Cohen, Dippell and Everist, P.C.

Before The
FEDERAL COMMUNICATIONS COMMISSION
Washington, D.C. 20554

In the Matter of	)	
	)	
Revitalization of the AM Radio Service	)	MB Docket No. 13-249

Reply Comments
on Behalf of
COHEN, DIPPELL AND EVERIST, P.C.

The following reply comments are submitted on behalf of Cohen, Dippell and Everist, P.C. ("CDE") and is in response to the Notice of Proposed Rulemaking released by the Federal Communications Commission on October 31, 2013. CDE and its predecessors have practiced before the Federal Communications Commission ("FCC") for over 75 years in broadcast and telecommunications matters. The firm or its predecessors have been located in Washington, DC since 1937 and performed professional consulting engineering services to the communication industry.

The undersigned is licensed as a Professional Engineer in the District of Columbia and has been in continuous employment with this firm or its predecessors for over fifty (50) years.

There are many worthwhile comments which the FCC should consider and if necessary issue further notices of proposed rulemaking. One of the comments raises the issue of minimum radiation efficiencies. Attached is an article by Ronald W. P. King entitled, "Electromagnetic Surface Waves". The article introduces the factor of ground conductivities on the vertical radiator elevation patterns. This article and approach to determine elevation patterns from standard vertical radiators may be helpful in the FCC continued deliberations on AM service improvement.

These reply comments provide an update by supplying the analysis under the heading "Interim Technical Steps To Revitalize AM Broadcast" on Page 6 and the introduction on Page 7 of this firm's comments. The submission made to the Technical Subgroup of Radio Advisory Committee, dated May 10, 1988, is the basis of this firm's comments on Pages 7, 8 and 9.

The Commission is to be commended for the undertaking of such a timely and necessary task.

Respectfully Submitted,

COHEN, DIPPELL AND EVERIST, P.C.

Donald G. Everist
President

DATE: March 20, 2014

TO:	Technical Subgroup of Radio Advisory Committee
FROM:	Donald G. Everist
SUBJECT:	Mathematical Representation of Probability of 10% Skywave Signals Appearing at a Location Simultaneously
DATE:	May 10, 1988

The following is a mathematical representation of the probability of multiple 10% skywave signals simultaneously appearing at a location. This document is a result of John Reiser's special effort and contribution. The following formula has been utilized:

$$p_k = C_k^n p^k (1-p)^{n-k}$$

$$= n!/k!(n-k)!\ p^k (1-p)^{n-k}, \quad 0\ k\ n.$$

WHERE:

p is the probability

n is the independent trials

k is "successes"

c is

For eight total possible events with a single probability of 0.1, the probability is:

Number Of Events	Probability Of Exactly X Events	Probability Of 1 to X or less Events Occurring
0	0.430	--
1	0.382	0.382
2	0.148	0.530
3	0.03	0.562
4	0.004	0.567
5	0.0004	0.567
6	0.00002	0.567
7	0.0000007	0.567
8	0.000000009	0.567

For eight total possible events with a single probability of 0.5, the probability is:

Number Of Events	Probability Of Exactly X Events	Probability Of 1 to X or less Events Occurring
0	0.004	--
1	0.031	0.031
2	0.110	0.141
3	0.219	0.360
4	0.273	0.633
5	0.219	0.852
6	0.109	0.961
7	0.031	0.992
8	0.003	0.995

Assumption: The eight total events are independent

IEEE Antennas and Propagation Society Newsletter, December 1986

Feature Article

Electromagnetic Surface Waves

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1. Introduction

Electromagnetic waves that are guided along a boundary between two electrically different media are called surface waves. Actually there are a number of types of such waves with quite different properties. Among the best known are those that travel along so-called surface waveguides, like dielectric-coated, corrugated, or otherwise modified metal surfaces. These are not lateral waves. Surface waves along the smooth boundary between two dielectrics with permittivities $\epsilon_1 > \epsilon_2$ occur in the less dense region 2 when the angle of incidence in region 1 exceeds the critical angle. The incident field is then totally reflected in region 1 and there is no refracted field in region 2. However, the boundary conditions require the plane wave that travels parallel to the boundary in region 1 to extend into region 2 where its amplitude decreases exponentially in the direction perpendicular to the surface and to the direction of propagation. This is a true surface wave in region 2 but it is not a lateral wave.

When a vertical electric dipole with the electric moment $Ih_e = 1$ Am is erected on the earth or sea for radio communication, as shown in Fig. 1, the electric field in the air is often represented in the spherical coordinates r, Θ, Φ in the form:

$$E_\Theta = -\frac{i\omega\mu_0}{4\pi}\frac{e^{ik_2r}}{r}(1+f_{er})\sin\Theta, \tag{1}$$

where Θ is measured from the vertical axis, r is the radial distance to the point of observation, and

$$f_{er} = \frac{N^2\cos\Theta - (N^2-\sin^2\Theta)^{1/2}}{N^2\cos\Theta + (N^2-\sin^2\Theta)^{1/2}} \tag{2}$$

is the plane-wave reflection coefficient. N is the complex index of refraction. The wave number of the earth or sea is $k_1 = \beta_1 + i\alpha_1 = \omega[\mu_0(\epsilon_1 + i\sigma_1/\omega)]^{1/2}$, that of the air is $k_0 = \omega(\mu_0\epsilon_0)^{1/2}$. The magnitude of E_Θ is shown in Fig. 1 for sea water, lake water, and dry earth. Also shown is the field when region 1 is a perfect conductor ($N \to \infty$). It is seen that since from (2) $f_{er} = -1$ when $\Theta = \pi/2$ for all *finite* values of N, $E_\Theta = 0$ along the entire equatorial plane. On the other hand, with the perfect conductor $f_{er} = 1$ when $\Theta = \pi/2$, so that E_Θ has a maximum. Actually, the field is not zero over any of the media represented in Fig. 1. The formula (1) is incomplete. The field of the vertical dipole is not a plane wave and the boundary conditions on the tangential electric and magnetic fields are not satisfied (as are plane waves) by an incident and reflected field in the air and a refracted field in the earth or sea. A surface wave with unusual properties is also required. The complete field was derived by Sommerfeld [1]. In its association with radio communication over the earth, the associated surface wave was called the *Norton surface wave* after K. A. Norton [2], [3] who pioneered in its approximate evaluation and graphical representation in the manner illustrated in Fig. 2. In more general occurrences it is known as a lateral wave.

