Electromagnetic Wave Propagation on a Thin Wire Above Earth

(Invited Paper)

Robert G. Olsen, *Fellow, IEEE*, Jeffrey L. Young, *Member, IEEE*, and David C. Chang, *Fellow, IEEE*

***Abstract*—The electromagnetic properties of a current on a thin horizontal wire above a flat lossy earth is reviewed. Attention is given to the historical development of the topic, starting with the seminal work of Carson. Particularly, the importance of Professor Wait's contribution to the initial understanding of the modal and radiative behaviors of the current, as described in his influential paper [1], is discussed in detail. A description of Wait's full wave analysis is provided to show how that analysis justified many of the assumptions embedded in Carson's result and how that same analysis later led to a fuller understanding of the current's spatial spectrum. Although no rigorous proof is known to exist with respect to the completeness of this spectrum, a necessary condition for completeness is offered; the basis of this condition is the measurable input conductance of the wire. The paper concludes with a short discussion on the various extensions of Wait's classic work that have been provided over the last two decades.**

***Index Terms*—Ground wave propagation, multimode transmission lines.**

I. INTRODUCTION

CALCULATION of the interaction between electromagnetic fields and an electrically thin horizontal infinitely long wire in free-space above a homogeneous conducting earth is an important canonical problem in electromagnetics. This problem and its numerous extensions have spawned an enormous number of contributions to the scientific literature since a solution was first attempted in the early part of the 20th century. One of the important contributors to the solution of this problem was Prof. J. R. Wait. His contributions will be emphasized here.

Consider the problem shown in Fig. 1. Here, an electrically thin wire of radius a is located in a medium characterized by permittivity $\epsilon_1 = \epsilon_{r1}\epsilon_\circ$, permeability $\mu_1 = \mu_{r1}\mu_\circ$, and conductivity σ_1, where $\epsilon_\circ$ and $\mu_\circ$ are, respectively, the permittivity and permeability of free-space. In the special case that this medium is free-space, $\epsilon_1 = \epsilon_\circ$, $\mu_1 = \mu_\circ$ and $\sigma_1 = 0$. The wire is parallel to and a height h above an interface between its host medium and a homogeneous conducting earth. The earth is characterized by permittivity $\epsilon_2 = \epsilon_{r2}\epsilon_\circ$, permeability $\mu_2 = \mu_{r2}\mu_\circ$ and conductivity σ_2. Here, the wire is assumed to be a perfect conductor but might also be characterized by a surface impedance Z_w as described below.

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R. G. Olsen is with the School of Electrical Engineering and Computer Science Washington State University Pullman, WA 99164-2752 USA.

J. L. Young is with the MRC Institute, University of Idaho, Moscow, ID 83844-1024 USA (e-mail: jyoung@mrc.uidaho.edu).

D. C. Chang is with the Polytechnic University Brooklyn, NY 11201 USA.

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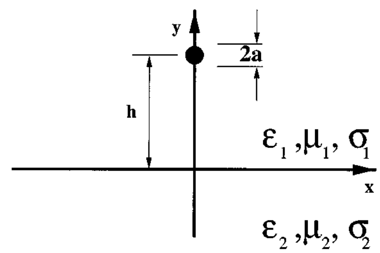

Fig. 1. A thin wire over a homogeneous half-space.

Wait's "exact" modal equation for this geometry from his influential paper on this subject will be the starting point [1]. The classic low-frequency Carson equation and the quasistatic analysis of Kikuchi will be discussed as a special cases. The works of Wait, Carson, and Kikuchi are valid, provided the wire is electrically thin; exact conditions on what constitutes a thin wire will be provided. Wait's complex image theory will also be used to identify a more physically intuitive, alternative interpretation of Carson's equation. To complete the single wire propagation problem, sections on the excitation problem, the spatial spectrum of the current and the physical interpretation of that spectrum will be discussed. Finally, several problems which are extensions to the single wire propagation problem will be presented.

