1 z} e^{-\gamma_0 \rho}}{2\pi(\sigma_1 + i\omega\epsilon_1)\rho^2}(1 + \gamma_0 \rho A)$	0	$-\frac{p e^{-\gamma_1 z} e^{-\gamma_0 \rho}}{2\pi(\sigma_1 + i\omega\epsilon_1)\rho^3} \times (1 + \gamma_0 \rho + \gamma_0^2 \rho^2 A)$
VMD	0	$-\frac{m e^{-\gamma_1 z} e^{-\gamma_0 \rho}}{2\pi(\sigma_1 + i\omega\epsilon_1)\rho^4}(1 + \gamma_1 h) \times (3 + 3\gamma_0 \rho + \gamma_0^2 \rho^2)$	0
HED	$\frac{p \cos \phi e^{-\gamma_1 z} e^{-\gamma_0 \rho}}{2\pi(\sigma_1 + i\omega\epsilon_1)\rho^3} \times (1 - \gamma_1 h + \gamma_0 \rho - \gamma_0^2 \rho^2 nB)$	$\frac{p \sin \phi e^{-\gamma_1 z} e^{-\gamma_0 \rho}}{2\pi(\sigma_1 + i\omega\epsilon_1)\rho^3} [2 + \gamma_1 h + \gamma_0 \rho (1 + A + \gamma_1 h)]$	$-\frac{p \cos \phi e^{-\gamma_1 z} e^{-\gamma_0 \rho}}{2\pi(\sigma_1 + i\omega\epsilon_1)\rho^3} \times [(3 + 3\gamma_0 \rho) \sin \psi - \Delta \gamma_0 \rho + \gamma_0^2 \rho^2 B]$
HMD	$\frac{\gamma_1 m \cos \phi e^{-\gamma_1 z} e^{-\gamma_0 \rho}}{2\pi(\sigma_1 + i\omega\epsilon_1)\rho^3} \times (1 + \gamma_0 \rho + \gamma_0^2 \rho^2 A)$	$\frac{\gamma_1 m \sin \phi e^{-\gamma_1 z} e^{-\gamma_0 \rho}}{2\pi(\sigma_1 + i\omega\epsilon_1)\rho^3} \times [2 + \gamma_0 \rho (1 + A)]$	$\frac{m \cos \phi e^{-\gamma_1 z} e^{-\gamma_0 \rho}}{2\pi(\sigma_1 + i\omega\epsilon_1)\rho^2} \times (\gamma_0^2)(1 + \gamma_0 \rho A)$

Formulas When $\rho \gg h$ ($|n^2| \geq 10$, $\rho \geq 106$, $\rho \geq 5z$)

	H_p	H_ϕ	H_z
	0	$\frac{pe^{-\gamma_1 z} e^{-\gamma_0 \rho}}{2\pi\rho^2} (1 + \gamma_0 \rho A)$	0
	$-\frac{me^{-\gamma_1 z} e^{-\gamma_0 \rho}}{2\pi\gamma_1 \rho^4} (1 + \gamma_1 h)$ $\times (3 + 3\gamma_0 \rho + \gamma_0^2 \rho^2)$	0	$-\frac{me^{-\gamma_1 z} e^{-\gamma_0 \rho}}{2\pi(\gamma_1^2 - \gamma_0^2) \rho^5} (1 + \gamma_1 h)$ $\times (9 + 9\gamma_0 \rho + 4\gamma_0^2 \rho^2 + \gamma_0^3 \rho^3)$
$\gamma_0 \rho + \gamma_0^2 \rho^2 B]$	$\frac{p \sin \phi e^{-\gamma_1 z} e^{-\gamma_0 \rho}}{2\pi\gamma_1 \rho^3} [2 + \gamma_1 h$ $+ \gamma_0 \rho (1 + A + \gamma_1 h)]$	$-\frac{p \cos \phi e^{-\gamma_1 z} e^{-\gamma_0 \rho}}{2\pi\gamma_1 \rho^3}$ $\times (1 - \gamma_1 h + \gamma_0 \rho - \gamma_0^2 \rho^2 nB)$	$\frac{p \sin \phi e^{-\gamma_1 z} e^{-\gamma_0 \rho}}{2\pi(\gamma_1^2 - \gamma_0^2) \rho^4} (1 + \gamma_1 h)$ $\times (3 + 3\gamma_0 \rho + \gamma_0^2 \rho^2)$
	$\frac{m \sin \phi e^{-\gamma_1 z} e^{-\gamma_0 \rho}}{2\pi\rho^3}$ $\times [2 + \gamma_0 \rho (1 + A)]$	$-\frac{m \cos \phi e^{-\gamma_1 z} e^{-\gamma_0 \rho}}{2\pi\rho^3}$ $\times (1 + \gamma_0 \rho + \gamma_0^2 \rho^2 A)$	$\frac{m \sin \phi e^{-\gamma_1 z} e^{-\gamma_0 \rho}}{2\pi\gamma_1 \rho^4}$ $\times (3 + 3\gamma_0 \rho + \gamma_0^2 \rho^2)$