2. Vertical Dipole in Air on the Surface of the Earth

a. The Field in the Air; Radio Transmission

The complete field of a unit vertical electric dipole (electric moment $I_zh_e = 1$ Am) located in the air (region 2, $z' \geq 0$) at a height d over the surface of the earth or sea (region 1, $z' \leq 0$) consists of the three cylindrical components E_ρ, $E_{z'}$, and B_ϕ. At (ρ, z') in the air it is accurately given by three integrals [4, eqs. (29)–(31)] of which the following one for $E_{2z'}$ is representative:

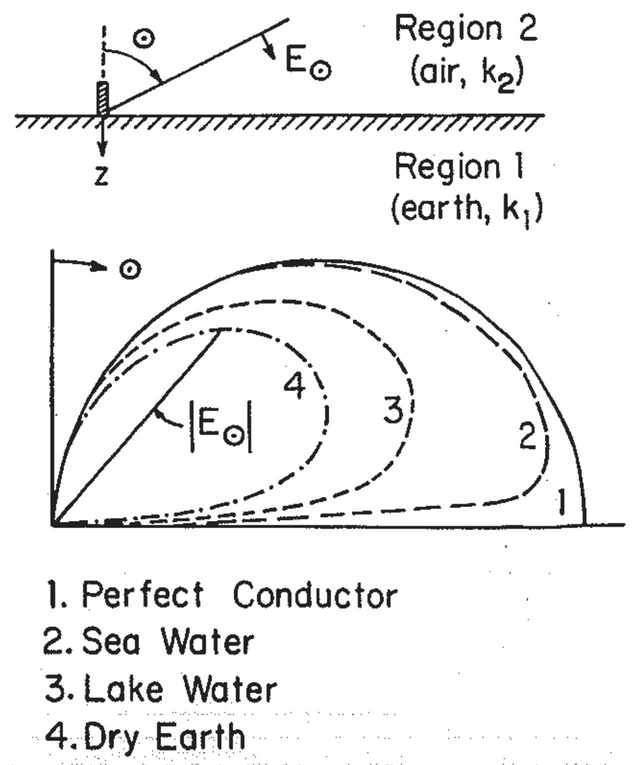

Figure 1. Far field of vertical dipole, not including the lateral wave.

$$E_{2z'}(\rho,z') = -\frac{\omega\mu_0 k_1^2}{2\pi k_2^2}\int_0^\infty \frac{e^{i\gamma_2 z'}}{N} J_0(\lambda\rho)\lambda^3\,d\lambda, \tag{3}$$

where $N = k_1^2\gamma_2 + k_2^2\gamma_1$ and $\gamma_j = (k_j^2 - \lambda^2)^{1/2}$ with $j = 1, 2$. This formula is equivalent to the expressions of Sommerfeld [1], Baños [5], and others who express the components of the field as unevaluated derivatives of the Hertz potential. Subject to the inequality

$$|k_1^2| \gg k_2^2 \qquad \text{or} \qquad |k_1| \geq 3k_2, \tag{4}$$

the integral (3) and those for the other components have been evaluated with the following result for $E_{2z'}$:

$$E_{2z'}(\rho,z') = E^d_{2z'}(\rho,z') + E^i_{2z'}(\rho,z') + E^L_{2z'}(\rho,z'), \tag{5}$$

where

$$E^d_{2z'}(\rho,z') = \frac{\omega\mu_0}{4\pi k_2} e^{ik_2 r_1}\left[\left(\frac{ik_2}{r_1} - \frac{1}{r_1^2} - \frac{i}{k_2 r_1^3}\right) - \left(\frac{z'-d}{r_1}\right)^2\left(\frac{ik_2}{r_1} - \frac{3}{r_1^2} - \frac{3i}{k_2 r_1^3}\right)\right] \tag{6a}$$

is the direct field of the dipole as if in an infinite medium at $(0, d)$;

$$E^i_{2z'}(\rho,z') = \frac{\omega\mu_0}{4\pi k_2} e^{ik_2 r_2}\left[\left(\frac{ik_2}{r_2} - \frac{1}{r_2^2} - \frac{i}{k_2 r_2^3}\right) - \left(\frac{z'+d}{r_2}\right)^2\left(\frac{ik_2}{r_2} - \frac{3}{r_2^2} - \frac{3i}{k_2 r_2^3}\right)\right] \tag{6b}$$

is the field of an identical image dipole at $(0, -d)$; and

$$E^L_{2z'}(\rho,z') = -\frac{\omega\mu_0}{2\pi k_2} e^{ik_2\rho} e^{ik_2(z'+d)^2/2\rho} \times \frac{k_2^3}{k_1}\left(\frac{\pi}{k_2\rho}\right)^{1/2} e^{-iP}\mathcal{F}(P) \tag{6c}$$

is the lateral-wave field. In (6a-c),

$$r_1 = [\rho^2 + (z'-d)^2]^{1/2}, \quad r_2 = [\rho^2 + (z'+d)^2]^{1/2},$$

$$z' = -z, \tag{7a}$$

$$P = (R + Z' + D)^2/R, \tag{7b}$$

$$R = k_2^3\rho/2k_1^2, \quad Z' = k_2^2 z'/2k_1, \quad D = k_2^2 d/2k_1; \tag{7c}$$

$$\mathcal{F}(P) = \tfrac{1}{2}(1+i) - C_2(P) - iS_2(P) = \int_P^\infty \frac{e^{it}}{\sqrt{2\pi t}}\,dt. \tag{8}$$

Here, $C_2(P) + iS_2(P)$ is the Fresnel integral.

