AD A139057

(15)

NUSC Technical Report 6883
11 January 1984

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

Peter R. Bannister
Submarine Electromagnetic Systems Department

Naval Underwater Systems Center
Newport, Rhode Island / New London, Connecticut



Approved for public release; distribution unlimited.

## 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).

The analysis and write up of this report was performed while the author was occupying the Research Chair in Applied Physics at the Naval Postgraduate School, Monterey, CA. The author would especially like to thank Professors Otto Heinz and John Dyer and Dean Bill Tolles for recommending him to occupy this post and NAVSEA (Code 63R) for sponsoring the Chair.

The Technical Reviewer for this report was Anthony Bruno.

**Reviewed and Approved:** 11 January 1984

D. F. Dence

**D. F. Dence**
**Head, Submarine Electromagnetic**
**Systems Department**

The author of this report is located at the
New London Laboratory, Naval Underwater Systems Center,
New London, Connecticut 06320.

# REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

| | |
|---|---|
| 1. REPORT NUMBER | TR 6883 |
| 2. GOVT ACCESSION NO. | AD-A139 057 |
| 3. RECIPIENT'S CATALOG NUMBER | |
| 4. TITLE (and Subtitle) | NEW FORMULAS THAT EXTEND NORTON'S FARFIELD ELEMENTARY DIPOLE EQUATIONS TO THE QUASI-NEARFIELD RANGE |
| 5. TYPE OF REPORT & PERIOD COVERED | |
| 6. PERFORMING ORG. REPORT NUMBER | |
| 7. AUTHOR(s) | Peter R. Bannister |
| 8. CONTRACT OR GRANT NUMBER(s) | |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS | Naval Underwater Systems Center<br>New London Laboratory<br>New London, Connecticut 06320 |
| 10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS | A59007 |
| 11. CONTROLLING OFFICE NAME AND ADDRESS | |
| 12. REPORT DATE | 11 January 1984 |
| 13. NUMBER OF PAGES | |
| 14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) | |
| 15. SECURITY CLASS. (of this report) | UNCLASSIFIED |
| 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE | |

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Air-to-Air Propagation
Electromagnetic Fields
Horizontal Electric Dipole
Horizontal Magnetic Dipole
Vertical Electric Dipole
Vertical Magnetic Dipole

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

DD FORM 1 JAN 73 1473

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 $\geq$10 skin depths from the source, and (3) the measurement distance is $\geq$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

# LIST OF TABLES

## GLOSSARY OF SYMBOLS

A $\dfrac{\sin \psi_1 + \Delta_1 F(w)}{\sin \psi_1 + \Delta_1} = \left(\dfrac{1 + \Gamma_{II}}{2}\right) + \left(\dfrac{1 - \Gamma_{II}}{2}\right) F(w)$

B $\dfrac{\sin^2 \psi_1 - \Delta_1^2 F(w)}{\sin \psi_1 + \Delta_1} = \left(\dfrac{1 + \Gamma_{II}}{2}\right) \sin \psi_1 - \left(\dfrac{1 - \Gamma_{II}}{2}\right) \Delta_1 F(w) = \sin \psi_1 - \Delta_1 A$

D $(\rho^2 + h^2)^{1/2}$ (meters)

$E_\rho$ Horizontal electric-field component in the $\rho$ direction (volts/meter)

$E_\phi$ Horizontal electric-field component in the $\phi$ 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 ($h \geq 0$) of transmitting antenna with respect to earth's surface (meters)

HED Horizontal electric dipole

HMD Horizontal magnetic dipole

$H_\rho$ Horizontal magnetic-field component in the $\rho$ direction (amperes/meter)

$H_\phi$ Horizontal magnetic-field component in the $\phi$ 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 $\gamma_1/\gamma_0$, index of refraction

$n_0$ $120\pi$, 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) |
| $S_1$ | $\mathrm{Exp}(-\gamma_0 R_1)/R_1$, 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) |
| $\Gamma_{\parallel}$ | $\dfrac{\sin \psi_1 - \Delta_1}{\sin \psi_1 + \Delta_1}$, Fresnel reflection coefficient for vertical polarization |
| $\Gamma_{\perp}$ | $\dfrac{\sin \psi_1 - n_1}{\sin \psi_1 + n_1}$, Fresnel reflection coefficient for horizontal polarization |
| $\gamma_0$ | $(-\omega^2 \mu_0 \varepsilon_0)^{1/2} = i2\pi/\lambda_0$, upper half-space (air) propagation constant (meters$^{-1}$) |
| $\gamma_1$ | $(i\omega\mu_1\sigma_1 - \omega^2\mu_1\varepsilon_1)^{1/2}$, lower half-space (earth) propagation constant (meters$^{-1}$) |
| $\Delta$ | $\gamma_0/\gamma_1 = 1/n$ |
| $\Delta_1$ | $\Delta(1 - \Delta^2 \cos^2 \psi_1)^{1/2}$ |
| $\delta$ | $\left(\dfrac{2}{\omega\mu_0\sigma_1}\right)^{1/2}\left[\left(\dfrac{\omega^2\varepsilon_1^2}{\sigma_1^2} + 1\right)^{1/2} - \dfrac{\omega\varepsilon_1}{\sigma_1}\right]^{-1/2}$, skin depth in the water or earth (meters) |
| $\varepsilon_0$ | $\approx 10^{-9}/36\pi$ farads/meter, permittivity of free space |
| $\varepsilon_1$ | Permittivity of lower half-space (earth) (farads/meter) |
| $\lambda$ | Dummy integration variable in the basic Sommerfeld integrals (meters$^{-1}$) |
| $\lambda_0$ | Wavelength in free space (meters) |

| | |
|---|---|
| $\rho$ | $(x^2 + y^2)^{1/2}$ radial distance in a cylindrical coordinate system (meters) |
| $\sigma_1$ | Conductivity of the lower half-space (earth) (Siemens/meter) |
| $\phi$ | $\tan^{-1} (y/x)$, azimuth angle in a cylindrical coordinate system |
| $\mu \sim \mu_0$ | $= 4\pi \quad 10^{-7}$ henries/meter, permeability of free space |
| $\psi$ | $\tan^{-1} (z/\rho)$ or $\tan^{-1} (h/\rho)$, elevation angle |
| $\psi_0$ | $\tan^{-1} [(z - h)/\rho]$, elevation angle |
| $\psi_1$ | $\tan^{-1} [(z + h)/\rho]$, elevation angle |
| $\omega$ | $2\pi f$ 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 ($\lambda_0$), 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 ($\delta$). The new subsurface-to-air and air-to-subsurface propagation formulas reduce to previously derived results[4-10] when the measurement distance is much less than, or comparable to, $\lambda_0$. Norton's[1,2,3] (corrected) air-to-air propagation formulas are summarized by King,[11] while Kraichman[12] 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 Kraichman[12] are only valid when the conduction currents in the water or earth are much greater than the displacement currents (i.e., $\sigma_1 >> \omega\varepsilon_1$). Indeed, as long as $|n^2| = |\gamma_1^2/\gamma_0^2| >> 1$, the displacement currents can be included simply by replacing $\sigma_1$ by $\sigma_1 + i\omega\varepsilon_1$ 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 $\geq 5$ 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 ($\rho,\phi,z$) 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 $\sigma_1$ and dielectric constant $\varepsilon_1$ ($= \varepsilon_r \varepsilon_0$), 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 $\mu_0$, 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 $\geq 0$, the Sommerfeld integral expressions for the HED Hertz vector are[4,5,14]

$$\Pi_x = \frac{p}{4\pi i\omega\varepsilon_0}\left[\frac{e^{-\gamma_0 R_0}}{R_0} - \frac{e^{-\gamma_0 R_1}}{R_1} + \int_0^\infty \left(\frac{2u_0}{u_1 + u_0}\right) e^{-u_0(z+h)} J_0(\lambda\rho)\frac{\lambda}{u_0} d\lambda\right] \quad (1)$$

and

$$\Pi_z = \frac{p\cos\phi}{4\pi i\omega\varepsilon_0} \times \frac{\partial}{\partial\rho}\int_0^\infty \frac{2(u_1 - u_0)}{\gamma_1^2 u_0 + \gamma_0^2 u_1} e^{-u_0(z+h)} J_0(\lambda\rho)\lambda d\lambda\ , \quad (2)$$

where

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

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

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

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

$\gamma_0^2 = -\omega^2\mu_0\varepsilon_0$, and

$\gamma_1^2 = i\omega\mu_0(\sigma_1 + i\omega\varepsilon_1).$

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

$$\vec{\nabla} \cdot \vec{\Pi} = \frac{p\cos\phi}{4\pi i\omega\varepsilon_0} \times \frac{\partial}{\partial\rho}\left[\frac{e^{-\gamma_0 R_0}}{R_0} - \frac{e^{-\gamma_0 R_1}}{R_1} + \int_0^\infty \frac{2\gamma_0^2 e^{-u_0(z+h)}}{\gamma_1^2 u_0 + \gamma_0^2 u_1} J_0(\lambda\rho)\lambda d\lambda\right]. \quad (3)$$

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

$$\Pi_x \sim \frac{p}{4\pi i\omega\varepsilon_0}\left[\frac{e^{-\gamma_0 R_0}}{R_0} - \frac{e^{-\gamma_0 R_1}}{R_1} + \frac{2}{(\gamma_1^2 - \gamma_0^2)}\int_0^\infty (\gamma_1 - u_0) e^{-u_0(z+h)} J_0(\lambda\rho)\lambda d\lambda\right]. \quad (4)$$

Since Sommerfeld's integral, $S_1$, is equal to

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

then,

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

and

$$\int_0^\infty u_0 e^{-u_0(z+h)} J_0(\lambda\rho)\lambda d\lambda = \frac{\partial^2 S_1}{\partial(z + h)^2}$$

$$= -\frac{e^{-\gamma_0 R_1}}{R_1^3}\left[(1 + \gamma_0 R_1) - \sin^2 \psi_1(3 + 3\gamma_0 R_1 + \gamma_0^2 R_1^2)\right] , \tag{7}$$

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

$$\Pi_x \sim \frac{p}{4\pi i\omega\varepsilon_0}\left\{\frac{e^{-\gamma_0 R_0}}{R_0} - \frac{e^{-\gamma_0 R_1}}{R_1} + \frac{2e^{-\gamma_0 R_1}}{(\gamma_1^2 - \gamma_0^2)R_1^3}\right.$$

$$\left. \times \left[(1 + \gamma_1 R_1 \sin \psi_1)(1 + \gamma_0 R_1) - \sin^2 \psi_1(3 + 3\gamma_0 R_1 + \gamma_0^2 R_1^2)\right]\right\} . \tag{8a}$$

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 $\gamma_1$.[3,11,15] This change is equivalent to setting the normalized surface impedance, $\Delta_1$, equal to

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

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

Since $|\gamma_1^2| >> |\gamma_0^2|$, 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

$$\Pi_x \sim \frac{p}{4\pi i\omega\varepsilon_0}\left\{\frac{e^{-\gamma_0 R_0}}{R_0} - \frac{e^{-\gamma_0 R_1}}{R_1} + \frac{2e^{-\gamma_0 R_1}}{(\gamma_1^2 - \gamma_0^2)R_1^3}\right.$$

$$\left. \times \left[(1 + \sqrt{X}\gamma_1 R_1 \sin\psi_1)(1 + \gamma_0 R_1) - \sin^2\psi_1 (3 + 3\gamma_0 R_1 + \gamma_0^2 R_1^2)\right]\right\} , \tag{8b}$$

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

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

$$\Pi_x \sim \frac{p}{4\pi i\omega\varepsilon_0}\left\{\frac{e^{-\gamma_0 R_0}}{R_0} + \frac{e^{-\gamma_0 R_1}}{R_1}\right.$$

$$\left. \times \left[\frac{2\gamma_0 \sin\psi_1}{(\gamma_1^2 - \gamma_0^2)}(\gamma_1\sqrt{X} - \gamma_0 \sin\psi_1) - 1\right]\right\} . \tag{10}$$