II. BACKGROUND

Originally, the "wire over earth" problem was of interest because of its applications to electric power transmission and telephone communication systems. These systems operated at frequencies low enough that the wire height was a small fraction of a wavelength. In this case, almost all energy from a voltage or current source driving the wire is coupled into and propagates in the quasi-TEM mode. Thus, early work was restricted to finding the distributed parameters of an equivalent transmission line for this mode.

Carson reported the earliest solution to this problem in 1926 [2]. In that work, he calculated values for the distributed parameters of a quasi-TEM transmission line. In doing so, he made several approximations. They are the following:

1) the propagation constant does not differ significantly from that found in the dielectric and, therefore, Laplace's equation can be substituted for the two-dimensional wave equation in air;
2) the displacement current in the earth can be neglected;

3) the effect of earth conductivity on the parallel admittance per unit length is negligible.

These assumptions restrict the solution to low frequencies. Later, a more explicit statement of what is meant by "low frequency" will be given.

Aside from some small improvements, such as the inclusion of displacement currents in earth by Wise [3], the equivalent transmission line approach remained unchanged until the early 1950s [3]. A good summary of this early work can be found in the book by Sunde [4].

Despite the development of a satisfactory low-frequency solution, researchers remained interested in the high-frequency behavior of such systems. Both curiosity and potential applications such as antennas above earth, lightning and electromagnetic pulse effects on power lines and geologic remote sensing drove research in this area. Kikuchi, for example, in the mid 1950s derived an exact modal equation for very thin wires above earth, which, although published in English, was not widely known at the time [5], [6]. In this work, he used quasi-static and asymptotic expansions of the exact modal equation to investigate the transition from quasi-TEM to surface wave propagation During the same time period, there was some activity in Russia concerning this problem [7]–[9]. Although an exact solution to the problem was reported, this work never appeared in English and, hence, was unknown outside of Russia until the 1970s. A discussion of this work can be found in Kuester *et al.* [9], [10].

About this time, Prof. Wait became interested in the problem and published an exact modal equation for a thin wire above earth that was an extension of Kikuchi's equation [1]. This work was widely distributed and through such exposure became well known. It is repeated here as the starting point for our development.

III. Exact Modal Equation

A full wave analysis of the propagation characteristics of an electromagnetic wave on a thin wire over a homogeneous half-space is conveniently accomplished by means of potential vectors of which Wait chose the Hertz scalar potentials Π_z and Π_z^* [1]. The geometry of the problem under consideration is depicted in Fig. 1. The vector potentials allow one to separate Maxwell's equations into TM and TE sets and to cast the electric field $\mathbf{E}$ and magnetic field $\mathbf{H}$ in terms Π_z and Π_z^*. After establishing solutions for Π_z and Π_z^* and satisfying the requisite boundary conditions for the same, Wait showed that the propagation constant (i.e., $j\beta$) for the wave on the wire could be couched in terms of the standard transmission line modal equation

$$j\beta = \sqrt{ZY} \tag{1}$$

where

Z	equivalent series transmission line impedance;
Y	equivalent shunt transmission line admittance;
Z and Y	functions of β.

In equation form

$$Z = [2\pi]^{-1}[j\omega\mu_1]\,[\Lambda + 2(Q - jP)] \tag{2}$$

and

$$Y = [2\pi]\,[j\omega\epsilon_1]\,[\Lambda + 2(N - jM)]^{-1}. \tag{3}$$

The modal equation is based upon the assumption that the wire's radius is small, which, for now, will not be rigorously quantified. The other terms in the previous two equations are given by

$$\Lambda = K_\circ\left(ja\sqrt{k_1^2 - \beta^2}\right) - K_\circ\left(j2h\sqrt{k_1^2 - \beta^2}\right) \tag{4}$$

$$Q - jP = \int_0^\infty \frac{e^{-2u_1 h}}{u_1 + u_2}\cos(\lambda a)\,d\lambda \tag{5}$$

and

$$N - jM = k_1^2\int_0^\infty \frac{e^{-2u_1 h}}{k_2^2 u_1 + k_1^2 u_2}\cos(\lambda a)\,d\lambda. \tag{6}$$

The symbols employed above are ascribed the following meanings or definitions: $K_\circ(z)$ is the modified Bessel function of order zero; $u_1 = \sqrt{\lambda^2 + \beta^2 - k_1^2}$ and $u_2 = \sqrt{\lambda^2 + \beta^2 - k_2^2}$, with the additional assumption that the real part of these quantities is positive; $k_1 = \omega\sqrt{\mu_1(\epsilon_1 - j\sigma_1/\omega)}$ and $k_2 = \omega\sqrt{\mu_2(\epsilon_2 - j\sigma_2/\omega)}$, with the additional assumption that the imaginary part of these quantities is negative.