The field on the boundary $z' = 0$ when the dipole is also on the boundary, i.e., when $d = 0$, is:

$$E_{1z'}(\rho,0) = E_{2z'}(\rho,0) = \frac{\omega\mu_0}{2\pi k_2} e^{ik_2\rho} g(k_2\rho, k_1), \tag{9}$$

where

$$g(k_2\rho, k_1) = \frac{ik_2}{\rho} - \frac{1}{\rho^2} - \frac{i}{k_2\rho^3} - \frac{k_2^3}{k_1}\left(\frac{\pi}{k_2\rho}\right)^{1/2} e^{-iR}\mathcal{F}(R). \tag{10}$$

The quantity $R = k_2^3\rho/2k_1^2$ is the magnitude of the well known "numerical distance" of Sommerfeld. In (10), the first three terms are the field in the equatorial plane of a z'-directed unit electric dipole in air. They are dominant in the near field where $R < 1$, since there the Fresnel-integral term is negligibly small. They constitute the entire field at all radial distances when region 1 is a perfect conductor with $\sigma_1 = \infty$, $k_1 \sim \infty$, since then the Fresnel-integral term vanishes identically. In the far field defined by $R \geq 4$, the $1/\rho$ term in (10) dominates among the first three so that the field over a perfect conductor reduces to the familiar form

$$E_{2z'}(\rho,0) \sim \frac{i\omega\mu_0}{2\pi}\frac{e^{ik_2\rho}}{\rho}. \tag{11}$$

For all other types of media, the Fresnel-integral term assumes the following far-field form:

$$-\frac{k_2^3}{k_1}\left(\frac{\pi}{k_2\rho}\right)^{1/2} e^{-iR}\mathcal{F}(R) = -\frac{ik_2}{\rho} - \frac{k_1^2}{k_2^2\rho^2}, \tag{12}$$

so that the complete far field becomes

$$E_{2z'}(\rho,0) \sim -\frac{\omega\mu_0 k_1^2}{2\pi k_2^3}\frac{e^{ik_2\rho}}{\rho^2}. \tag{13}$$

Thus, along the air–earth boundary, the far field has the form $1/\rho^2$ and not $1/\rho$. It is determined by the Fresnel-integral term in which the $1/\rho$ part exactly cancels the $1/\rho$ far field (11) of the dipole with image. The vertical electric field given by (5) and along the boundary by (9) is that used in all radio communication over the surface of the earth or sea when both the transmitter and receiver are on the surface. The field patterns are like those in Fig. 1 except that with finite σ they do not vanish when $\Theta = \pi/2$ but reduce to the relatively small value given by (9).

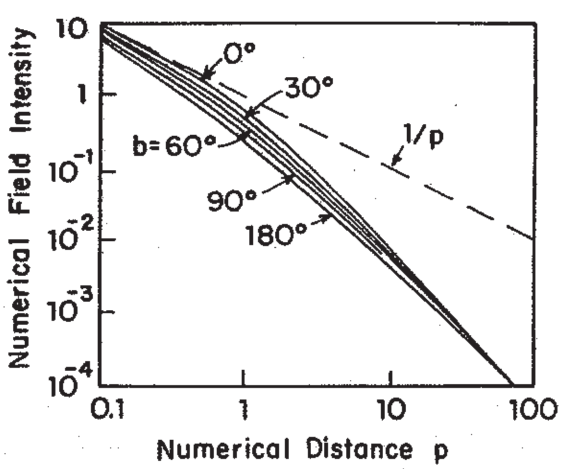

Figure 2. Decay of ground wave intensity with radial distance ϱ as contained in numerical distance $p = |p| \exp(ib) = ik_2^3\varrho/2k_1^2$ (Norton's graphs).

b. The Field in the Earth or Sea; Communication with Submarines

The field at radial distances ρ and depth z in the ocean (region 1, $z \geq 0$) due to a vertical dipole in the air on the surface of the earth or sea is of importance in communicating with submerged submarines. For this purpose the radial component of the electric field is most useful. It is given by an integral similar to (3) and has the following integrated form:

$$E_{1\rho}(\rho, z) = -\frac{\omega\mu_0}{2\pi k_1} e^{ik_1 z} e^{ik_2\rho} f(k_2\rho, k_1), \tag{14a}$$

where

$$f(k_2\rho, k_1) = \frac{ik_2}{\rho} - \frac{1}{\rho^2} - \frac{k_2^3}{k_1}\left(\frac{\pi}{k_2\rho}\right)^{1/2} e^{-iR}\mathcal{F}(R). \tag{14b}$$

Since the far-field form of the Fresnel integral given by (12) applies when $R \geq 4$ and since with it $E_{1\rho}(\rho, z)$ decreases as $1/\rho^2$, it is advantageous to select a frequency for which the desired range of ρ is in the intermediate zone in which the Fresnel-integral term is small and the $1/\rho$ term in (14b) dominates. This occurs when

$$1 \leq k_2\rho \leq |k_1^2/k_2^2|. \tag{15}$$

The quantity $20\log_{10}|E_{1\rho}(\rho, z)|$ in this range with $\rho = 5{,}000$ km is shown in Fig. 3. For each depth in the ocean there is an optimum frequency for a maximum received signal. This decreases as the depth increases. In the frequency range from 20 to 30 kHz—used by the Navy transmitter at Cutler, ME—the optimum depth is seen to be in the range from $z = 10$ to $z = 20$ m. As the depth increases further, the magnitude of the electric field decreases very rapidly. In order to communicate with submarines at greater depths, lower frequencies must be used. This is not practical using vertical dipoles.