The quantity

$$\frac{2\gamma_0 \sin\psi_1 (\gamma_1\sqrt{X} - \gamma_0 \sin\psi_1)}{\gamma_1^2 - \gamma_0^2} \times \frac{(\gamma_1\sqrt{X} + \gamma_0 \sin\psi_1)}{(\gamma_1\sqrt{X} + \gamma_0 \sin\psi_1)}$$

$$= \frac{2\gamma_0 \sin\psi_1}{\gamma_1\sqrt{X} + \gamma_0 \sin\psi_1} = \frac{2 \sin\psi_1}{n_1 + \sin\psi_1} = 1 + \Gamma_\perp , \tag{11}$$

where

$$\Gamma_\perp = \frac{\sin\psi_1 - n_1}{\sin\psi_1 + n_1} \tag{12}$$

is the Fresnel reflection coefficient for horizontal polarization and

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

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

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

$$\Pi_x \sim \frac{p}{4\pi i\omega\varepsilon_0}\left(\frac{e^{-\gamma_0 R_0}}{R_0} + \Gamma_\perp \frac{e^{-\gamma_0 R_1}}{R_1}\right) , \tag{14}$$

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

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

$$\Pi_z \sim \frac{p \cos \phi}{2\pi i\omega\varepsilon_0\gamma_1} \times \frac{\partial}{\partial\rho}\int_0^\infty \frac{(1 - u_0/\gamma_1)}{u_0 + \gamma_0\Delta} e^{-u_0(z+h)} J_0(\lambda\rho)\lambda d\lambda \ . \tag{15}$$

Since

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

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

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

Therefore, equation (15) reduces to

$$\Pi_z \sim \frac{p \cos \phi}{2\pi i\omega\varepsilon_0\gamma_1} \times \frac{\partial}{\partial\rho}\left[\int_0^\infty e^{-u_0(z+h)} J_0(\lambda\rho)\frac{\lambda}{u_0}\, d\lambda - P - \frac{1}{\gamma_1}\int_0^\infty e^{-u_0(z+h)} J_0(\lambda\rho)\lambda d\lambda\right] , \tag{18}$$

where

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

From equations (5) and (6),

$$\Pi_z \sim \frac{p \cos \phi}{2\pi i\omega\varepsilon_1\gamma_1} \times \frac{\partial}{\partial\rho}\left[\frac{e^{-\gamma_0 R_1}}{R_1} - P - \frac{\sin \psi_1}{\gamma_1 R_1^2}(1 + \gamma_0 R_1)e^{-\gamma_0 R_1}\right] . \tag{20}$$

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

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

where

$$w' = -\gamma_0 R_1 \Delta^2/2 \tag{22}$$

and

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

If we replace $\Delta$ by $\Delta_i$[3,11,15] (equation (9)),

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

where

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

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

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

where

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

is the Sommerfeld surface-wave attenuation function and

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

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

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

equation (20) reduces to

$$\Pi_z \sim \frac{p\cos\phi}{2\pi i\omega\varepsilon_0\gamma_1} \times \frac{\partial}{\partial\rho}\left[\frac{Ae^{-\gamma_0 R_1}}{R_1} - \frac{\sin\psi_1}{\gamma_1 R_1^2}(1 + \gamma_0 R_1)e^{-\gamma_0 R_1}\right] . \quad (30)$$

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

$$B = \sin \psi_1 - \Delta_1 A = \left(\frac{1 + \Gamma_{II}}{2}\right)\sin \psi_1 - \left(\frac{1 - \Gamma_{II}}{2}\right)\Delta_1 F(w)$$
$$= \frac{\sin^2 \psi_1 - \Delta_1^2 F(w)}{\sin \psi_1 + \Delta_1} . \tag{31}$$

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

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

and

$$w_0 = -\frac{\gamma_0 \rho}{2} \Delta_1^2 . \tag{33}$$

When $\rho^2 >> (z + h)^2$, Wait[4,15] has shown that

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

and

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

Extensive numerical results for the function $F(w_0)$ have been provided by Wait[15] and King and Schlak.[16]

Since the factor A (equation (29)) is different from unity only when (1) the angle $\psi_1$ 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 $|\gamma_1^2| >> |\gamma_0^2|$ and $|\Delta_1| \sin \psi_1 << 1$,

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

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

$$\Pi_z \sim -\frac{p\cos\phi\cos\psi_1 e^{-\gamma_0 R_1}}{2\pi i\omega\varepsilon_0\gamma_1 R_1^2}\left[(1+\gamma_0 R_1 A) - \frac{\sin\psi_1}{\gamma_1 R_1}(3+3\gamma_0 R_1 + \gamma_0^2 R_1^2)\right] . \quad (37)$$

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

$$\vec{\nabla}\cdot\vec{\Pi} \sim \frac{p\cos\phi}{4\pi i\omega\varepsilon_0}\times\frac{\partial}{\partial\rho}\left[\frac{e^{-\gamma_0 R_0}}{R_0} - \frac{e^{-\gamma_0 R_1}}{R_1} + \frac{2}{n^2}\int_0^\infty \frac{e^{-u_0(z+h)}}{u_0+\gamma_0\Delta} J_0(\lambda\rho)\lambda d\lambda\right] . \quad (38)$$

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 $\Pi_z$ component results in

$$\begin{aligned}\vec{\nabla}\cdot\vec{\Pi} &\sim \frac{p\cos\phi}{4\pi i\omega\varepsilon_0}\times\frac{\partial}{\partial\rho}\left[\frac{e^{-\gamma_0 R_0}}{R_0} - \frac{e^{-\gamma_0 R_1}}{R_1} + \frac{2}{n^2}\left(\frac{e^{-\gamma_0 R_1}}{R_1} - P\right)\right]\\ &\sim \frac{p\cos\phi}{4\pi i\omega\varepsilon_0}\times\frac{\partial}{\partial\rho}\left[\frac{e^{-\gamma_0 R_0}}{R_0} - \frac{e^{-\gamma_0 R_1}}{R_1} + \frac{2Ae^{-\gamma_0 R_1}}{n^2 R_1}\right]\\ &\sim -\frac{p\cos\phi}{4\pi i\omega\varepsilon_0}\left[(1+\gamma_0 R_0)\cos\psi_0\frac{e^{-\gamma_0 R_0}}{R_0^2} - (1+\gamma_0 R_1)\cos\psi_1\frac{e^{-\gamma_0 R_1}}{R_1^2}\right.\\ &\quad\left. + \frac{2}{n^2}(1+\gamma_0 R_1 A)\cos\psi_1\frac{e^{-\gamma_0 R_1}}{R_1^2}\right] .\end{aligned} \quad (39)$$

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

$$\begin{aligned}\vec{E} &= -\gamma_0^2\vec{\Pi} + \vec{\nabla}(\vec{\nabla}\times\vec{\Pi})\\ \vec{H} &= i\omega\varepsilon_0(\vec{\nabla}\times\vec{\Pi}) .\end{aligned} \quad (40)$$

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 $|n^2| >> 1$ and $Re(\gamma_1 R_1) >> 1$. However, for most cases, the requirement that $|n^2| \geq 10$ and $R_1 \geq 10\delta$ is sufficient. When $|\gamma_0 R_1| << 1$, they reduce to Bannister's quasi-near range results.[7,10]

When $|\gamma_0 R_1| >> 1$, they reduce to Norton's farfield range results[1,2,3,11] (for $|n^2| >> 1$). For convenience, the farfield expressions ($|\gamma_0 R_1| >> 1$) 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 be substituting $\gamma_1/Q$ for $\gamma_1$, 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 $\rho \to \infty$. 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 Wait[15] 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 $\rho >> z$, and in table 8 for $z >> \rho$. 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 $|n^2| >> 1$, $Re(\gamma_1 R) >> 1$, and $R >> |h|$. However, for most cases, the requirement that $|n^2| \geq 10$, $R \geq 10\delta$, and $R \geq 5|h|$ is sufficient.

When $|\gamma_0 R| << 1$, they reduce to Bannister's quasi-near range formulas,[7,10] which are tabulated in Kraichman[12] (with $\sigma_1$ 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 Kraichman[12] (with $\sigma_1$ replaced by $\sigma_1 + i\omega\epsilon_1$). Furthermore, when $h = 0$ and $|\gamma_0 R| >> 1$, 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 $\rho >> h$, and in table 12 for $h >> \rho$. 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 $|n^2| >> 1$, $\mathrm{Re}(\gamma_1 D) >> 1$, and $D >> |z|$. However, for most cases, the requirement that $|n^2| \geq 10$, $D \geq 10\delta$, and $D \geq 5|z|$ is sufficient.

When $|\gamma_0 D| << 1$, they reduce to Bannister's quasi-near range formulas,[7,10] which are tabulated in Kraichman[12] (with $\sigma_1$ replaced by $\sigma_1 + i\omega\varepsilon_1$). 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 Kraichman[12] (with $\sigma_1$ replaced by $\sigma_1 + i\omega\varepsilon_1$). Furthermore, when $z = 0$ and $|\gamma_0 D| >> 1$, 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 $|n^2| >> 1$ and $\mathrm{Re}(\gamma_1 \rho) >> 1$. However, the requirement that $|n^2| \geq 10$ and $\rho \geq 10\delta$ is sufficient. When either (1) $|\gamma_0 \rho| << 1$, (2) $F(w_0) \sim 1$, or (3) $|\gamma_0 \rho| >> 1$, they reduce to previously derived results.[4-12] Note that the function F in this table is equal to $F(w_0)$.

## DISCUSSION

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

$$\Gamma_{\parallel} \sim \frac{\sin \psi_1 - \Delta}{\sin \psi_1 + \Delta} \tag{41}$$

and

$$\Gamma_{\perp} \sim \frac{\sin \psi_1 - n}{\sin \psi_1 + n} \sim -1 + \frac{2 \sin \psi_1}{n} . \tag{42}$$

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 $\Delta$, the horizontal distance $\rho$ will be much greater than the sum of the transmitting and receiving antenna heights $(z + h)$. In the limit as $\psi_1$ approaches zero, $A \sim F(w_0)$ and $B \sim -\Delta F(w_0)$, where

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

and

$$w_0 = -\frac{\gamma_0 \rho}{2} \Delta^2 . \tag{44}$$

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

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

and we can make use of his tabulated results[15] 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 $H_\phi$ component is

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

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

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

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

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

Since

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

then,

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

Therefore, equation (48) reduces to

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

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

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

which is the result listed in table 6.

In following this procedure, we discovered a small error in the HED and HMD $E_\phi$ and $H_\rho$ farfield subsurface-to-air and subsurface-to-subsurface propagation equations tabulated in tables 3.1 and 3.2 of Kraichman[12] (and also in equation (14) of Wait[4]). 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, $E_\rho >> E_\phi$ and $H_\phi >> H_\rho$.

## 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) $|n^2| \geq 10$, (2) the measurement distance is $\geq$10 skin depths from the source, and (3) the measurement distance is $\geq$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 $\sigma_2$ and dielectric constant $\varepsilon_2$). 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 $i\omega\varepsilon_0$ by $\sigma_2 + i\omega\varepsilon_2$.