IV. Reduction to Carson's Results

As Wait pointed out, the earlier work of Carson represents a special case of the general result of (1). Specifically, if $|a\sqrt{k_1^2 - \beta^2}| \ll 1$, $|2h\sqrt{k_1^2 - \beta^2}| \ll 1$, $2h \gg a$, $|k_1 h| \ll 1$, and $|k_1^2/k_2^2| \ll 1$, then the small argument approximation of the Bessel function can be invoked, $Q - jP$ can be simplified, and $N - jM$ can be neglected [1]. With these approximations in place, the modal equation for the equivalent transmission line mode can be solved in closed-form; the final equation is identical to that first reported by Carson

$$\beta = k_1\sqrt{1 - J_c/\ln(2h/a)} \tag{7}$$

where J_c is the approximate integral of $2(Q - jP)$ and is given by

$$J_c = \frac{2}{k_2^2}\int_0^\infty (u - \lambda)e^{-2\lambda h}\,d\lambda \tag{8}$$

with $u = \sqrt{\lambda^2 - k_2^2}$. For these same approximations

$$Z_c \approx [2\pi]^{-1}[j\omega\mu_1]\,[\ln(2h/a) + J_c] \tag{9}$$

and

$$Y_c \approx [2\pi]\,[j\omega\epsilon_1]\,[\ln(2h/a)] \tag{10}$$

where the subscript c denotes a Carson result.

From the previous assumptions, the transmission line mode is essentially a quasi-TEM mode. The prefix *quasi* indicates that a true TEM mode is not possible with a lossy earth, since Ohm's law requires a longitudinal electric field if current is to return through the earth. When the earth is a perfect conductor, however, the current returns on the earth's surface and the longitudinal electric field vanishes; only then is the mode truly TEM.

Carson's integral in (8) can also be expressed as a series that was given by Carson. This series can be found in [2] and in the more accessible reference [11]. Unfortunately, Carson, himself said about this series, "It is to be regretted that the foregoing formulas appear so complicated." However, he also noted that only the leading terms of the series are of importance for many practical cases [2], [4]. By considering this leading term it will be possible to first find a simpler solution and then, by comparison with Wait's work on complex image theory, to identify a simple equivalent problem that can provide some physical insight into Carson's result.

Consider the first term of the expansion of Carson's series for the integral J_c. Using this in (9), an approximation for the equivalent series impedance of the wire over earth (valid for $2k_2h \ll 1$) is [4]

$$Z_c \approx \frac{\omega\mu_1}{8} + \frac{j\omega\mu_1}{2\pi}\left\{\left[\ln\left(\frac{\sqrt{2}\delta}{a}\right)\right] + \ln(0.926)\right\} \quad (11)$$

where $\delta = \sqrt{2/(\omega\mu_2\sigma_2)}$ is the skin depth of the earth. This same series impedance can be calculated using the "complex image theory," which (although apparently developed earlier in Russia [12] and published in Russian) was independently developed by Wait and Spies in 1969 [13]. In this paper, the quasi-static electromagnetic fields of a line source in free-space above earth were found to be equivalent to those of the line source plus a "complex image" in free-space. The complex image is a line source with a "complex depth" equal to $h + (1 - j)\delta$, as shown in Fig. 2. Using this idea plus one additional term of the series developed by Wait and Spies, the series impedance becomes

$$Z_I \approx \frac{\omega\mu_1}{8} + \frac{j\omega\mu_\circ}{2\pi}\left\{\left[\ln\left(\frac{\sqrt{2}\delta}{a}\right)\right] + \ln(0.900)\right\} \quad (12)$$

which is almost identical to the result from Carson's series.