3. Vertical Dipole in the Sea; Conductivity of the Earth's Crust

An interesting application of the vertical dipole near a boundary and the lateral waves it generates is to the measurement of the conductivity of the oceanic crust (region 2, $z \leq 0$). For this purpose the dipole is located in the sea (region 1, $z \geq 0$) at a small height d above the sea floor or it is extended from this all the way to the surface of the sea [6]. Measurements are made on or at a small height z above the sea floor. The preferred quantity to be measured is the magnetic field at very low frequencies. This is given by an integral similar to (3). It has the following integrated form:

$$B_{1\phi}(\rho, z) = B_{1\phi}^d(\rho, z) + B_{1\phi}^i(\rho, z) + B_{1\phi}^L(\rho, z), \tag{16a}$$

with

$$B_{1\phi}^d(\rho, z) = -\frac{\mu_0}{4\pi} e^{ik_1 r_1}\left(\frac{ik_1}{r_1} - \frac{1}{r_1^2}\right)\left(\frac{\rho}{r_1}\right), \tag{16b}$$

$$B_{1\phi}^i(\rho, z) = \frac{\mu_0}{4\pi} e^{ik_1 r_2}\left(\frac{ik_1}{r_2} - \frac{1}{r_2^2}\right)\left(\frac{\rho}{r_2}\right), \tag{16c}$$

$$B_{1\phi}^L(\rho, z) = -\frac{\mu_0 k_2^2}{2\pi k_1^2} e^{ik_1(z+d)} e^{ik_2\rho} f(k_2\rho, k_1), \tag{16d}$$

where $r_1 = [\rho^2 + (z-d)^2]^{1/2}$, $r_2 = [\rho^2 + (z+d)^2]^{1/2}$, and $f(k_2\rho, k_1)$ is defined in (14b). The direct field of the dipole is given by (16b), the field of the image dipole is given by (16c), and the lateral wave by (16d). Note that when the source dipole is in the denser region 1 and the point of observation is on the boundary surface $z = 0$, the image field is the *negative* of the direct field, so that the lateral-wave field $B_{1\phi}^L(\rho, 0)$ is the entire field.

In practice measurements are made at extremely low frequencies and within relatively small radial distances where the Fresnel-integral term is negligibly small and the significant magnetic field is

$$B_{1\phi}(\rho, 0) = B_{1\phi}^L(\rho, 0) \sim -\frac{\mu_0\sigma_2}{2\pi\sigma_1}\left(\frac{ik_2}{\rho} - \frac{1}{\rho^2}\right)e^{ik_2\rho}e^{ik_1 d}. \tag{17}$$

The application of this formula [7] to actual measurements made on the sea floor [6] is illustrated in Fig. 4. The dipole extended from the surface to the floor of the sea—a distance

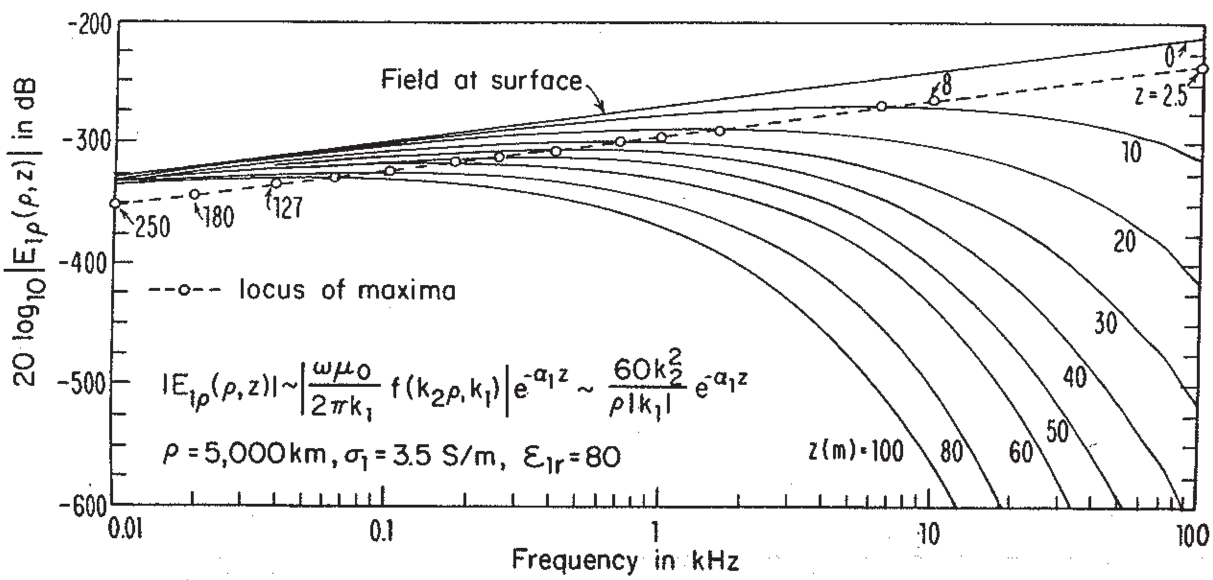

Figure 3. Radial electric field at depth z and $\rho = 5{,}000$ km due to vertical electric dipole in air on the surface of sea water as a function of the frequency, with z as parameter.