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 $|n^2| >> 1$. When the measurement distance is $\geq$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 Fo

| Dipole Type | $E_\rho$ | $E_\phi$ |
|---|---|---|
| VED | $\frac{-p}{4\pi i\omega\epsilon_0}\Big\{(3 + 3\gamma_0R_0 + \gamma_0^2R_0^2)\sin\psi_0\cos\psi_0\frac{e^{-\gamma_0R_0}}{R_0^3}$ <br> $+ (3 + 3\gamma_0R_1 + \Gamma_{\parallel}\gamma_0^2R_1^2)\sin\psi_1\cos\psi_1\frac{e^{-\gamma_0R_1}}{R_1^3}$ <br> $- \frac{2\gamma_1\cos\psi_1 e^{-\gamma_0R_1}}{n^2R_1^2}\Big[1 + \Big(\frac{1-\Gamma_{\parallel}}{2}\Big)F(w)\gamma_0R_1\Big]\Big\}$ | 0 |
| VMD | 0 | $-\frac{i\omega\mu_0 m}{4\pi}\Big\{(1 + \gamma_0R_0)\cos\psi_0\frac{e^{-\gamma_0R_0}}{R_0^2} - (1 +$ <br> $+ \frac{2\cos\psi_1 e^{-\gamma_0R_1}}{(\gamma_1^2 - \gamma_0^2)R_1^4}[(1 + \gamma_1R_1\sin\psi_1)(3 +$ <br> $- \sin^2\psi_1(15 + 15\gamma_0R_1 + 6\gamma_0^2R_1^2 + \gamma_0^3R_1^3)]$ |
| HED | $\frac{p\cos\phi}{4\pi i\omega\epsilon_0}\Big\{[(3\cos^2\psi_0 - 1)(1 + \gamma_0R_0) - \gamma_0^2R_0^2\sin^2\psi_0]\frac{e^{-\gamma_0R_0}}{R_0^3}$ <br> $- [(3\cos^2\psi_1 - 1)(1 + \gamma_0R_1) - \Gamma_{\parallel}\gamma_0^2R_1^2\sin^2\psi_1]\frac{e^{-\gamma_0R_1}}{R_1^3}$ <br> $+ \frac{2e^{-\gamma_0R_1}}{n^2R_1^3}\Big[1 - \gamma_1R_1\sin\psi_1 + \gamma_0R_1 + \Big(\frac{1-\Gamma_{\parallel}}{2}\Big)F(w)\gamma_0^2R_1^2\Big]\Big\}$ | $\frac{p\sin\phi}{4\pi i\omega\epsilon_0}\Big\{(1 + \gamma_0R_0 + \gamma_0^2R_0^2)\frac{e^{-\gamma_0R_0}}{R_0^3} - (1 +$ <br> $+ \frac{2e^{-\gamma_0R_1}}{n^2R_1^3}[(2 + \gamma_1R_1\sin\psi_1) + \gamma_0R_1(1 +$ <br> $- \sin^2\psi_1(3 + 3\gamma_0R_1 + \gamma_0^2R_1^2)]\Big\}$ |
| HMD | $-\frac{i\omega\mu_0 m\cos\phi}{4\pi}\Big\{(1 + \gamma_0R_0)\sin\psi_0\frac{e^{-\gamma_0R_0}}{R_0^2}$ <br> $+ (1 + \Gamma_{\parallel}\gamma_0R_1)\sin\psi_1\frac{e^{-\gamma_0R_1}}{R_1^2}$ <br> $- \frac{2e^{-\gamma_0R_1}}{\gamma_1R_1^3}\Big[1 + \gamma_0R_1 + \Big(\frac{1-\Gamma_{\parallel}}{2}\Big)F(w)\gamma_0^2R_1^2\Big]\Big\}$ | $\frac{i\omega\mu_0 m\sin\phi}{4\pi}\Big\{(1 + \gamma_0R_0)\sin\psi_0\frac{e^{-\gamma_0R_0}}{R_0^2} +$ <br> $+ \frac{2e^{-\gamma_0R_1}}{\gamma_1R_1^3}[2 + \gamma_0R_1(1 + A) - \sin^2\psi_1(3$ |

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

| $E_\phi$ | $E_z$ |
|---|---|
| 0 | $-\frac{p}{4\pi i\omega\epsilon_0}\left\{[(1 - 3\sin^2\psi_0)(1 + \gamma_0R_0) + \gamma_0^2R_0^2\cos^2\psi_0]\frac{e^{-\gamma_0R_0}}{R_0^3} + [(1 - 3\sin^2\psi_1)(1 + \gamma_0R_1) + \Gamma_{\parallel}\gamma_0^2R_1^2\cos^2\psi_1]\frac{e^{-\gamma_0R_1}}{R_1^3} + (1 - \Gamma_{\parallel})F(w)\gamma_0^2R_1^2\cos^2\psi_1\frac{e^{-\gamma_0R_1}}{R_1^3}\right\}$ |
| os $\psi_0 \frac{e^{-\gamma_0R_0}}{R_0^2} - (1 + \gamma_0R_1)\cos\psi_1\frac{e^{-\gamma_0R_1}}{R_1^2}$ <br> $+ \gamma_1R_1\sin\psi_1)(3 + 3\gamma_0R_1 + \gamma_0^2R_1^2)$ <br> $R_1 + 6\gamma_0^2R_1^2 + \gamma_0^3R_1^3)]\}$ | 0 |
| $\gamma_0^2R_0^2)\frac{e^{-\gamma_0R_0}}{R_0^3} - (1 + \gamma_0R_1 + \gamma_0^2R_1^2)\frac{e^{-\gamma_0R_1}}{R_1^3}$ <br> $\sin\psi_1) + \gamma_0R_1(1 + A + \gamma_1R_1\sin\psi_1)$ <br> $+ \gamma_0^2R_1^2)]\}$ | $\frac{p\cos\phi}{4\pi i\omega\epsilon_0}\left\{(3 + 3\gamma_0R_0 + \gamma_0^2R_0^2)\sin\psi_0\cos\psi_0\frac{e^{-\gamma_0R_0}}{R_0^3} - (3 + 3\gamma_0R_1 + \Gamma_{\parallel}\gamma_0^2R_1^2)\sin\psi_1\cos\psi_1\frac{e^{-\gamma_0R_1}}{R_1^3} + \frac{2\gamma_1\cos\psi_1 e^{-\gamma_0R_1}}{n^2R_1^2}\left[1 + \left(\frac{1 - \Gamma_{\parallel}}{2}\right)F(w)\gamma_0R_1\right]\right\}$ |
| $_0)\sin\psi_0\frac{e^{-\gamma_0R_0}}{R_0^2} + (1 + \gamma_0R_1)\sin\psi_1\frac{e^{-\gamma_0R_1}}{R_1^2}$ <br> $+ A) - \sin^2\psi_1(3 + 3\gamma_0R_1 + \gamma_0^2R_1^2)]\}$ | $\frac{i\omega\mu_0 m\cos\phi}{4\pi}\left[(1 + \gamma_0R_0)\cos\psi_0\frac{e^{-\gamma_0R_0}}{R_0^2} + (1 + \Gamma_{\parallel}\gamma_0R_1)\cos\psi_1\frac{e^{-\gamma_0R_1}}{R_1^2} + (1 - \Gamma_{\parallel})F(w)\gamma_0R_1\cos\psi_1\frac{e^{-\gamma_0R_1}}{R_1^2}\right]$ |

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

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

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

| $H_\phi$ | $H_z$ |
|---|---|
| $s\ \psi_0 \frac{e^{-\gamma_0 R_0}}{R_0^2} + (1 + \Gamma_{11}\gamma_0 R_1)\cos\psi_1 \frac{e^{-\gamma_0 R_1}}{R_1^2}$ <br> $\gamma_0 R_1 \cos\psi_1 \frac{e^{-\gamma_0 R_1}}{R_1^2}\Big]$ | 0 |
| 0 | $-\frac{m}{4\pi}[(1 - 3\sin^2\psi_0)(1 + \gamma_0 R_0) + \gamma_0^2 R_0^2 \cos^2\psi_0]\frac{e^{-\gamma_0 R_0}}{R_0^3}$ <br> $- [(1 - 3\sin^2\psi_1)(1 + \gamma_0 R_1) + \gamma_0^2 R_1^2 \cos^2\psi_1]\frac{e^{-\gamma_0 R_1}}{R_1^3}$ <br> $+ \frac{2e^{-\gamma_0 R_1}}{(\gamma_1^2 - \gamma_0^2)R_1^5}\Big\{(1 + \gamma_1 R_1 \sin\psi_1)[(9 + 9\gamma_0 R_1 + 4\gamma_0^2 R_1^2 + \gamma_0^3 R_1^3)$ <br> $- \sin^2\psi_1(15 + 15\gamma_0 R_1 + 6\gamma_0^2 R_1^2 + \gamma_0^3 R_1^3)]$ <br> $- \sin^2\psi_1(75 + 75\gamma_0 R_1 + 33\gamma_0^2 R_1^2 + 6\gamma_0^3 R_1^3)$ <br> $+ \sin^4\psi_1(105 + 105\gamma_0 R_1 + 45\gamma_0^2 R_1^2 + 6\gamma_0^3 R_1^3)\Big\}$ |



2

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

| Dipole Type | $H_\rho$ | $H_\phi$ |
|---|---|---|
| HED | $-\frac{p \sin\phi}{4\pi}\left\{(1+\gamma_0 R_0)\sin\psi_0 \frac{e^{-\gamma_0 R_0}}{R_0^2} - (1+\gamma_0 R_1)\sin\psi_1 \frac{e^{-\gamma_0 R_1}}{R_1^2}\right.$<br>$\left. - \frac{2e^{-\gamma_0 R_1}}{\gamma_1 R_1^3}[2+\gamma_0 R_1(1+A) - \sin^2\psi_1(3+3\gamma_0 R_1+\gamma_0^2 R_1^2)]\right\}$ | $-\frac{p \cos\phi}{4\pi}\left\{(1+\gamma_0 R_0)\sin\psi_0 \frac{e^{-\gamma_0 \ldots}}{R \ldots}\right.$ [illegible]<br>$\cdot (1+\Gamma_{\parallel}\gamma_0 R_1)\sin\psi_1 \frac{e^{-\gamma_0 R_1}}{R_1^2}$<br>$+ \frac{2e^{-\gamma_0 R_1}}{\gamma_1 R_1^3}\left[1+\gamma_0 R_1+\left(\frac{1-\Gamma_{\parallel}}{2}\right)F \ldots\right.$ [illegible] |
| HMD | $\frac{m \sin\phi}{4\pi}\left\{[2(1+\gamma_0 R_0) - \sin^2\psi_0(3+3\gamma_0 R_0+\gamma_0^2 R_0^2)]\frac{e^{-\gamma_0 R_0}}{R_0^3}\right.$<br>$\left. + [2(1+\gamma_0 R_1 A) - \sin^2\psi_1(3+3\gamma_0 R_1+\gamma_0^2 R_1^2)]\frac{e^{-\gamma_0 R_1}}{R_1^3}\right\}$ | $-\frac{m \cos\phi}{4\pi}\left[(1+\gamma_0 R_0+\gamma_0^2 R_0^2)\frac{e^{-\gamma \ldots}}{\ldots}\right.$ [illegible]<br>$+ (1+\gamma_0 R_1+\Gamma_{\parallel}\gamma_0^2 R_1^2)\frac{e^{-\gamma_0 R_1}}{R_1^3}$<br>$\left. + (1-\Gamma_{\parallel})F(w)\gamma_0^2 R_1^2 \frac{e^{-\gamma_0 R_1}}{R_1^3}\right]$ |

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

| $H_\phi$ | $H_z$ |
| --- | --- |
| $\ldots + \gamma_0 R_0)\sin\psi_0 \frac{e^{-\gamma_0 R_0}}{R_0^2}$ <br> $\ldots_1)\sin\psi_1 \frac{e^{-\gamma_0 R_1}}{R_1^2}$ <br> $\ldots + \gamma_0 R_1 + \left(\frac{1 - \Gamma_{11}}{2}\right) F(w)\gamma_0^2 R_1^2 \Big]\Big]\Big\}$ | $\frac{p \sin\phi}{4\pi}\Big\{(1 + \gamma_0 R_0)\cos\psi_0 \frac{e^{-\gamma_0 R_0}}{R_0^2} - (1 + \gamma_0 R_1)\cos\psi_1 \frac{e^{-\gamma_0 R_1}}{R_1^2}$ <br> $+ \frac{2\cos\psi_1 e^{-\gamma_0 R_1}}{(\gamma_1^2 - \gamma_0^2)R_1^4}[(1 + \gamma_1 R_1 \sin\psi_1)(3 + 3\gamma_0 R_1 + \gamma_0^2 R_1^2)$ <br> $- \sin^2\psi_1(15 + 15\gamma_0 R_1 + 6\gamma_0^2 R_1^2 + \gamma_0^3 R_1^3)]\Big\}$ |
| $\ldots + \gamma_0 R_0 + \gamma_0^2 R_0^2)\frac{e^{-\gamma_0 R_0}}{R_0^3}$ <br> $\ldots + \Gamma_{11}\gamma_0^2 R_1^2)\frac{e^{-\gamma_0 R_1}}{R_1^3}$ <br> $\ldots(w)\gamma_0^2 R_1^2 \frac{e^{-\gamma_0 R_1}}{R_1^3}\Big]$ | $\frac{m \sin\phi}{4\pi}\Big\{(3 + 3\gamma_0 R_0 + \gamma_0^2 R_0^2)\sin\psi_0 \cos\psi_0 \frac{e^{-\gamma_0 R_0}}{R_0^3}$ <br> $+ (3 + 3\gamma_0 R_1 + \gamma_0^2 R_1^2)\sin\psi_1 \cos\psi_1 \frac{e^{-\gamma_0 R_1}}{R_1^3}$ <br> $+ \frac{2\cos\psi_1 e^{-\gamma_0 R_1}}{\gamma_1 R_1^4}[(3 + 3\gamma_0 R_1 + \gamma_0^2 R_1^2)$ <br> $- \sin^2\psi_1(15 + 15\gamma_0 R_1 + 6\gamma_0^2 R_1^2 + \gamma_0^3 R_1^3)]\Big\}$ |