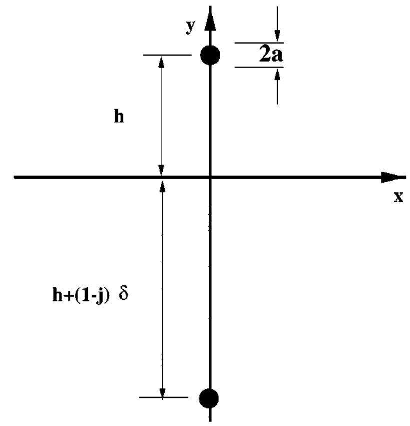

Fig. 2. Geometry of the complex image.

V. Relation to Kikuchi's Work

The earlier results of Kikuchi [5] are embedded in the Wait's full wave solution. Specifically, if a is vanishingly small, then the small argument approximation may be invoked for $K_\circ(ja\sqrt{k_1^2 - \beta^2})$ and the $\cos(a\lambda)$ term in the integrals $Q - jP$ and $N - jM$ may be set to unity. Based upon these assumptions, the result of Wait and the result of Kikuchi are one and the same.

While Carson's result is essentially a low frequency approximation of the transmission line mode, Kikuchi's result is associated with the entire frequency spectrum of this same mode. Specifically, he showed theoretically and experimentally that the transmission line quasi-TEM mode reverts to a TM mode as frequency increases [14]. This result emphasizes that Carson's low-frequency quasi-TEM mode is more correctly a TM mode with a relatively small longitudinal electric field. This longitudinal component is essential to the satisfaction of all tangential boundary conditions at the air–earth interface and is responsible for returning longitudinal currents flowing in the earth. As frequency increases there exists a high field concentration about the wire and large longitudinal displacement currents that act as return currents in the air, thus minimizing the role of the earth as a current return path.

It is seen from the previous paragraph that the transmission line modal behaviors of a current on a wire above earth were well understood before Wait. However, as a later section will further elaborate, the transmission line mode is only one part of the current's spatial spectrum and is insufficient in characterizing the measurable electromagnetic properties of the wire (for various heights, conductivities, frequencies, etc.).

VI. Boundary Conditions on the Wire

We note that the aforementioned modal equation was derived by assuming that the wires are perfect conductors. Such an assumption is not strictly needed since nonperfectly conducting wires can be characterized by an axial impedance, which in turn, is invoked in an axial impedance boundary condition. The condition is a relationship between the axial current (or the azimuthal external magnetic field) and the longitudinal electric field of the wire. As Wait *et al.* showed in many papers, such as [15], a more general modal equation for wave propagation along wires or coated cables can be derived that includes axial impedance effects. In fact, the axial impedance operator is not restricted to cross sectionally homogeneous wires. Axial impedance operators can be developed for insulated wires, coaxial cables, and the like (provided, of course, that the outermost dimension is small so that the cable can be regarded as thin). For example, in the paper by Chang and Wait, it was shown suing the axial impedance concept that the propagation constant associated with a buried insulated wire operating in the ELF frequency range is highly insensitive to depth [16].

What rigorously constituted a thin wire was not entirely obvious, even at the time of Wait's 1972 paper. However, an argument can be made that equations like (1) are exact if the azimuthal variation of the fields about the vicinity of a wire is zero. To understand the true field structure about the wire, Pogorzelski and Chang expanded the current into azimuthal modes and deduced the modal equation associated with the

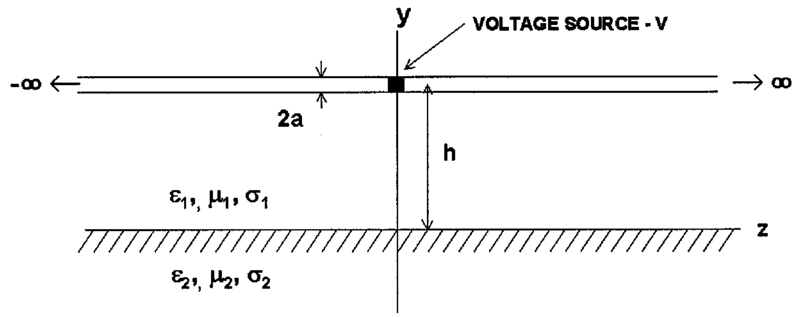

Fig. 3. An infinite horizontal wire of radius a and of height h driven by a voltage source of amplitude V and gap length b.