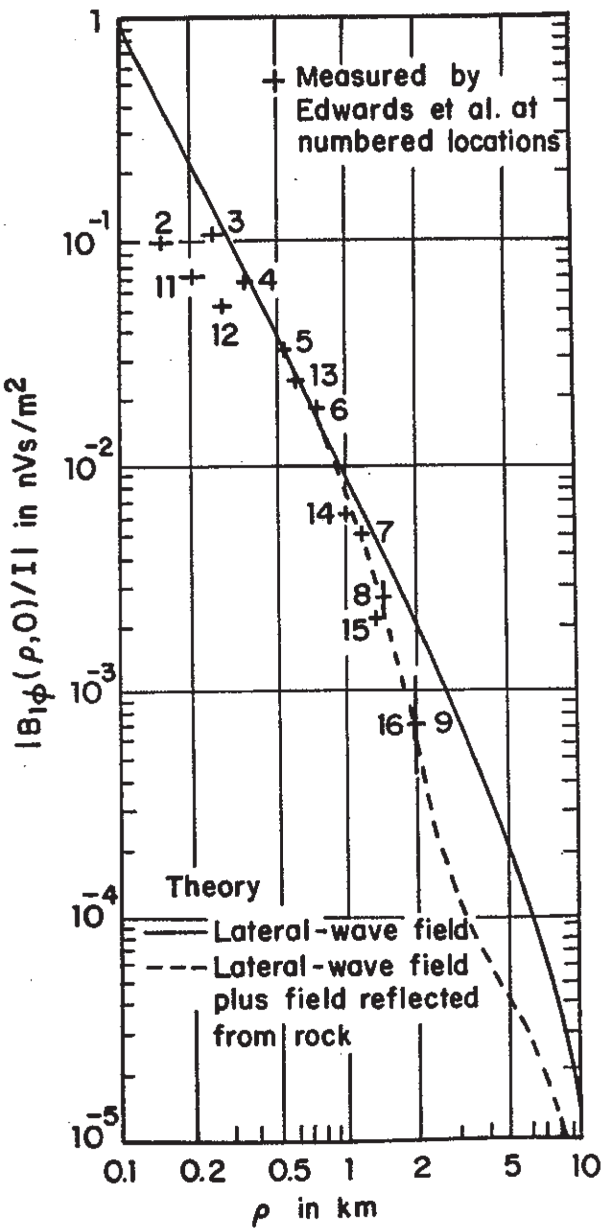

Figure 4. Magnetic field measured by Edwards, et al. and field calculated from lateral-wave formula; dashed curve includes correction for reflection from rock layer below. f = 0.125 Hz; σ_1 = 2.85 S/m, σ_2 = 0.4 S/m, σ_3 = 0.01 S/m; D_1 = 640 m, D_2 = 600 m.

of 640 m. The sea floor consisted of a layer of sediment 600 m thick over rock. The conductivity of the sea water was known to be 2.85 S/m; the conductivities of the sediment, $\sigma_2 = 0.4$ S/m, and the rock, $\sigma_3 = 0.01$ S/m, were determined by fitting the theory to the measured points.

4. The Horizontal Dipole near a Boundary between Sea and Air or Sea and Oceanic Crust

a. The Dipole in the Sea or Earth

When a unit electric dipole is located in the earth or sea *parallel* to the air surface or in the sea *parallel* to the sea floor, it generates a complicated electromagnetic field that includes all six components: E_ρ, E_ϕ, E_z and B_ρ, B_ϕ, B_z [8]. The largest component of the electric field is E_ρ for which the exact integral in region 1 is [8]:

$$E_{1\rho}(\rho,\phi,z) = -\frac{\omega\mu_0}{4\pi k_1^2}\cos\phi\Big(\int_0^\infty \{k_1^2 J_0(\lambda\rho) - (\lambda^2/2)[J_0(\lambda\rho) - J_2(\lambda\rho)]\} \times \gamma_1^{-1} e^{i\gamma_1|z-d|}\lambda\, d\lambda + \int_0^\infty \{(\gamma_1 Q/2)[J_0(\lambda\rho) - J_2(\lambda\rho)] - (k_1^2 P/2\gamma_1)[J_0(\lambda\rho) + J_2(\lambda\rho)]\} \times e^{i\gamma_1(z+d)}\lambda\, d\lambda\Big), \qquad (18)$$

where

$$Q = \frac{k_1^2\gamma_2 - k_2^2\gamma_1}{k_1^2\gamma_2 + k_2^2\gamma_1}, \quad P = \frac{\gamma_2 - \gamma_1}{\gamma_2 + \gamma_1}, \qquad (19a)$$

$$\gamma_j = (k_j^2 - \lambda^2)^{1/2}, \quad j = 1, 2. \qquad (19b)$$

The corresponding integrated formula, subject to $|k_1^2| \gg |k_2^2|$ or $|k_1| \geq 3|k_2|$ is [9]:

$$E_{1\rho}(\rho,\phi,z) = E_{1\rho}^d(\rho,\phi,z) + E_{1\rho}^L(\rho,\phi,z); \quad z \geq 0, \qquad (20a)$$

where

$$E_{1\rho}^d(\rho,\phi,z) = \frac{\omega\mu_0}{2\pi k_1^2}\cos\phi\left(\frac{k_1}{\rho^2} + \frac{i}{\rho^3}\right)e^{ik_1 r_1} \qquad (20b)$$

is the direct field and

$$E_{1\rho}^L(\rho,\phi,z) = -\frac{\omega\mu_0 k_2}{2\pi k_1^2}\cos\phi\, g(k_2\rho, k_1)e^{ik_2\rho}e^{ik_1(z+d)} \qquad (20c)$$

is the lateral wave. The magnitude of this field in the form $20\log_{10}|E_{1\rho}(\rho,\phi,z)|$ is shown in Fig. 5 together with the mag-