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

| Dipole Type | $E_\rho$ | $E_\phi$ |
|---|---|---|
| VED | $\frac{\gamma_0 n_0 p}{4\pi}\left[\sin\psi_0 \cos\psi_0 \frac{e^{-\gamma_0 R_0}}{R_0} + \Gamma_{\parallel} \sin\psi_1 \cos\psi_1 \frac{e^{-\gamma_0 R_1}}{R_1}\right.$ $\left. - (1 - \Gamma_{\parallel})\Delta F(w)\cos\psi_1 \frac{e^{-\gamma_0 R_1}}{R_1}\right]$ | 0 |
| VMD | 0 | $-\frac{i\omega\mu_0\gamma_0 m}{4\pi}\left[\cos\psi_0 \frac{e^{-\gamma_0 R_0}}{R_0} - \cos\right.$ $+ \frac{2\cos\psi_1 e^{-\gamma_0 R_1}}{\gamma_0 n^2 R_1^2}(1 + \gamma_1 R_1 \sin$ |
| HED | $-\frac{\gamma_0 n_0 p \cos\phi}{4\pi}\left[\sin^2\psi_0 \frac{e^{-\gamma_0 R_0}}{R_0} - \Gamma_{\parallel} \sin^2\psi_1 \frac{e^{-\gamma_0 R_1}}{R_1}\right.$ $\left. - (1 - \Gamma_{\parallel})\Delta^2 F(w)\frac{e^{-\gamma_0 R_1}}{R_1}\right]$ | $\frac{\gamma_0 n_0 p \sin\phi}{4\pi}\left[\frac{e^{-\gamma_0 R_0}}{R_0} - \frac{e^{-\gamma_0 R_1}}{R_1}\right.$ $\left. + \frac{2e^{-\gamma_0 R_1}}{\gamma_0 n^2 R_1^2}(1 + A + \gamma_1 R_1 \sin\psi_1)\right]$ |
| HMD | $-\frac{i\omega\mu_0\gamma_0 m \cos\phi}{4\pi}\left[\sin\psi_0 \frac{e^{-\gamma_0 R_0}}{R_0} + \Gamma_{\parallel} \sin\psi_1 \frac{e^{-\gamma_0 R_1}}{R_1}\right.$ $\left. - (1 - \Gamma_{\parallel})\Delta F(w)\frac{e^{-\gamma_0 R_1}}{R_1}\right]$ | $\frac{i\omega\mu_0\gamma_0 m \sin\phi}{4\pi}\left\{\sin\psi_0 \frac{e^{-\gamma_0 R_0}}{R_0} +\right.$ $- \frac{2e^{-\gamma_0 R_1}}{nR_1}\left[\sin^2\psi_1 - \frac{1}{\gamma_0 R_1}(1 + A\right.$ |

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

| $E_\phi$ | $E_z$ |
|---|---|
| 0 | $-\frac{\gamma_0 n_0 p}{4\pi}\left[\cos^2\psi_0 \frac{e^{-\gamma_0 R_0}}{R_0} + \Gamma_{\parallel} \cos^2\psi_1 \frac{e^{-\gamma_0 R_1}}{R_1} + (1 - \Gamma_{\parallel})F(w)\cos^2\psi_1 \frac{e^{-\gamma_0 R_1}}{R_1}\right]$ |
| $\frac{i\omega\mu_0\gamma_0 m}{4\pi}\left[\cos\psi_0 \frac{e^{-\gamma_0 R_0}}{R_0} - \cos\psi_1 \frac{e^{-\gamma_0 R_1}}{R_1} \ldots \frac{\cos\psi_1 e^{-\gamma_0 R_1}}{\gamma_0 n^2 R_1^2}(1 + \gamma_1 R_1 \sin\psi_1)\right]$ | 0 |
| $\frac{\ldots p \sin\phi}{4\pi}\left[\frac{e^{-\gamma_0 R_0}}{R_0} - \frac{e^{-\gamma_0 R_1}}{R_1} \ldots \frac{e^{-\gamma_0 R_1}}{\gamma_0 n^2 R_1^2}(1 + A + \gamma_1 R_1 \sin\psi_1)\right]$ | $\frac{\gamma_0 n_0 p \cos\phi}{4\pi}\left[\sin\psi_0 \cos\psi_0 \frac{e^{-\gamma_0 R_0}}{R_0} - \Gamma_{\parallel} \sin\psi_1 \cos\psi_1 \frac{e^{-\gamma_0 R_1}}{R_1} + (1 - \Gamma_{\parallel})\Delta F(w)\cos\psi_1 \frac{e^{-\gamma_0 R_1}}{R_1}\right]$ |
| $\frac{\ldots\gamma_0 m \sin\phi}{4\pi}\left\{\sin\psi_0 \frac{e^{-\gamma_0 R_0}}{R_0} + \sin\psi_1 \frac{e^{-\gamma_0 R_1}}{R_1} \ldots \frac{e^{-\gamma_0 R_1}}{nR_1}\left[\sin^2\psi_1 - \frac{1}{\gamma_0 R_1}(1 + A - 3\sin^2\psi_1)\right]\right\}$ | $\frac{i\omega\mu_0\gamma_0 m \cos\phi}{4\pi}\left[\cos\psi_0 \frac{e^{-\gamma_0 R_0}}{R_0} + \Gamma_{\parallel} \cos\psi_1 \frac{e^{-\gamma_0 R_1}}{R_1} + (1 - \Gamma_{\parallel})F(w)\cos\psi_1 \frac{e^{-\gamma_0 R_1}}{R_1}\right]$ |

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

| Dipole Type | $H_\rho$ | $H_\phi$ |
|---|---|---|
| VED | 0 | $\frac{p}{4\pi}\left[\cos\psi_0 \frac{e^{-\gamma_0 R_0}}{R_0} + \Gamma_{\parallel} \cos\psi_1 \frac{e^{-\gamma_0 R_1}}{R_1} + (1 - \Gamma_{\parallel})F(w)\cos\psi_1 \frac{e^{-\gamma_0 R_1}}{R_1}\right]$ |
| VMD | $\frac{\gamma_0^2 m}{4\pi}\left[\sin\psi_0 \cos\psi_0 \frac{e^{-\gamma_0 R_0}}{R_0} - \sin\psi_1 \cos\psi_1 \frac{e^{-\gamma_0 R_1}}{R_1} + \frac{2\cos\psi_1 e^{-\gamma_0 R_1}}{nR_1}\left(\sin^2\psi_1 - \frac{1}{\gamma_0 R_1}\right)\right]$ | 0 |
| HED | $-\frac{\gamma_0 p \sin\phi}{4\pi}\left\{\sin\psi_0 \frac{e^{-\gamma_0 R_0}}{R_0} - \sin\psi_1 \frac{e^{-\gamma_0 R_1}}{R_1} + \frac{2e^{-\gamma_0 R_1}}{nR_1}\left[\sin^2\psi_1 - \frac{1}{\gamma_0 R_1}(1 + A - 3\sin^2\psi_1)\right]\right\}$ | $-\frac{\gamma_0 p \cos\phi}{4\pi}\left[\sin\psi_0 \frac{e^{-\gamma_0 R_0}}{R_0} - \Gamma_{\parallel} \sin\psi_1\ e \ldots + (1 - \Gamma_{\parallel})\Delta F(w)\frac{e^{-\gamma_0 R_1}}{R_1}\right]$ |
| HMD | $-\frac{\gamma_0^2 m \sin\phi}{4\pi}\left\{\left[\sin^2\psi_0 - \frac{1}{\gamma_0 R_0}(2 - 3\sin^2\psi_0)\right]\frac{e^{-\gamma_0 R_0}}{R_0} + \left[\sin^2\psi_1 - \frac{1}{\gamma_0 R_1}(2A - 3\sin^2\psi_1)\right]\frac{e^{-\gamma_0 R_1}}{R_1}\right\}$ | $-\frac{\gamma_0^2 m \cos\phi}{4\pi}\left[\frac{e^{-\gamma_0 R_0}}{R_0} + (\Gamma_{\parallel})\frac{e^{-\gamma_0 R_1}}{R_1} + (1 - \Gamma_{\parallel})F(w)\frac{e^{-\gamma_0 R_1}}{R_1}\right]$ |

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

| $H_\phi$ | $H_z$ |
|---|---|
| $\frac{p}{4\pi}\left[\cos\psi_0 \frac{e^{-\gamma_0 R_0}}{R_0} + \Gamma_{\parallel} \cos\psi_1 \frac{e^{-\gamma_0 R_1}}{R_1} + (1 - \Gamma_{\parallel})F(w)\cos\psi_1 \frac{e^{-\gamma_0 R_1}}{R_1}\right]$ | 0 |
| 0 | $-\frac{\gamma_0^2 m}{4\pi}\left[\cos^2\psi_0 \frac{e^{-\gamma_0 R_0}}{R_0} - \cos^2\psi_1 \frac{e^{-\gamma_0 R_1}}{R_1} + \frac{2\cos^2\psi_1 e^{-\gamma_0 R_1}}{\gamma_0 n^2 R_1^2}(1 + \gamma_1 R_1 \sin\psi_1)\right]$ |
| $-\frac{\gamma_0 p \cos\phi}{4\pi}\left[\sin\psi_0 \frac{e^{-\gamma_0 R_0}}{R_0} - \Gamma_{\parallel} \sin\psi_1 \frac{e^{-\gamma_0 R_1}}{R_1} + (1 - \Gamma_{\parallel})\Delta F(w)\frac{e^{-\gamma_0 R_1}}{R_1}\right]$ | $\frac{\gamma_0 p \sin\phi}{4\pi}\left[\cos\psi_0 \frac{e^{-\gamma_0 R_0}}{R_0} - \cos\psi_1 \frac{e^{-\gamma_0 R_1}}{R_1} + \frac{2\cos\psi_1 e^{-\gamma_0 R_1}}{\gamma_0 n^2 R_1^2}(1 + \gamma_1 R_1 \sin\psi_1)\right]$ |
| $-\frac{\gamma_0^2 m \cos\phi}{4\pi}\left[\frac{e^{-\gamma_0 R_0}}{R_0} + (\Gamma_{\parallel})\frac{e^{-\gamma_0 R_1}}{R_1} + (1 - \Gamma_{\parallel})F(w)\frac{e^{-\gamma_0 R_1}}{R_1}\right]$ | $\frac{\gamma_0^2 m \sin\phi}{4\pi}\left[\sin\psi_0 \cos\psi_0 \frac{e^{-\gamma_0 R_0}}{R_0} + \sin\psi_1 \cos\psi_1 \frac{e^{-\gamma_0 R_1}}{R_1} - \frac{2\cos\psi_1 e^{-\gamma_0 R_1}}{nR_1}\left(\sin^2\psi_1 - \frac{1}{\gamma_0 R_1}\right)\right]$ |



1 2

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

| Dipole Type | $E_\rho$ | $E_\phi$ |
|---|---|---|
| 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 | $\frac{p \cos \phi e^{-\gamma_1 h} e^{-\gamma_0 R}}{2\pi(\sigma_1 + i\omega\epsilon_1)R^3}(1 - \gamma_1 R \sin \psi$ $+ \gamma_0 R - \gamma_0^2 R^2 nB)$ | $\frac{p \sin \phi e^{-\gamma_1 h} e^{-\gamma_0 R}}{2\pi(\sigma_1 + i\omega\epsilon_1)R^3}[2 + \gamma_1 R \sin \psi + \gamma_0 R($ $+ \gamma_1 R \sin \psi) - \sin^2 \psi(3 + 3\gamma_0 R + \gamma_0^2 R^2)$ |
| HMD | $\frac{\gamma_1 m \cos \phi e^{-\gamma_1 h} e^{-\gamma_0 R}}{2\pi(\sigma_1 + i\omega\epsilon_1)R^3}(1 - \gamma_1 R \sin \psi$ $+ \gamma_0 R - \gamma_0^2 R^2 nB)$ | $\frac{\gamma_1 m \sin \phi e^{-\gamma_1 h} e^{-\gamma_0 R}}{2\pi(\sigma_1 + i\omega\epsilon_1)R^3}[2 + \gamma_1 R \sin \psi + \gamma$ $+ \gamma_1 R \sin \psi) - \sin^2 \psi(3 + 3\gamma_0 R + \gamma_0^2 R^2$ |