first three modes. The precise condition for the thin wire approximation can be found in [17, eq. (69)]. However, in terms of a "back-of-the-envelope" formula, one may wish to employ [17, eq. (72)], which states that the azimuthal current modes can be neglected if $(a/(2h))\ln(2h/a) \ll 1$.

VII. Current Spectrum: Mathematics and History

In [1, eq. (19)], Wait presented a calculation of the current induced on the wire by a voltage source of gap length b (i.e., wire gap length) inserted in series with the wire [1]. The geometry for this problem is shown in Fig. 3. The total current $I_t(z)$ was written as an inverse spatial Fourier transform. In the limit as $b \to 0$, the result became

$$I_t(z) = \frac{V}{j\omega\mu_1}\int_{-\infty}^{\infty}\frac{e^{-j\beta z}}{D(\beta)}\,d\beta \tag{13}$$

where $D(\beta) = Z + \beta^2/Y$. For $z > 0$ the integral of (13) can be evaluated by closing the integration contour on the lower half of the complex β plane. To keep the integrand single-valued (or analytic) within and on the contour, the integral along the real axis is equal to the sum of several integrals, each with its own physical significance. There are three types of integrals: Integrals about the various poles of $D(\beta)$ (i.e., modal integrals), integrals along the various branch cuts of $D(\beta)$ (i.e., radiation integrals) and an integral about the lower, infinitely extended semi-circle. This latter contribution is zero by virtue of the radiation condition and the branch-cut definitions, which specify that the real parts of the various multivalued functions be greater than zero. This specification defines the proper Riemann sheet. (See Fig. 4 for a detailed depiction of the integration contour.) The existence of each integral and its relative importance to the spectral description of the current are discussed next.

As mentioned earlier, the transmission line solution was first given by Carson and further explained by Kikuchi. Both of these solutions are manifestations of the residue calculation about the pole at $\beta = \beta_T$. Wait surmised that the current spectrum is made complete by evaluating the integral along the two branch cuts emanating from the branch-points at $\beta = k_1$ and at $\beta = k_2$, respectively. However, while Wait's claim that, "beyond a wavelength it (the quasi-TEM modal current) completely dominates I_r (the continuous spectrum currents) so it is of prime physical interest," is valid at high frequencies under some conditions, it is also valid under less restrictive conditions at low frequencies.

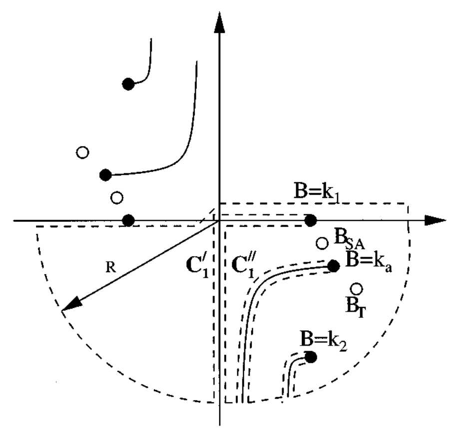

Fig. 4. The integration path on the complex β plane. Here $R \to \infty$ and $k_a = k_1k_2/\sqrt{(k_1^2 + k_2^2)}$.

Specifically, the quasi-TEM modal current dominates the continuous spectrum currents over the entire wire if: 1) the wire height is small relative to free-space wavelength and 2) the earth is a reasonably good conductor at the frequencies of interest. Since these conditions hold for many low-frequency systems, the quasi-TEM current can be, and has been assumed to be, the total (or complete) current.