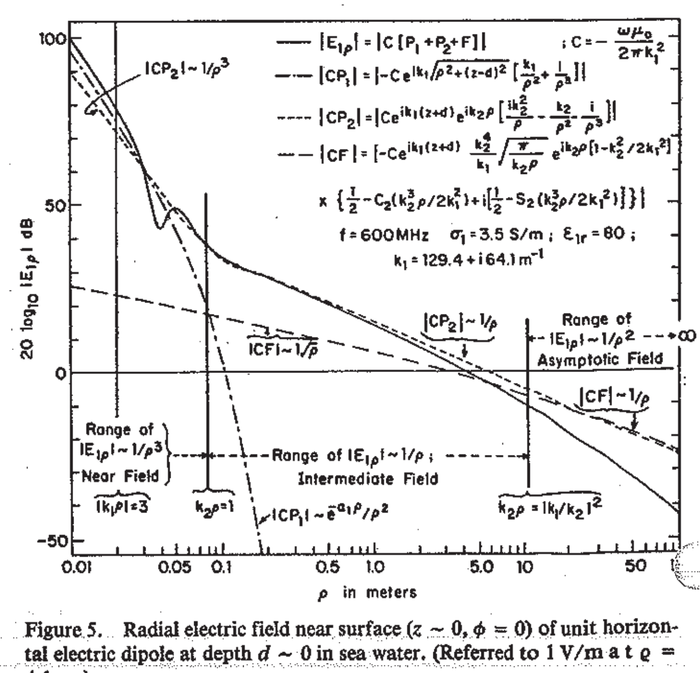

Figure 5. Radial electric field near surface ($z \sim 0, \phi = 0$) of unit horizontal electric dipole at depth $d \sim 0$ in sea water. (Referred to 1 V/m a t ϱ = 4.1 m.)

nitude of its principal parts. Note the three ranges with approximate $1/\rho^3$, $1/\rho$, and $1/\rho^2$ radial dependences. The other five components have corresponding formulas [10], [11]. In (20c), $g(k_2\rho, k_1)$ is defined in (10). The associated field in region 2 is [12]:

$$E_{2\rho}(\rho,\phi,z) = -\frac{\omega\mu_0}{2\pi k_1} e^{ik_1 d}\cos\phi\left(\frac{ik_2}{r_0} - \frac{1}{r_0^2}\right)e^{ik_2 r_0} \times\left[\frac{z}{r_0} + \frac{k_2}{k_1}(1+\mathcal{G})\right], \quad (21a)$$

where $r_0 = (\rho^2 + z^2)^{1/2}$ and

$$\mathcal{G} = i(2\pi R)^{1/2} e^{-i(R-Z)^2/R}\mathcal{F}[(R-Z)^2/R]; \; Z \leq 0, \quad (21b)$$

with $R = k_2^3\rho/2k_1^2$ and $Z = k_2^2 z/2k_1$. $\mathcal{F}(P)$ is defined in (8) with $P = (R-Z)^2/R$. The field (21a) is shown in Fig. 6. The observed minima occur near $z' = -z = \rho$ Re (k_2/k_1).

The field (20a-c) in region 1 is seen to consist of a lateral-wave term and a direct-field term. When region 1 is earth or sea, the attenuation of the direct field is so rapid that the entire field at even moderate distances is due to the lateral wave. In region 2 the field includes a spherical wave that travels outward in all directions in the half-space $z \leq 0$ and a lateral wave that travels radially close to the boundary $z = 0$.

1) *Communication with Submarines*

One or more horizontal dipoles or better, a parallel array of N horizontal insulated traveling-wave antennas [8], [13] arranged a short distance d below the surface of the ocean [14] provide a suitable radiating system for communicating by means of lateral waves with submarines. The effective electric moment of the array over that of a unit dipole is NIh_e, where I is the current and h_e the effective length of each element [14, eq. (43)]. Such an array can be designed to provide significant fields at depths of 50 m or more at frequencies which are optimum in a range near 1 kHz.

2) *Exploration of the Oceanic Crust*

Horizontal dipole antennas of appropriate design [13], [15] are used on the sea floor for the geophysical exploration of the oceanic crust. For such applications [16], [17], low frequencies are used for which $\omega\epsilon_1 \ll \sigma_1$, $\omega\epsilon_2 \ll \sigma_2$, so that $k_1 \sim (i\omega\mu_0\sigma_1)^{1/2}$ and $k_2 \sim (i\omega\mu_0\sigma_2)^{1/2}$. Also the radial distances involved are within the range $|k_2\rho| \leq |k_1/k_2|^2$, so that the Fresnel-integral term is negligibly small. Of primary interest is the field in region 2, the oceanic crust. This is given by (21a,b) and the associated other five components. Knowledge of the depth of penetration of the lateral wave into region 2 is of primary importance for the correct interpretation of measured fields. This has been studied in terms of the locus of the Poynting vector [12]. Sample graphs are in Fig. 7 which indicate that the lateral wave follows a shallow logarithmic contour from the source back to the surface. The maximum depth of penetration for the radial distance of transmission ρ_0 is $z'_m = (\sigma_2/\sigma_1)^{1/2}\rho_0/2.718$. Note that the ratio of the horizontal to the vertical scale in Fig. 7 is 10 to 1. Evidently the depth of penetration is quite small compared to the radial distance of transmission. This is of significance in the interpretation of measurements of the electric or magnetic field made in the sea. Models of the oceanic crust that consist of horizontal layers with different conductivities produce upward reflections that contribute to the measured field in the sea. However, this is at most a small fraction of the total field [12] which consists primarily of the lateral wave.