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

| $E_\phi$ | $E_z$ |
|---|---|
| 0 | $-\frac{pe^{-\gamma_1 h}e^{-\gamma_0 R}}{2\pi(\sigma_1 + i\omega\epsilon_1)R^3}[(1 - 3\sin^2\psi)(1 + \gamma_0 R) + \gamma_0^2 R^2 A\cos^2\psi]$ |
| $\ldots{}_1^{h}e^{-\gamma_0 R}$ / $\ldots\epsilon_1)R^4$ $[(1 + \gamma_1 R\sin\psi)(3 + 3\gamma_0 R$ $\ldots{}^2\,\psi(15 + 15\gamma_0 R + 6\gamma_0^2R^2 + \gamma_0^3R^3)]$ | 0 |
| $\ldots{}^{-\gamma_0 R}$ / $\ldots)R^3$ $[2 + \gamma_1 R\sin\psi + \gamma_0 R(1 + A$ $\ldots\sin^2\psi(3 + 3\gamma_0 R + \gamma_0^2R^2)]$ | $\frac{\gamma_1 p\cos\phi\cos\psi e^{-\gamma_1 h}e^{-\gamma_0 R}}{2\pi(\sigma_1 + i\omega\epsilon_1)R^2}(1 + \gamma_0 RA)$ |
| $\ldots h_e{}^{-\gamma_0 R}$ / $\ldots{}_1)R^3$ $[2 + \gamma_1 R\sin\psi + \gamma_0 R(1 + A$ $\ldots\sin^2\psi(3 + 3\gamma_0 R + \gamma_0^2R^2)]$ | $\frac{\gamma_1^2 m\cos\phi\cos\psi e^{-\gamma_1 h}e^{-\gamma_0 R}}{2\pi(\sigma_1 + i\omega\epsilon_1)R^2}(1 + \gamma_0 RA)$ |

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

| Dipole Type | $H_\rho$ | $H_\phi$ | |
|---|---|---|---|
| VED | 0 | $\frac{p \cos \psi e^{-\gamma_1 h} e^{-\gamma_0 R}}{2\pi n^2 R^2}(1 + \gamma_0 RA)$ | |
| 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 | - m [illegible] / 2π [illegible] - si [illegible] - si [illegible] + si [illegible] |
| HED | $\frac{p \sin \phi e^{-\gamma_1 h} e^{-\gamma_0 R}}{2\pi\gamma_1 R^3}[2 + \gamma_0 R(1 + A)$ $- \sin^2 \psi(3 + 3\gamma_0 R + \gamma_0^2 R^2)]$ | $-\frac{p \cos \phi e^{-\gamma_1 h} e^{-\gamma_0 R}}{2\pi\gamma_1 R^3}(1 + \gamma_0 R + \gamma_0^2 R^2 A)$ | p si [illegible] + $\gamma_0^2$ [illegible] |
| HMD | $\frac{m \sin \phi e^{-\gamma_1 h} e^{-\gamma_0 R}}{2\pi R^3}[2 + \gamma_0 R(1 + A)$ $- \sin^2 \psi(3 + 3\gamma_0 R + \gamma_0^2 R^2)]$ | $-\frac{m \cos \phi e^{-\gamma_1 h} e^{-\gamma_0 R}}{2\pi R^3}(1 + \gamma_0 R + \gamma_0^2 R^2 A)$ | m si [illegible] + $\gamma$ [illegible] |

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

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

Table 7. Subsurface-to-Air Propagation Formulas When ρ >>

| Dipole Type | $E_\rho$ | $E_\phi$ | $E_z$ | |
|---|---|---|---|---|
| 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 | $\frac{p\cos\phi e^{-\gamma_1 h_e - \gamma_0\rho}}{2\pi(\sigma_1 + i\omega\epsilon_1)\rho^3}(1 - \gamma_1 z$ $+ \gamma_0\rho - \gamma_0^2\rho^2 nB)$ | $\frac{p\sin\phi e^{-\gamma_1 h_e - \gamma_0\rho}}{2\pi(\sigma_1 + i\omega\epsilon_1)\rho^3}[2 + \gamma_1 z$ $+ \gamma_0\rho(1 + A + \gamma_1 z)]$ | $\frac{\gamma_1 p\cos\phi e^{-\gamma_1 h_e - \gamma_0\rho}}{2\pi(\sigma_1 + i\omega\epsilon_1)\rho^2}$ $\times (1 + \gamma_0\rho A)$ | p s ... × ... |
| HMD | $\frac{\gamma_1 m\cos\phi e^{-\gamma_1 h_e - \gamma_0\rho}}{2\pi(\sigma_1 + i\omega\epsilon_1)\rho^3}(1 - \gamma_1 z$ $+ \gamma_0\rho - \gamma_0^2\rho^2 nB)$ | $\frac{\gamma_1 m\sin\phi e^{-\gamma_1 h_e - \gamma_0\rho}}{2\pi(\sigma_1 + i\omega\epsilon_1)\rho^3}[2 + \gamma_1 z$ $+ \gamma_0\rho(1 + A + \gamma_1 z)]$ | $\frac{\gamma_1^2 m\cos\phi e^{-\gamma_1 h_e - \gamma_0\rho}}{2\pi(\sigma_1 + i\omega\epsilon_1)\rho^2}$ $\times (1 + \gamma_0\rho A)$ | m s ... × ... |

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

| $E_z$ | $H_\rho$ | $H_\phi$ | $H_z$ |
|---|---|---|---|
| $\frac{\ldots e^{-\gamma_1 h} e^{-\gamma_0\rho}}{(\ldots_1 + i\omega\varepsilon_1)\rho^3} (\ldots \gamma_0\rho + \gamma_0^2\rho^2 A)$ | 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 | $-\frac{m e^{-\gamma_1 h} e^{-\gamma_0\rho}}{2\pi(\gamma_1^2 - \gamma_0^2)\rho^5}(1 + \gamma_1 z) \times (9 + 9\gamma_0\rho + 4\gamma_0^2\rho^2 + \gamma_0^3\rho^3)$ |
| $\frac{\ldots \phi e^{-\gamma_1 h} e^{-\gamma_0\rho}}{(\ldots + i\omega\varepsilon_1)\rho^2} (\ldots \gamma_0\rho A)$ | $\frac{p \sin\phi e^{-\gamma_1 h} e^{-\gamma_0\rho}}{2\pi\gamma_1\rho^3} \times [2 + \gamma_0\rho(1 + A)]$ | $-\frac{p \cos\phi e^{-\gamma_1 h} e^{-\gamma_0\rho}}{2\pi\gamma_1\rho^3} \times (1 + \gamma_0\rho + \gamma_0^2\rho^2 A)$ | $\frac{p \sin\phi e^{-\gamma_1 h} e^{-\gamma_0\rho}}{2\pi(\gamma_1^2 - \gamma_0^2)\rho^4}(1 + \gamma_1 z) \times (3 + 3\gamma_0\rho + \gamma_0^2\rho^2)$ |
| $\frac{\ldots \phi e^{-\gamma_1 h} e^{-\gamma_0\rho}}{(\ldots + i\omega\varepsilon_1)\rho^2} (\ldots_0\rho A)$ | $\frac{m \sin\phi e^{-\gamma_1 h} e^{-\gamma_0\rho}}{2\pi\rho^3} \times [2 + \gamma_0\rho(1 + A)]$ | $-\frac{m \cos\phi e^{-\gamma_1 h} e^{-\gamma_0\rho}}{2\pi\rho^3} \times (1 + \gamma_0\rho + \gamma_0^2\rho^2 A)$ | $\frac{m \sin\phi e^{-\gamma_1 h} e^{-\gamma_0\rho}}{2\pi\gamma_1\rho^4}(1 + \gamma_1 z) \times (3 + 3\gamma_0\rho + \gamma_0^2\rho^2)$ |

Table 8. Subsurface-to-Air Propagation Formulas

| Dipole Type | $E_\rho$ | $E_\phi$ | $E_z$ |
|---|---|---|---|
| VED | $\frac{p \sin\psi \cos\psi e^{-\gamma_1 h} e^{-\gamma_0 z}}{2\pi(\sigma_1 + i\omega\varepsilon_1)z^3}$ $\times (3 + 3\gamma_0 z + \gamma_0^2 z^2)$ | 0 | $-\frac{p e^{-\gamma_1 h} e^{-\gamma_0 z}}{2\pi(\sigma_1 + i\omega\varepsilon_1)z^3}[(1 - 3\sin^2\psi)$ $\times (1 + \gamma_0 z) + \gamma_0^2 z^2 \cos^2\psi]$ |
| VMD | 0 | $-\frac{\gamma_1 m \sin\psi \cos\psi e^{-\gamma_1 h} e^{-\gamma_0 z}}{2\pi(\sigma_1 + i\omega\varepsilon_1)z^3}$ $\times (3 + 3\gamma_0 z + \gamma_0^2 z^2)$ | 0 |
| HED | $-\frac{\gamma_1 p \cos\phi \sin\psi e^{-\gamma_1 h} e^{-\gamma_0 z}}{2\pi(\sigma_1 + i\omega\varepsilon_1)z^2}$ $\times (1 + \gamma_0 z)$ | $\frac{\gamma_1 p \sin\phi \sin\psi e^{-\gamma_1 h} e^{-\gamma_0 z}}{2\pi(\sigma_1 + i\omega\varepsilon_1)z^2}$ $\times (1 + \gamma_0 z)$ | $\frac{\gamma_1 p \cos\phi \cos\psi e^{-\gamma_1 h} e^{-\gamma_0 z}}{2\pi(\sigma_1 + i\omega\varepsilon_1)z^2}$ $\times (1 + \gamma_0 z)$ |
| HMD | $-\frac{\gamma_1^2 m \cos\phi \sin\psi e^{-\gamma_1 h} e^{-\gamma_0 z}}{2\pi(\sigma_1 + i\omega\varepsilon_1)z^2}$ $\times (1 + \gamma_0 z)$ | $\frac{\gamma_1^2 m \sin\phi \sin\psi e^{-\gamma_1 h} e^{-\gamma_0 z}}{2\pi(\sigma_1 + i\omega\varepsilon_1)z^2}$ $\times (1 + \gamma_0 z)$ | $\frac{\gamma_1^2 m \cos\phi \cos\psi e^{-\gamma_1 h} e^{-\gamma_\iota z}}{2\pi(\sigma_1 + i\omega\varepsilon_1)z^2}$ $\times (1 + \gamma_0 z)$ |

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

| | $H_\rho$ | $H_\phi$ | $H_z$ |
|---|---|---|---|
| ...(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 | $\frac{m \sin \psi e^{-\gamma_1 h} e^{-\gamma_0 z}}{\pi\gamma_1 z^4}$ $\times (3 + 3\gamma_0 z + \gamma_0^2 z^2)$ |
| ...$^h e^{-\gamma_0 z}$ / ...$z^2$ | $-\frac{p \sin \phi e^{-\gamma_1 h} e^{-\gamma_0 z}}{2\pi\gamma_1 z^3}$ $\times (1 + \gamma_0 z + \gamma_0^2 z^2)$ | $-\frac{p \cos \phi e^{-\gamma_1 h} e^{-\gamma_0 z}}{2\pi\gamma_1 z^3}$ $\times (1 + \gamma_0 z + \gamma_0^2 z^2)$ | $\frac{p \sin \phi \sin \psi \cos \psi e^{-\gamma_1 h} e^{-\gamma_0 z}}{2\pi\gamma_1 z^3}$ $\times (3 + 3\gamma_0 z + \gamma_0^2 z^2)$ |
| ...$^h e^{-\gamma_0 z}$ / ...$z^2$ ... | $-\frac{m \sin \phi e^{-\gamma_1 h} e^{-\gamma_0 z}}{2\pi z^3}$ $\times (1 + \gamma_0 z + \gamma_0^2 z^2)$ | $-\frac{m \cos \phi e^{-\gamma_1 h} e^{-\gamma_0 z}}{2\pi z^3}$ $\times (1 + \gamma_0 z + \gamma_0^2 z^2)$ | $\frac{m \sin \phi \sin \psi \cos \psi e^{-\gamma_1 h} e^{-\gamma_0 z}}{2\pi z^3}$ $\times (3 + 3\gamma_0 z + \gamma_0^2 z^2)$ |