Table 12. Air-to-Subsurface Propagation Formulas When

Dipole Type	E_ρ	E_ϕ	E_z
VED	$-\frac{\gamma_1 p \cos \psi e^{-\gamma_1 z} e^{-\gamma_0 h}}{2\pi(\sigma_1 + i\omega\epsilon_1)h^2}$ $\times (1 + \gamma_0 h)$	0	$-\frac{pe^{-\gamma_1 z} e^{-\gamma_0 h}}{2\pi(\sigma_1 + i\omega\epsilon_1)h^3}[(1 + \gamma_0 h)$ $\times (1 - 3 \sin^2 \psi) + \gamma_0^2 h^2 \cos^2 \psi]$
VMD	0	$-\frac{\gamma_1 m \sin \psi \cos \psi e^{-\gamma_1 z} e^{-\gamma_0 h}}{2\pi(\sigma_1 + i\omega\epsilon_1)h^3}$ $\times (3 + 3\gamma_0 h + \gamma_0^2 h^2)$	0
HED	$-\frac{\gamma_1 p \cos \phi \sin \psi e^{-\gamma_1 z} e^{-\gamma_0 h}}{2\pi(\sigma_1 + i\omega\epsilon_1)h^2}$ $\times (1 + \gamma_0 h)$	$\frac{\gamma_1 p \sin \phi \sin \psi e^{-\gamma_1 z} e^{-\gamma_0 h}}{2\pi(\sigma_1 + i\omega\epsilon_1)h^2}$ $\times (1 + \gamma_0 h)$	$-\frac{p \cos \phi \sin \psi \cos \psi e^{-\gamma_1 z} e^{-\gamma_0 h}}{2\pi(\sigma_1 + i\omega\epsilon_1)h^3}$ $\times (1 - 3\gamma_0 h + \gamma_0^2 h^2)$
HMD	$\frac{\gamma_1 m \cos \phi e^{-\gamma_1 z} e^{-\gamma_0 h}}{2\pi(\sigma_1 + i\omega\epsilon_1)h^3}$ $\times (1 + \gamma_0 h + \gamma_0^2 h^2)$	$-\frac{\gamma_1 m \sin \phi e^{-\gamma_1 z} e^{-\gamma_0 h}}{2\pi(\sigma_1 + i\omega\epsilon_1)h^3}$ $\times (1 + \gamma_0 h + \gamma_0^2 h^2)$	$\frac{\gamma_0^2 m \cos \phi \cos \psi e^{-\gamma_1 z} e^{-\gamma_0 h}}{2\pi(\sigma_1 + i\omega\epsilon_1)h^2}$ $\times (1 + \gamma_0 h)$

on Formulas When $h \gg \rho$ ($|n^2| \geq 10$, $h \geq 10\delta$, $h \geq 5z$)

	H_p	H_ϕ	H_z
$(1 + \gamma_0 h)$ $\gamma_0^2 h^2 \cos^2 \psi]$	0	$\frac{p \cos \psi e^{-\gamma_1 z} e^{-\gamma_0 h}}{2\pi h^2}$ $\times (1 + \gamma_0 h)$	0
	$\frac{m \sin \psi \cos \psi e^{-\gamma_1 z} e^{-\gamma_0 h}}{2\pi h^3}$ $\times (3 + 3\gamma_0 h + \gamma_0^2 h^2)$	0	$\frac{m \sin \psi e^{-\gamma_1 z} e^{-\gamma_0 h}}{\pi \gamma_1 h^4}$ $\times (3 + 3\gamma_0 h + \gamma_0^2 h^2)$
$\frac{p e^{-\gamma_1 z} e^{-\gamma_0 h}}{\epsilon_1 h^3}$	$\frac{p \sin \phi \sin \psi e^{-\gamma_1 z} e^{-\gamma_0 h}}{2\pi h^2}$ $\times (1 + \gamma_0 h)$	$\frac{p \cos \phi \sin \psi e^{-\gamma_1 z} e^{-\gamma_0 h}}{2\pi h^2}$ $\times (1 + \gamma_0 h)$	$\frac{p \sin \phi \sin \psi \cos \psi e^{-\gamma_1 z} e^{-\gamma_0 h}}{2\pi \gamma_1 h^3}$ $\times (3 + 3\gamma_0 h + \gamma_0^2 h^2)$
$\frac{p e^{-\gamma_1 z} e^{-\gamma_0 h}}{2}$	$-\frac{m \sin \phi e^{-\gamma_1 z} e^{-\gamma_0 h}}{2\pi h^3}$ $\times (1 + \gamma_0 h + \gamma_0^2 h^2)$	$-\frac{m \cos \phi e^{-\gamma_1 z} e^{-\gamma_0 h}}{2\pi h^3}$ $\times (1 + \gamma_0 h + \gamma_0^2 h^2)$	$-\frac{m \sin \phi \cos \psi e^{-\gamma_1 z} e^{-\gamma_0 h}}{2\pi \gamma_1 h^4}$ $\times (12 + 12\gamma_0 h + 5\gamma_0^2 h^2 + \gamma_0^3 h^3)$