3) *Lateral Waves in an Anisotropic Region*

Lateral waves are also generated by a horizontal electric dipole near the sea floor when the oceanic crust is well approximated by a half-space that is anisotropic in its conductivity. Specifically, the vertical conductivity σ_{2z} may differ from the horizontal conductivity $\sigma_{2x} = \sigma_{2y}$. Integrated formulas for the six components of the lateral-wave electromagnetic field have been derived [18] under these conditions and applied to the determination of the conductivity

$$\sigma_2 = \begin{bmatrix} \sigma_{2x} & 0 & 0 \\ 0 & \sigma_{2y} & 0 \\ 0 & 0 & \sigma_{2z} \end{bmatrix} \quad (22)$$

of the earth's crust. This is accomplished by comparison with the measurements of Young and Cox [17]. These and the theoretical results are shown in Fig. 8.

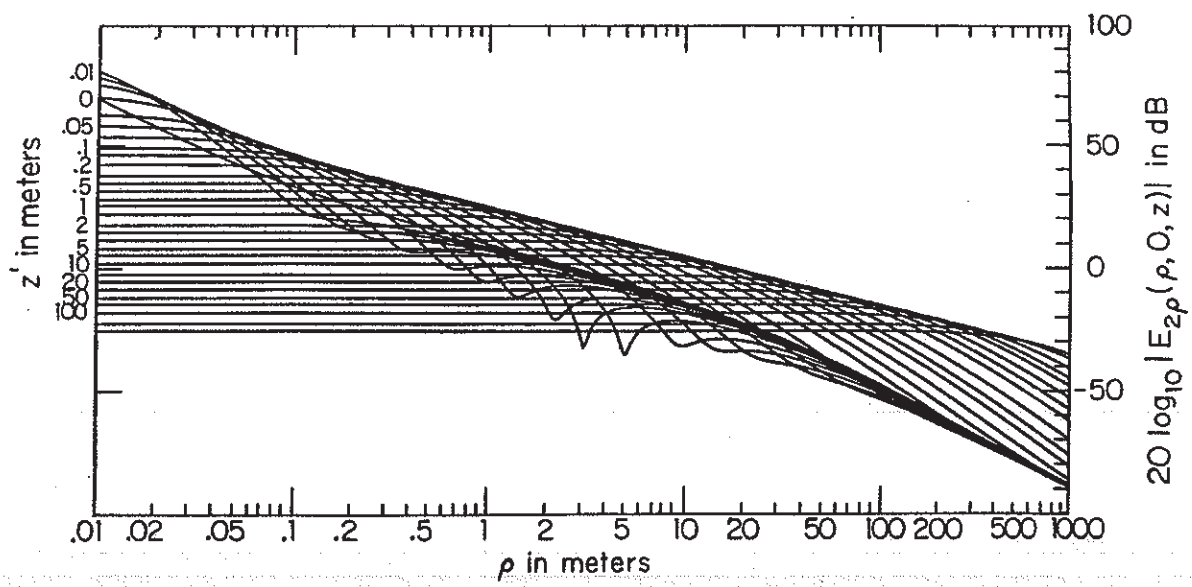

Figure 6. Radial electric field in air due to a unit horizonal electric dipole in salt water (σ_1 = 3.5 S/m, ϵ_{1r} = 80) at depth d = 7 mm; f = 600 MHz.

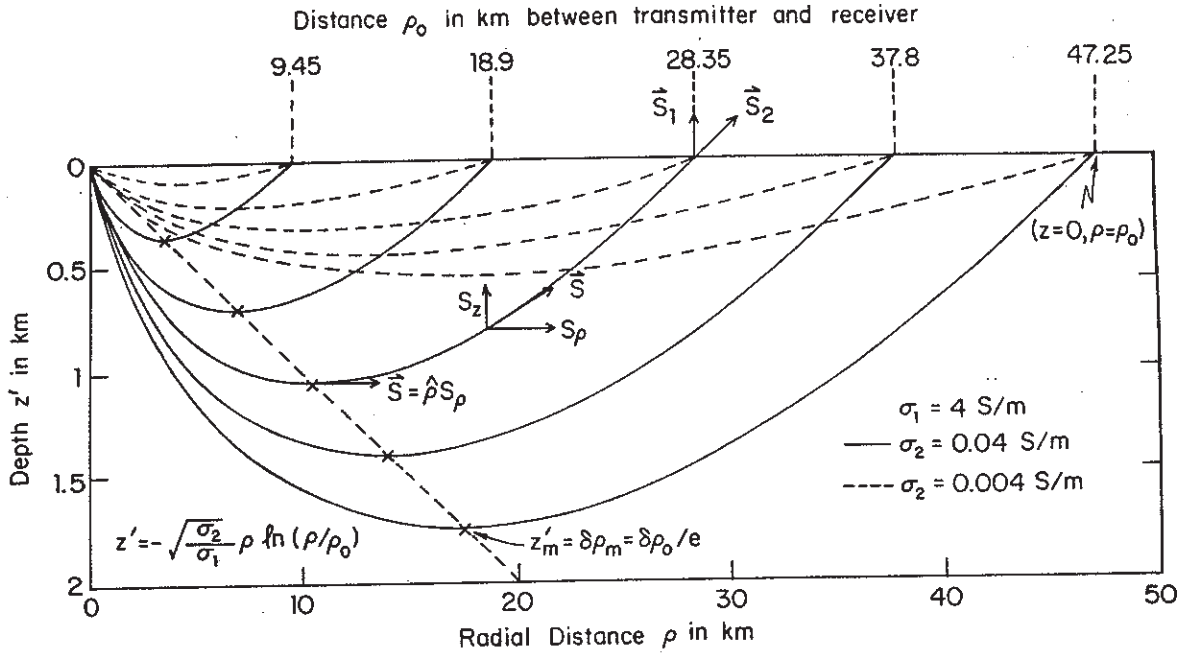

Figure 7. Locus of Poynting vector for field of electric type in half-space model of lithosphere; $k_1 \sim (i\omega\mu_0\sigma_1)^{1/2}$, $k_2 \sim (i\omega\mu_0\sigma_2)^{1/2}$; $f = 1$ Hz. At $z = 0$, $S_{1\rho} = (s_2/s_1)\, S_{2\rho}$ and $S_{1z} = S_{2z}$.