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

| Dipole Type | $E_\rho$ | $E_\phi$ |
|---|---|---|
| VED | $-\dfrac{\gamma_1 p \cos\psi e^{-\gamma_1 z} e^{-\gamma_0 D}}{2\pi(\sigma_1 + i\omega\varepsilon_1)D^2}(1 + \gamma_0 DA)$ | 0 |
| VMD | 0 | $-\dfrac{m \cos\psi e^{-\gamma_1 z} e^{-\gamma_0 D}}{2\pi(\sigma_1 + i\omega\varepsilon_1)D^4}[(1 + \gamma_1 D \sin\psi)(3$ <br> $- \sin^2\psi(15 + 15\gamma_0 D + 6\gamma_0^2 D^2 + \gamma_0^3 D^3)]$ |
| HED | $\dfrac{p \cos\phi e^{-\gamma_1 z} e^{-\gamma_0 D}}{2\pi(\sigma_1 + i\omega\varepsilon_1)D^3}(1 - \gamma_1 D \sin\psi + \gamma_0 D - \gamma_0^2 D^2 nB)$ | $\dfrac{p \sin\phi e^{-\gamma_1 z} e^{-\gamma_0 D}}{2\pi(\sigma_1 + i\omega\varepsilon_1)D^3}[2 + \gamma_1 D \sin\psi$ <br> $+ \gamma_0 D(1 + A + \gamma_1 D \sin\psi) - \sin^2\psi(3 +$ |
| HMD | $\dfrac{\gamma_1 m \cos\phi e^{-\gamma_1 z} e^{-\gamma_0 D}}{2\pi(\sigma_1 + i\omega\varepsilon_1)D^3}(1 + \gamma_0 D + \gamma_0^2 D^2 A)$ | $\dfrac{\gamma_1 m \sin\phi e^{-\gamma_1 z} e^{-\gamma_0 D}}{2\pi(\sigma_1 + i\omega\varepsilon_1)D^3}[2 + \gamma_0 D(1 + A)$ <br> $- \sin^2\psi(3 + 3\gamma_0 D + \gamma_0^2 D^2)]$ |

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

| $E_\phi$ | $E_z$ |
|---|---|
| 0 | $-\frac{pe^{-\gamma_1 z}e^{-\gamma_0 D}}{2\pi(\sigma_1 + i\omega\varepsilon_1)D^3}[(1 - 3\sin^2\psi)(1 + \gamma_0 D)$ $+ \gamma_0^2 D^2 A \cos^2\psi]$ |
| $\frac{{}^{-\gamma_1 z}e^{-\gamma_0 D}}{\ldots i\omega\varepsilon_1)D^4}[(1 + \gamma_1 D \sin\psi)(3 + 3\gamma_0 D + \gamma_0^2 D^2)$ $5 + 15\gamma_0 D + 6\gamma_0^2 D^2 + \gamma_0^3 D^3)]$ | 0 |
| $\frac{{}_1{}^z e^{-\gamma_0 D}}{\ldots\omega\varepsilon_1)D^3}[2 + \gamma_1 D \sin\psi$ $A + \gamma_1 D \sin\psi) - \sin^2\psi(3 + 3\gamma_0 D + \gamma_0^2 D^2)]$ | $-\frac{p\cos\phi\cos\psi e^{-\gamma_1 z}e^{-\gamma_0 D}}{2\pi(\sigma_1 + i\omega\varepsilon_1)D^3}[(3 + 3\gamma_0 D)\sin\psi$ $- \gamma_0 A D + \gamma_0^2 D^2 B]$ |
| $\frac{{}^{-\gamma_1 z}e^{-\gamma_0 D}}{\ldots i\omega\varepsilon_1)D^3}[2 + \gamma_0 D(1 + A)$ $+ 3\gamma_0 D + \gamma_0^2 D^2)]$ | $\frac{m\cos\phi\cos\psi e^{-\gamma_1 z}e^{-\gamma_0 D}}{2\pi(\sigma_1 + i\omega\varepsilon_1)D^2}(\gamma_0^2)(1 + \gamma_0 D A)$ |



2

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

| Dipole Type | $H_\rho$ | $H_\phi$ |
|---|---|---|
| VED | 0 | $\frac{p \cos \psi e^{-\gamma_1 z} e^{-\gamma_0 D}}{2\pi D^2}(1 + \gamma_0 DA)$ |
| 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 ($|n^2| \geq 10$, $D \geq 10\delta$, $D \geq 5z$)

| $H_\phi$ | $H_z$ |
|---|---|
| $\frac{{}_1{}^{z} e^{-\gamma_0 D}}{\ldots}(1 + \gamma_0 DA)$ | 0 |
| 0 | $-\frac{me^{-\gamma_1 z}e^{-\gamma_0 D}}{2\pi(\gamma_1^2 - \gamma_0^2)D^5}\Big\{(1 + \gamma_1 D \sin\psi)[(9 + 9\gamma_0 D + 4\gamma_0^2 D^2 + \gamma_0^3 D^3)$ $- \sin^2\psi(15 + 15\gamma_0 D + 6\gamma_0^2 D^2 + \gamma_0^3 D^3)] - \sin^2\psi(75 + 75\gamma_0 D$ $+ 33\gamma_0^2 D^2 + 6\gamma_0^3 D^3) + \sin^4\psi(105 + 105\gamma_0 D + 45\gamma_0^2 D^2 + 6\gamma_0^3 D^3)\Big\}$ |
| $\frac{\gamma_1 z e^{-\gamma_0 D}}{D^3}(1 - \gamma_1 D \sin\psi + \gamma_0 D - \gamma_0^2 D^2 nB)$ | $\frac{p \sin\phi \cos\psi e^{-\gamma_1 z}e^{-\gamma_0 D}}{2\pi(\gamma_1^2 - \gamma_0^2)D^4}[(1 + \gamma_1 D \sin\psi)(3 + 3\gamma_0 D + \gamma_0^2 D^2)$ $- \sin^2\psi(15 + 15\gamma_0 D + 6\gamma_0^2 D^2 + \gamma_0^3 D^3)]$ |
| $\frac{\gamma_1 z e^{-\gamma_0 D}}{{}^3}(1 + \gamma_0 D + \gamma_0^2 D^2 A)$ | $\frac{m \sin\phi \cos\psi e^{-\gamma_1 z}e^{-\gamma_0 D}}{2\pi\gamma_1 D^4}[(3 + 3\gamma_0 D + \gamma_0^2 D^2)$ $- \sin^2\psi(15 + 15\gamma_0 D + 6\gamma_0^2 D^2 + \gamma_0^3 D^3)]$ |



1 2

Table 11. Air-to-Subsurface Propagation Formulas When

| Dipole Type | $E_\rho$ | $E_\phi$ | $E_z$ |
| --- | --- | --- | --- |
| VED | $-\frac{\gamma_1 p e^{-\gamma_1 z} e^{-\gamma_0 \rho}}{2\pi(\sigma_1 + i\omega\varepsilon_1)\rho^2}(1 + \gamma_0 \rho A)$ | 0 | $-\frac{p e^{-\gamma_1 z} e^{-\gamma_0 \rho}}{2\pi(\sigma_1 + i\omega\varepsilon_1)\rho^3}$ <br> $\times (1 + \gamma_0 \rho + \gamma_0^2 \rho^2 A)$ |
| VMD | 0 | $-\frac{m e^{-\gamma_1 z} e^{-\gamma_0 \rho}}{2\pi(\sigma_1 + i\omega\varepsilon_1)\rho^4}(1 + \gamma_1 h)$ <br> $\times (3 + 3\gamma_0 \rho + \gamma_0^2 \rho^2)$ | 0 |
| HED | $\frac{p \cos \phi e^{-\gamma_1 z} e^{-\gamma_0 \rho}}{2\pi(\sigma_1 + i\omega\varepsilon_1)\rho^3}$ <br> $\times (1 - \gamma_1 h + \gamma_0 \rho - \gamma_0^2 \rho^2 nB)$ | $\frac{p \sin \phi e^{-\gamma_1 z} e^{-\gamma_0 \rho}}{2\pi(\sigma_1 + i\omega\varepsilon_1)\rho^3}[2 + \gamma_1 h$ <br> $+ \gamma_0 \rho(1 + A + \gamma_1 h)]$ | $-\frac{p \cos \phi e^{-\gamma_1 z} e^{-\gamma_0 \rho}}{2\pi(\sigma_1 + i\omega\varepsilon_1)\rho^3}$ <br> $\times [(3 + 3\gamma_0 \rho)\sin \psi - \Delta\gamma_0 \rho + \gamma_0^2 \rho^2 B]$ |
| HMD | $\frac{\gamma_1 m \cos \phi e^{-\gamma_1 z} e^{-\gamma_0 \rho}}{2\pi(\sigma_1 + i\omega\varepsilon_1)\rho^3}$ <br> $\times (1 + \gamma_0 \rho + \gamma_0^2 \rho^2 A)$ | $\frac{\gamma_1 m \sin \phi e^{-\gamma_1 z} e^{-\gamma_0 \rho}}{2\pi(\sigma_1 + i\omega\varepsilon_1)\rho^3}$ <br> $\times [2 + \gamma_0 \rho(1 + A)]$ | $\frac{m \cos \phi e^{-\gamma_1 z} e^{-\gamma_0 \rho}}{2\pi(\sigma_1 + i\omega\varepsilon_1)\rho^2}$ <br> $\times (\gamma_0^2)(1 + \gamma_0 \rho A)$ |

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

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



2

Table 12. Air-to-Subsurface Propagation Formulas When

| Dipole Type | $E_\rho$ | $E_\phi$ | $E_z$ |
|---|---|---|---|
| VED | $-\dfrac{\gamma_1 p \cos\psi e^{-\gamma_1 z} e^{-\gamma_0 h}}{2\pi(\sigma_1 + i\omega\varepsilon_1)h^2}$ $\times (1 + \gamma_0 h)$ | 0 | $-\dfrac{p e^{-\gamma_1 z} e^{-\gamma_0 h}}{2\pi(\sigma_1 + i\omega\varepsilon_1)h^3}[(1 + \gamma_0 h)$ $\times (1 - 3\sin^2\psi) + \gamma_0^2 h^2 \cos^2\psi]$ |
| VMD | 0 | $-\dfrac{\gamma_1 m \sin\psi \cos\psi e^{-\gamma_1 z} e^{-\gamma_0 h}}{2\pi(\sigma_1 + i\omega\varepsilon_1)h^3}$ $\times (3 + 3\gamma_0 h + \gamma_0^2 h^2)$ | 0 |
| HED | $-\dfrac{\gamma_1 p \cos\phi \sin\psi e^{-\gamma_1 z} e^{-\gamma_0 h}}{2\pi(\sigma_1 + i\omega\varepsilon_1)h^2}$ $\times (1 + \gamma_0 h)$ | $\dfrac{\gamma_1 p \sin\phi \sin\psi e^{-\gamma_1 z} e^{-\gamma_0 h}}{2\pi(\sigma_1 + i\omega\varepsilon_1)h^2}$ $\times (1 + \gamma_0 h)$ | $-\dfrac{p \cos\phi \sin\psi \cos\psi e^{-\gamma_1 z} e^{-\gamma_0 h}}{2\pi(\sigma_1 + i\omega\varepsilon_1)h^3}$ × ([illegible] $3\gamma_0 h + \gamma_0^2 h^2)$ |
| HMD | $\dfrac{\gamma_1 m \cos\phi e^{-\gamma_1 z} e^{-\gamma_0 h}}{2\pi(\sigma_1 + i\omega\varepsilon_1)h^3}$ $\times (1 + \gamma_0 h + \gamma_0^2 h^2)$ | $-\dfrac{\gamma_1 m \sin\phi e^{-\gamma_1 z} e^{-\gamma_0 h}}{2\pi(\sigma_1 + i\omega\varepsilon_1)h^3}$ $\times (1 + \gamma_0 h + \gamma_0^2 h^2)$ | $\dfrac{\gamma_0^2 m \cos\phi \cos\psi e^{-\gamma z} e^{-\gamma_0 h}}{2\pi(\sigma_1 + i\omega\varepsilon_1)h^2}$ $\times (1 + \gamma_0 h)$ |