Table 13. Surface-to-Surface Propagation Formulas for ρ

Dipole Type	E_ρ	E_ϕ	E_z	H_z
VED	$-\frac{\gamma_1 p e^{-\gamma_0 \rho}}{2\pi(\sigma_1 + i\omega\epsilon_1)\rho^2}$ $\times (1 + \gamma_0 \rho F)$	0	$-\frac{p e^{-\gamma_0 \rho}}{2\pi i \omega \epsilon_0 \rho^3}$ $\times (1 + \gamma_0 \rho + \gamma_0^2 \rho^2 F)$	
VMD	0	$-\frac{i\omega\mu_0 m e^{-\gamma_0 \rho}}{2\pi(\gamma_1^2 - \gamma_0^2)\rho^4}$ $\times (3 + 3\gamma_0 \rho + \gamma_0^2 \rho^2)$	0	$-\frac{m e^{-\gamma_0 \rho}}{2\pi\gamma_1 \rho^4}$ $\times (3 + 3\gamma_0 \rho + \gamma_0^2 \rho^2)$
HED	$\frac{p \cos \phi e^{-\gamma_0 \rho}}{2\pi(\sigma_1 + i\omega\epsilon_1)\rho^3}$ $\times (1 + \gamma_0 \rho + \gamma_0^2 \rho^2 F)$	$\frac{p \sin \phi e^{-\gamma_0 \rho}}{2\pi(\sigma_1 + i\omega\epsilon_1)\rho^3}$ $\times [2 + \gamma_0 \rho(1 + F)]$	$\frac{i\omega\mu_0 p \cos \phi e^{-\gamma_0 \rho}}{2\pi\gamma_1 \rho^2}$ $\times (1 + \gamma_0 \rho F)$	$\frac{p \sin \phi e^{-\gamma_0 \rho}}{2\pi\gamma_1 \rho^3}$ $\times [2 + \gamma_0 \rho(1 + F)]$
HMD	$\frac{i\omega\mu_0 m \cos \phi e^{-\gamma_0 \rho}}{2\pi\gamma_1 \rho^3}$ $\times (1 + \gamma_0 \rho + \gamma_0^2 \rho^2 F)$	$\frac{i\omega\mu_0 m \sin \phi e^{-\gamma_0 \rho}}{2\pi\gamma_1 \rho^3}$ $\times [2 + \gamma_0 \rho(1 + F)]$	$\frac{i\omega\mu_0 m \cos \phi e^{-\gamma_0 \rho}}{2\pi\rho^2}$ $\times (1 + \gamma_0 \rho F)$	$\frac{m \sin \phi e^{-\gamma_0 \rho}}{2\pi\rho^3}$ $\times [2 + \gamma_0 \rho(1 + F)]$

Propagation Formulas for $\rho \geq 106$ ($|n^2| \geq 10$, $z = h = 0^+$)

	H_ρ	H_ϕ	H_z
$\gamma_0^2 \rho^2 F$	0	$\frac{\rho e^{-\gamma_0 \rho}}{2\pi \rho^2} (1 + \gamma_0 \rho F)$	0
	$-\frac{m e^{-\gamma_0 \rho}}{2\pi \gamma_1 \rho^4}$ $\times (3 + 3\gamma_0 \rho + \gamma_0^2 \rho^2)$	0	$-\frac{m e^{-\gamma_0 \rho}}{2\pi (\gamma_1^2 - \gamma_0^2) \rho^5}$ $\times (9 + 9\gamma_0 \rho + 4\gamma_0^2 \rho^2 + \gamma_0^3 \rho^3)$
$\gamma_0 \rho$	$\frac{\rho \sin \phi e^{-\gamma_0 \rho}}{2\pi \gamma_1 \rho^3}$ $\times [2 + \gamma_0 \rho (1 + F)]$	$-\frac{\rho \cos \phi e^{-\gamma_0 \rho}}{2\pi \gamma_1 \rho^3}$ $\times (1 + \gamma_0 \rho + \gamma_0^2 \rho^2 F)$	$\frac{\rho \sin \phi e^{-\gamma_0 \rho}}{2\pi (\gamma_1^2 - \gamma_0^2) \rho^4}$ $\times (3 + 3\gamma_0 \rho + \gamma_0^2 \rho^2)$
$\gamma_0 \rho$	$\frac{m \sin \phi e^{-\gamma_0 \rho}}{2\pi \rho^3}$ $\times [2 + \gamma_0 \rho (1 + F)]$	$-\frac{m \cos \phi e^{-\gamma_0 \rho}}{2\pi \rho^3}$ $\times (1 + \gamma_0 \rho + \gamma_0^2 \rho^2 F)$	$\frac{m \sin \phi e^{-\gamma_0 \rho}}{2\pi \gamma_1 \rho^4}$ $\times (3 + 3\gamma_0 \rho + \gamma_0^2 \rho^2)$

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