b. The Dipole in the Air

Lateral electromagnetic waves are also generated by the currents in a horizontal electric dipole or traveling-wave antenna when this is located at a small height d over the surface of the earth or sea. Such an antenna is actually an eccentrically insulated antenna [8, Ch. 1] lying on the surface of the earth or sea. The radial electric field generated by it is given by (20a-c) in the earth or sea and by (21a,b) in the air with $d \sim 0$. On the surface $z = 0$, the lateral-wave field for a unit dipole is

$$E^L_{1\rho}(\rho,0) = E^L_{2\rho}(\rho,0) = -\frac{\omega\mu_0 k_2}{2\pi k_1^2}\cos\phi\, g(k_2\rho, k_1), \qquad (23)$$

where $g(k_2\rho, k_1)$ is defined in (10).

An important type of antenna for radio communication and over-the-horizon radar is the wave antenna or Beverage antenna. This consists of a long horizontal wire over the earth terminated at each end in a suitable resistor so that a traveling wave of current is maintained by the driving voltage. The properties of such an antenna for transmitting lateral waves or for receiving them are analyzed in [19].

A second application of the horizontal-wire antenna over the earth is in remote sensing. The lateral-wave field generated by a horizontal antenna lying on the surface of the earth travels along that surface in the air and continuously diffuses vertically down into the earth. If the properties of the earth change as in the presence of a reservoir of oil or a vein of iron ore, the incident field is reflected or scattered back to the surface where it can be detected by a receiver that is systematically moved over the surface [20], [21]. In this way a two-dimensional pattern of the boundaries of the scattering object or region can be constructed.

5. Conclusion

Vertical and horizontal electric dipoles near the surface between electrically different half-spaces excite lateral waves that travel close to the boundary. They have unusual properties in that their amplitude decreases with radial distance in three steps. There is a near-field range bounded by $k_2\rho \leq 1$ where the radial field decreases as $1/\rho^3$, an intermediate range bounded by $1 \leq k_2\rho \leq |k_1^2/k_2^2|$ where the rate of decrease is $1/\rho$, and finally a far-field range bounded by $|k_1^2/k_2^2| \leq k_2\rho$ where E_ρ decreases as $1/\rho^2$. This entire radial dependence is multiplied by the exponential $e^{ik_2\rho}$. If k_2 is real as for air, there is no exponential attenuation. If $k_2 = \beta_2 + i\alpha_2$ is complex as for the rock in the oceanic crust, there is an exponential attenuation in addition to the decrease in amplitude due to the $1/\rho^3$, $1/\rho$, and $1/\rho^2$ ranges. The lateral-wave field of electric type, consisting of E_ρ, E_z and B_ϕ, penetrates region 2 only along shallow logarithmic paths before returning to the boundary. The lateral-wave field of magnetic type, consisting of B_ρ, B_z and E_ϕ, penetrates more deeply along paths that

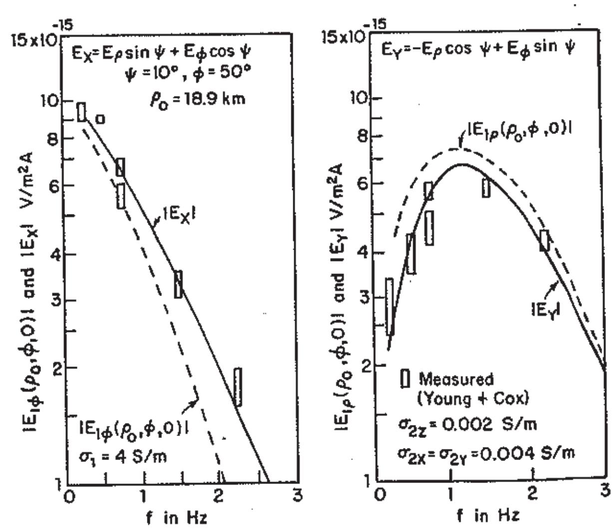

Figure 8. Comparison of surface-wave field components calculated for a one-dimensionally anisotropic rock with sea-floor measurements by Young and Cox.

are almost semicircular. The field of magnetic type has no $1/\rho$ range as does the field of electric type. Owing to these properties, the lateral-wave field has numerous useful applications some of which have been outlined in this review.

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George W. Swenson, Jr. is Professor of Electrical Engineering and of Astronomy at the University of Illinois at Urbana-Champaign, where he was for many years the director of the Vermilion River Observatory and designer of its two large radio telescopes. He has served at different times as Head of each of his academic departments. From 1964 to 1968 he was on leave from the University to serve as Chairman of the VLA (very large array) Design Group and as Manager of the VLA Project at the National Radio Astronomy Observatory (NRAO). With A. R. Thompson of NRAO and J. R. Moran of the Harvard-Smithsonian Center for Astrophysics, he has recently coauthored a major treatise: "Interferometry and Synthesis in Radio Astronomy" (John Wiley-Interscience, New York, 1986). His principle research publications have been concerned with radio astronomy observations, radio telescope design, correlator arrays and image synthesis, and radio propagation. Prior to joining the Univesity of Illinois in 1956, he served on the faculties of Washington University, University of Alaska, and Michigan State University. He received his technical education at Michigan Tech, Stanford, M.I.T., and at Wisconsin, from which he received the Ph.D. in electrical engineering in 1951. He is a Fellow of the IEEE and of AAAS and a member of the National Academy of Engineering. In 1984 he was a Guggenheim Fellow and in the same year received the Citation for Distinguished Service to Engineering from the University of Wisconsin.

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