...on Formulas When h >> ρ ($|n^2| \geq 10$, $h \geq 10\delta$, $h \geq 5z$)

| | $H_\rho$ | $H_\phi$ | $H_z$ |
|---|---|---|---|
| ...$1 + \gamma_0 h)$ ... $\gamma_0^2 h^2 \cos^2 \psi]$ | 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 | $\frac{m \sin \psi e^{-\gamma_1 z} e^{-\gamma_0 h}}{\pi \gamma_1 h^4}$ $\times (3 + 3\gamma_0 h + \gamma_0^2 h^2)$ |
| ...$\psi e^{-\gamma_1 z} e^{-\gamma_0 h}$ / ...$\varepsilon_1) h^3$ | $\frac{p \sin \phi \sin \psi e^{-\gamma_1 z} e^{-\gamma_0 h}}{2\pi h^2}$ $\times (1 + \gamma_0 h)$ | $\frac{p \cos \phi \sin \psi e^{-\gamma_1 z} e^{-\gamma_0 h}}{2\pi h^2}$ $\times (1 + \gamma_0 h)$ | $\frac{p \sin \phi \sin \psi \cos \psi e^{-\gamma_1 z} e^{-\gamma_0 h}}{2\pi \gamma_1 h^3}$ $\times (3 + 3\gamma_0 h + \gamma_0^2 h^2)$ |
| ...$z e^{-\gamma_0 h}$ | $-\frac{m \sin \phi e^{-\gamma_1 z} e^{-\gamma_0 h}}{2\pi h^3}$ $\times (1 + \gamma_0 h + \gamma_0^2 h^2)$ | $-\frac{m \cos \phi e^{-\gamma_1 z} e^{-\gamma_0 h}}{2\pi h^3}$ $\times (1 + \gamma_0 h + \gamma_0^2 h^2)$ | $-\frac{m \sin \phi \cos \psi e^{-\gamma_1 z} e^{-\gamma_0 h}}{2\pi \gamma_1 h^4}$ $\times (12 + 12\gamma_0 h + 5\gamma_0^2 h^2 + \gamma_0^3 h^3)$ |

Table 13. Surface-to-Surface Propagation Formulas for $\rho$

| Dipole Type | $E_\rho$ | $E_\phi$ | $E_z$ | H |
|---|---|---|---|---|
| VED | $-\dfrac{\gamma_1 p e^{-\gamma_0\rho}}{2\pi(\sigma_1 + i\omega\varepsilon_1)\rho^2}$ <br> $\times\ (1 + \gamma_0\rho F)$ | 0 | $-\dfrac{p e^{-\gamma_0\rho}}{2\pi i\omega\varepsilon_0\rho^3}$ <br> $\times\ (1 + \gamma_0\rho + \gamma_0^2\rho^2 F)$ | 0 |
| VMD | 0 | $-\dfrac{i\omega\mu_0 m e^{-\gamma_0\rho}}{2\pi(\gamma_1^2 - \gamma_0^2)\rho^4}$ <br> $\times\ (3 + 3\gamma_0\rho + \gamma_0^2\rho^2)$ | 0 | $-\dfrac{m e^{-\gamma_0\rho}}{2\pi\gamma_1\rho^4}$ <br> $\times\ (3 + 3\gamma$ |
| HED | $\dfrac{p\cos\phi e^{-\gamma_0\rho}}{2\pi(\sigma_1 + i\omega\varepsilon_1)\rho^3}$ <br> $\times\ (1 + \gamma_0\rho + \gamma_0^2\rho^2 F)$ | $\dfrac{p\sin\phi e^{-\gamma_0\rho}}{2\pi(\sigma_1 + i\omega\varepsilon_1)\rho^3}$ <br> $\times\ [2 + \gamma_0\rho(1 + F)]$ | $\dfrac{i\omega\mu_0 p\cos\phi e^{-\gamma_0\rho}}{2\pi\gamma_1\rho^2}$ <br> $\times\ (1 + \gamma_0\rho F)$ | $\dfrac{p\sin\phi e}{2\pi\gamma_1\rho^3}$ <br> $\times\ [2 + \gamma_0$ |
| HMD | $\dfrac{i\omega\mu_0 m\cos\phi e^{-\gamma_0\rho}}{2\pi\gamma_1\rho^3}$ <br> $\times\ (1 + \gamma_0\rho + \gamma_0^2\rho^2 F)$ | $\dfrac{i\omega\mu_0 m\sin\phi e^{-\gamma_0\rho}}{2\pi\gamma_1\rho^3}$ <br> $\times\ [2 + \gamma_0\rho(1 + F)]$ | $\dfrac{i\omega\mu_0 m\cos\phi e^{-\gamma_0\rho}}{2\pi\rho^2}$ <br> $\times\ (1 + \gamma_0\rho F)$ | $\dfrac{m\sin\phi e}{2\pi\rho^3}$ <br> $\times\ [2 + \gamma$ |

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

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

# REFERENCES


1. K. A. Norton, "The Propagation of Radio Waves Over the Surface of the Earth and in the Upper Atmosphere, Part I," Proceedings IRE, vol. 24, no. 10, 1936, pp. 1367-1387.

2. K. A. Norton, "The Propagation of Radio Waves Over the Surface of the Earth and in the Upper Atmosphere, Part II," Proceedings IRE, vol. 25, no. 9, 1937, pp. 1203-1236.

3. K. A. Norton, "The Polarization of Downcoming Ionospheric Radio Waves," FCC Report No. 60047, National Bureau of Standards, Boulder, CO, 1942.

4. J. R. Wait, "The Electromagnetic Fields of a Horizontal Dipole Antenna in the Presence of a Conducting Half-Space," Canadian Journal of Physics, vol. 39, no. 7, 1961, pp. 1017-1028.

5. A. Baños, Jr., Dipole Radiation in the Presence of a Conducting Half-Space, Pergamon Press, NY, 1966, 245 pp.

6. R. K. Moore and W. E. Blair, "Dipole Radiation in a Conducting Half-Space," Journal of Research of National Bureau of Standards, D Radio Propagation, vol. 65, no. 6, 1961, pp. 547-563.

7. P. R. Bannister, "The Quasi-Near Fields of Dipole Antennas," IEEE Transactions on Antennas and Propagation, vol. AP-15, no. 5, 1967, pp. 618-626.

8. P. R. Bannister, Utilization of the Reciprocity Theorem to Determine the Nearfield Air-to-Subsurface Propagation Formulas, USL Report 786, Naval Underwater Systems Center, New London, CT, 22 November 1966.

9. P. R. Bannister, Surface-to-Surface and Subsurface-to-Air Propagation of Electromagnetic Waves, USL Report 761, Naval Underwater Systems Center, New London, CT, 17 February 1967.

10. P. R. Bannister et al., Quasi-Static Electromagnetic Fields, NUSC Scientific and Engineering Studies, Naval Underwater Systems Center, New London, CT, February 1980, 515 pp.

11. R. J. King, "Electromagnetic Wave Propagation Over a Constant Impedance Plane," Radio Science, vol. 4, no. 3, 1969, pp. 255-268.

12. M. B. Kraichman, Handbook of Electromagnetic Propagation in Conducting Media, U. S. Government Printing Office, Washington, DC, 1970, Ch. 3.

13. P. R. Bannister, New Formulas for HED, HMD, VED, and VMD Subsurface-to-Subsurface Propagation, NUSC Technical Report 6881, Naval Underwater Systems Center, New London, CT (to be published).

14. A. Sommerfeld, "On the Propagation of Waves in Wireless Telegraphy," Annalen der Physik, vol. 81, no. 25, 1926, pp. 1135-1153.

15. J. R. Wait, Electromagnetic Waves in Stratified Media, Pergamon Press, NY, 1970.

16. R. J. King and G. A. Schlak, "Groundwave Attenuation Function for Propagation Over a Highly Inductive Earth," Radio Science, vol. 2, no. 7, 1967, pp. 687-693.

17. P. R. Bannister, Extension of Finitely Conducting Earth-Image Theory Results to Any Range, NUSC Technical Report 6885, Naval Underwater Systems Center, New London, CT (to be published).

INITIAL DISTRIBUTION LIST

| Addressee | No. of Copies |
|---|---|
| DARPA | 3 |
| DTIC | 15 |
| ONR (Code 425GG (J. Heacock), 428I0 (R. G. Joiner)) | 2 |
| ASN (T. P. Quinn (for C3), H. Hull (Rm SE 779) | 2 |
| NRL (Library, Dr. J. R. Davis (Code 7550), Dr. Frank Kelly) | 3 |
| NOSC (Library, R. A. Pappart, D.G. Morfitt, J. A. Ferguson, J. Bickel, F. P. Snyder, C. F. Ramstedt, P. Hansen, K. Grauer, W. Hart) | 10 |
| NAVELECSYSCOM (PME 110-11 (Dr. G. Brunhart), PME 110-X1 (Dr. Bodo Kruger), PME 110) | 3 |
| NAVAL SURFACE WEAPONS CENTER, WHITE OAK LAB. (J. J. Holmes, P. Wessel, K. Bishop, R. Brown, J. Cunningham, B. DeSavage, Library) | 7 |
| DWTNSRDC ANNA (W. Andahazy, F. E. Baker, P. Field, D. Everstine, B. Hood, D. Nixon) | 6 |
| NAVPGSCOL, MONTEREY (O. Heinz, P. Moose, A. Ochadlik, M. Thomas, W. M. Tolles, Library) | 6 |
| NCSC (K. R. Allen, R. H. Clark, M. J. Wynn, M. Cooper, E. Moritz, Library) | 5 |
| DIRECTOR, DEFENSE NUCLEAR AGENCY, RAAE, DDST, RAEV | 3 |
| R&D Assoicates, P.O. Box 9695, Marina del Rey, CA 90291 (C. GREIFINGER, P. Greifinger) | 2 |
| Pacific-Sierra Research Corp., 1456 Cloverfield Boulevard, Santa Monica, CA 90404 (E. C. Field) | 1 |
| Johns Hopkins University, Applied Physics Laboratory, Laurel, MD 20810 (L. Hart, J. Giannini, H. Ko, I Sugai) | 4 |
| University of California, Scripps Institute of Oceanography (C. S. Cox (Code A-030), H. G. Booker, J. Filloux, P. Young) | 5 |
| Lockheed Palo Alto Research Laboratory (W. Imhof, J. B. Reagan, E. E. Gaines, R. C. Gunton, R. E. Meyerott) | 5 |
| University of Texas, Geomagnetics and Electrical Geoscience Laboratory (F. X. Bostick, Jr.) | 1 |
| COMMANDER, AIR FORCE GEOPHYSICS LABORATORY (J. Aarons) | 1 |
| COMMANDER, ROME AIR DEVELOPMENT CENTER (J. P. Turtle, J. E. Rasmussen, W. I. Klemetti, P. A. Kossey, E. F. Altschuler) | 5 |
| Applied Science Assoicates, Inc., (Dr. Gary S. Brown) 105 E. Chatham St., Apex, NC 27502 | 1 |
| Computer Sciences Corp., Falls Church, VA 22046 (D. Blumberg, Senator R. Mellenberg, R. Heppe, F. L. Eisenbarth) | 4 |
| MIT Lincoln Labs. (M. L. Burrows, D. P. White, D. K. Willim, S. L. Bernstein, I. Richer) | 5 |
| Electromagnetic Sciences Lab. SRI International, Menlo Park, CA 94015 (Dr. David M. Bubenik) | 1 |
| Communications Research Centre (Dr. John S. Belrose) P.O. Box 11490, Station "H" Shirley Bay, Ottawa, Ontario, Canada K2H8S2 | 1 |
| Dr. Joseph P. deBettencourt, 18 Sterling St., West Newton, MA 02165 | 1 |
| Dr. Marty Abromavage, IITRE, Div. E., 10W 35th St., Chicago, IL 60616 | 1 |

INITIAL DISTRIBUTION LIST (Cont'd)

| Addressee | No. of Copies |
| --- | --- |
| Mr. Larry Ball, U.S. Dept. of Energy NURE Project Office, P.O. Box 2567, Grand Junction, CO 81502 | 1 |
| STATE DEPARTMENT ACDA MA-AT, Rm. 5499, Washington, DC 20451 (ADM T. Davies, R. Booth, N. Carrera) | 3 |
| GTE Sylvania, (R. Row, D. Boots, D. Esten) 189 B. St. Needham, MA 02194 | 3 |
| HARVARD UNIVERSITY, Gordon McKay Lab. (Prof. R. W. P. King, Prof. T. T. Wu) | 2 |
| University of Rhode Island, Dept. of Electrical Engineering (Prof. C. Polk) | 1 |
| University of Nebraska, Electrical Engineering Dept., (Prof. E. Bahar) | 1 |
| University of Toronto, EE Dept. (Prof. Keith Balmain) | 1 |
| NOAA/ERL (Dr. Donald E. Barrick) | 1 |
| University of Colorado, EE Dept. (Prof. Peter Beckmann) | 1 |
| Geophysical Observatory, Physics & Eng. Lab. DSIR Christchurch, New Zealand (Dr. Richard Barr) | 1 |
| General Electric Co., (C. Zierdt, A. Steinmayer) 3198 Chestnut St., Philadelphia, PA 19101 | 2 |
| University of Arizona, Elec. Eng. Dept., Bldg. 20 (Prof. J. W. Wait) Tuscon, AZ 85721 | 1 |
| U.S. NAVAL ACADEMY, Dept. of Applied Science (Dr. Frank L. Chi) | 1 |
| Stanford University, Radioscience Laboratory (Dr. Anthony Fraser-Smith), Durand Bldg., Rm. 205 | 1 |
| Stanford University, Stanford Electronics Laboratory (Prof. Bob Helliwell) | 1 |
| Colorado School of Mines, Department of Geophysics (Prof. A. Kaufman) | 1 |
| Prof. George V. Keller, Chairman, Group Seven, Inc., Irongate II, Executive Plaza, 777 So. Wadsworth Blvd., Lakewood, CO 80226 | 1 |
| NOAA, Pacific Marine Environ, Lab. (Dr. Jim Larsen) | 1 |
| MIT, Dept. of Earth/Planetary Sciences, Bldg. 54-314 (Prof. Gene Simmons) | 1 |
| Colorado School of Mines (Dr. C. Stoyer) | 1 |
| University of Victoria, (Prof. J. Weaver) Victoria, B.C. V8W 2Y2 Canada | 1 |
| Mr. Donald Clark, c/o Naval Security Group Command, 3801 Nebraska Ave., NW, Washington, DC 20390 | 1 |
| Prof. R. L. Dube, 13 Fairview Rd., Wilbraham, MA 01095 | 1 |
| U.S. Geological Survey, Rm. 1244 (Dr. Frank C. Frischknecht) Denver, CO 80225 | 1 |
| Mr. Larry Ginsberg, Mitre Corp., 1820 Dolly Madison Bldg. McLean, VA 22102 | 1 |
| Dr. Robert Morgan, Rt. 1, Box 187, Cedaredge, CO 81413 | 1 |
| Mr. A. D. Watt, Rt. 1, Box 183 1/2, Degaredge, CO 81413 | 1 |
| Dr. E. L. Maxwell, Atmospheric Sciences Dept., Colorado State University, Fort Collins, CO | 1 |
| Mr. Al Morrison, Purvis Systems, 3530 Camino Del Rio North, Suite 200, San Diego, CA 92108 | 1 |

INITIAL DISTRIBUTION LIST (Cont'd)

| Addressee | No. of Copies |
|---|---|
| NDRE, Division for Electronics (Dr. Trygve Larsen) P.O. Box 25, Kjeller, Norway | 1 |
| Belden Corp., Technical Research Center (Mr. Douglas O'Brien) Geneva, Illinois | 1 |
| University of Pennsylvania (Dr. Ralph Showers) Moore School of Elec. Eng., Philadelphia, PA 19174 | 1 |
| University of Houston, Director, Dept of Elec. Eng. (Prog. Liang C. Shen) | 1 |
| The University of Connecticut, Physics Dept., (Prof. O. R. Gilliam), Storrs, CT 06268 | 1 |
| Dr. David J. Thomson, Defence Research Establishment Pacific, F.M.O., Victoria, B.C., Canada | 1 |
| Dr. Robert Hansen, Box 215, Tarzana, CA 91356 | 1 |
| The University of Kansas, Remote Sensing Laboratory (Prof. R. K. Moore) Center for Research, Inc., Lawrence, Kansas | 1 |
| OT/ITS U.S. Dept. of Commerce (Dr. David A. Hill), Boulder, CO | 1 |
| Office of Telecommunications, Inst. for Telecommunications Services (Dr. Douglas D. Crombie, Director), Boulder, CO | 1 |
| University of Colorado, Dept. of Electrical Eng. (Prof. David C. Chang) | 1 |
| Dr. K. P. Spies, ITS/NTIA, U.S. Dept. of Commerce | 1 |
| The University of Connecticut, Dept. of Electrical Eng. & Computer Sci., Storrs, CT (Prof. Clarence Schultz, Prof. Mahmond A. Melehy) | 2 |
| Dr. Richard G. Geyer, 670 S. Estes St., Lakewood, CO | 1 |
| University of California, Lawrence Livermore Lab., (R. J. Lytle, E. K. Miller, R. J. King) | 3 |
| Kings College, Radiophysics Group (Prof. D. Llanwyn-Jones) Strand, London WC2R 2LS, England | 1 |
| Istituto di Electtrotechnica, Facotta di Ingegneria (Prof. Giorgio Tacconi) Viale Combiaso 6, 16145 Genova, Italy | 1 |
| Universite des Sciences de Lille (Prof. R. Gabillard) B. P. 36-59650 Villeneuve D'Ascq, Lille, France | 1 |
| Arthur D. Little, Inc., (Dr. A. G. Emslie, Dr., R. L. Lagace, R&D Div., Acorn Park, Cambridge, MA 02140 | 1 |
| University of Colorado, Dept. of Electrical Eng. (Prof. S. W. Maley) | |
| University of Washington, EE Dept. (Prof. A. Ishimaru) Seattle | |
| Dr. Svante Westerland, Kiruna Geofysiska Institute S981 01 Kiruna 1, Sweden | 1 |
| Dr. Harry C. Koons, The Aerospace Corp., P.O. Box 92957, Los Angeles, CA 90009 | 1 |
| Dr. Albert Essmann, Hoogewinkel 46, 23 Kiel 1, West Germany | 1 |
| Glenn S. Smith, School of Elec. Eng. Georgia Tech. Atlanta, GA | 1 |
| Dr. T. Lee, CIRES, Campus Box 449, University of Colorado | 1 |
| Dr. Jack Williams, RCA Camden, Mail Stop 1-2, Camden, NJ 08102 | 1 |
| Dr. Joseph Czika, Science Applications, Inc., 840 Westpark Dr. McLean, VA 22101 | 1 |
| Mr. Arnie Farstad, 390 So. 69th St., Boulder, CO 80303 | 1 |

INITIAL DISTRIBUTION LIST (Cont'd)

| Addressee | No. of Copies |
| --- | --- |
| NATO SACLANT ASW CENTER (Library) | 1 |
| USGS, Branch of Electromagnetism and Geomagnetism (Dr. James Towle) Denver, CO | 1 |
| NOAA, Pacific Maine Environ. Lab. (Dr. Jim Larsen) | 1 |
| University of Texas at Dallas, Geosciences Division, (Dr. Mark Landisman) | 1 |
| University of Wisconsin, Lewis G. Weeks Hall, Dept. of Geology and Geophysics (Dr. C. S. Clay) | 1 |
| Argonne National Laboratory, Bldg. 12 (Dr. Tony Vallentino) | 1 |
| IITRE, Div. E, Chicago (Dr. Marty Abromavage) | 1 |
| The University of Manitoba, Elec, Eng. Dept. (Prof. A. Mohsen) | 1 |
| Mr. Jerry Pucillo, Analytical Systems, Engineering Corp., Newport, RI 02840 | 1 |
| Dr. Misac N. Nabighian, Newmont Exploration Ltd., Tuscon | 1 |
| Dr. Fred Raab, Pohemus, P.O. Box 298, Essex Junction, VT 05452 | 1 |
| Dr. Louis H. Rorden, President, Develco, Inc., 404 Tasman Dr. Sunnyvale, CA 94086 | 1 |
| Dr. Eivind Trane, NDRE, P.O. Box 25, 2007 Kjeller, Norway | 1 |
| RCA David Sarnoff Research Center (K. Powers, J. Zennel, L. Stetz, H. Staras) | 4 |
| University of Illinois, Aeronomy Laboratory (Prof. C. F. Sechrist) | 1 |
| Dr. Cullen M. Crain, Rand Corp., Santa Monica, CA | 1 |
| Radioastronomisches Institute der Universität Bonn (Dr. H. Volland), 5300 Bonn-Endenich, Auf dem Hiigel 71 West Germany | 1 |
| Dr. John P. Wikswo, Jr., P.O. Box 120062 Acklen Station, Nashville | 1 |
| Mr. Lars Brock-Nannestad, DDRB Osterbrogades Kaserne, 2100 CVopenhagen O, Denmark | 1 |
| Institut de Physique du Globe (Dr. Edonard Selzer) 11 Quai St., Bernard, Tour 24 Paris Ve, France | 1 |
| Elektrophysikalisches Institut (Dr. Herbvert König) Technische Hochschule, Arcisstrasse 21, 8 Munich 2, West Germany | 1 |
| Raytheon Company (Dr. Mario Grossi) Portsmouth, RI | 1 |
| NISC, Code OOW (Mr. M. A. Koontz) Washington, DC | 1 |
| Polytechnic Institute of Brooklyn (Prof. Leo Felsen) | 1 |
| NOAA/ERL (Dr. Earl E. Gossard) R45X7, Boulder, CO 80302 | 1 |
| Dr. George H. Hagn, SRI-Washington, Rosslyn Plaza, Arlington, VA | 1 |
| NOAA/ERL (Dr. C. Gordon Little) R45 | 1 |
| Goddard Space Flight Ctr. (Dr. S. J. Durrani) Code 800.1 | 1 |
| ITS, Office of Telecon (Dr. Ken Steele) Boulder, CO 80302 | 1 |
| NTIA/ITS, U.S. Dept. of Commerce (Dr. A. D. Spaulding) | 1 |
| Stanford University, Elec. Eng. Dept. (Dr. O. G. Villard, Jr.) | 1 |
| Dr. D. Middleton, 127 East 91st St., New York, NY 10028 | 1 |
| University of California, Elec. Eng. & Computer Sci. Dept., Prof. K. K. Mei) | 1 |
| California Inst. of Technology, Jet Propulsion Lab., (Dr. Yahya Rahmat-Samii) | 1 |

INITIAL DISTRIBUTION LIST (Cont'd)

| Addressee | No. of Copies |
|---|---|
| Raytheon Service Co. (Dr. M. Soyda) Mt. Laurel, NJ 08054 | 1 |
| MITRE M/S W761 (Dr. W. Foster) McLean, VA | 1 |
| Max-Planck-Institut fur Aeromomie (Prof. P. Stubbe) 3400 Katlenburg-Lindau 3 FRG | 1 |
| University of Otago, Physics Dept. (Prof. R. L. Dowden) Dunedin, New Zealand | 1 |
| University of Leicester, Physics Dept. (Prof. T. B. Jones) Leicester, England | 1 |
| Naval Weapons Center, China Lake, Code 3814 (Dr. R. J. Dinger) | 1 |
| Dr. Claudia D. Tesche, Lutech, Inc., P.O. Box 1263, Berkeley | 1 |
| National Aeronautical Est., National Research Council, Flight Research Lab., (Dr. C. D. Harwick) Ottawa, K1AOR6, Canada | 1 |
| Colorado Research and Prediction Laboratory, Inc. (Dr. R. H. Doherty, Dr. J. R. Johler) Boulder, CO | 2 |
| University of Alberta, Physics Dept. (Prof. R. P. Singh) Edmonton, Alberta, Canada | 1 |
| ARF Products Inc., (Mr. Larry Stolarczyk), Raton, NM | 1 |
| NAVSEA, Code 63R | 1 |
| Rockwell Int'l Space Transportation Division, (Dr. David G. Aviv), Mail Stop AA-81, 12214 Lakewood Blvd., Dowrey, CA 90241 | 1 |
| Arizona State University, School of Engineering, Dept. of Electrical and Computer Engineering, (Prof. Constantine A. Balanis), Tempe, AZ 85287 | 1 |
| University of Massachusetts, Dept. of Electrical and Computer Engineering, (Prof. Robert E. McIntosh), Amherst, MA 01003 | 1 |
| Cairo University, Faculty of Engineering Electronics & Comm. Dept., (Dr. Samir F. Mahmond), Giza, Egypt | 1 |