Wait's belief that the current spectrum consisted of one discrete mode (i.e., transmission line mode) and two radiation integrals seemed reasonable based upon an informal inspection of $D(\beta)$. Yet a rigorous proof was not provided at that time and the question of completeness was raised by Olsen *et al.* [18], [19]. They argued that a necessary condition for completeness (sufficiency will discussed later) could be found by examining the input conductance of the wire. Specifically, if a voltage source is inserted into a gap within the wire and the total current is measured at that gap, then the input conductance $G = \text{Re}\{I_t(0)/V\}$ of the wire should approach the known input conductance of a wire in free-space as the wire height becomes infinite [20]. Based upon Wait's description of the current's spectrum, the theoretical experiment failed to predict the free-space result.

Further examination of the poles and branch cuts of $D(\beta)$ by Olsen *et al.* revealed that at least two terms were missing from Wait's spectral description. In addition to the pole associated with β_T, a second pole was also found, labeled *surface attached* and denoted as β_{SA}. Moreover, in addition to the two branch-points at $\beta = k_1, k_2$, a third branch point was discovered at $\beta = k_a = (k_1 k_2)/\sqrt{k_2^2 + k_1^2}$, where Im$\{k_a\} < 0$. The physical interpretation of these pole and branch-cut contributions is provided in a subsequent section.

With the current spectrum consisting of these five terms (i.e., integrals associated with these two poles and three branch cuts), the input conductance problem was revisited and the corresponding results agreed with the expected outcome. See Fig. 5 for a typical scenario. In that figure, the conductivities associated with β_T, β_{SA}, and the combined effects of two of the three branch-cut integrals (the integral about k_2 was ignored due to its overall insignificance to radiation in the upper half-space) are shown; the total and free-space conductivities are also shown. As expected, the total input conductance oscillates about 3.1 milli-mhos [20]. Clearly, for small heights, the transmission line component is dominant, which agrees with the common assertion that the total current can be approximated as just the quasi-TEM current. More importantly, based upon this figure and for the parameters considered, an argument can be made that all significant spectral current terms have been identified.

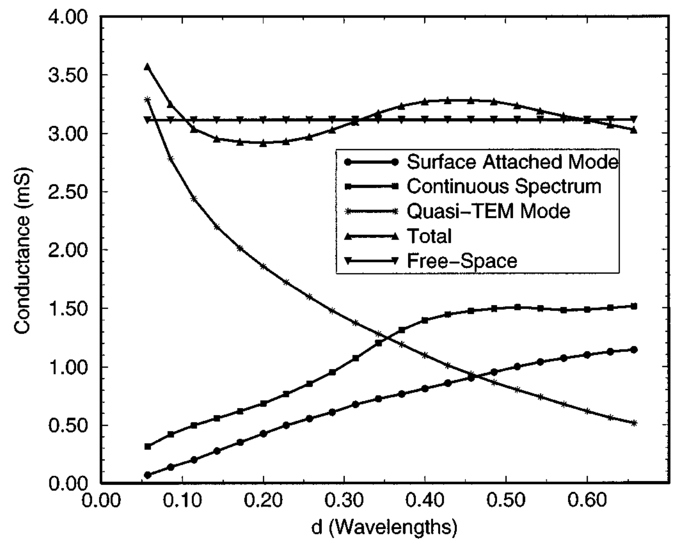

Fig. 5. Input conductance of the infinitely long wire. The individual contributions of modal and radiation terms are shown.

Unfortunately, no rigorous proof for sufficiency (to the authors' knowledge) has been provided that states that these five terms represent the complete spectrum of the current. After conducting numerical searches for additional poles and branch cuts, none have been found to exist. Hence, we conclude that these five terms adequately describe the important phenomenological aspects of the current. Any additional terms that may arise are anticipated to yield minute effects on the current's mathematical description. (We add parenthetically that dos Santos [21] did find a pole on the improper Riemann sheet, which represents a mode that violates the radiation condition. Experiments indicate that this mode might be a useful approximation to the total current for higher frequencies. If so, the mode would be analogous to a leaky wave on a structure such as a dielectric rod or a microstrip printed antenna [22].)

VIII. Current Spectrum: Physical Interpretation

With the spectrum of the current assumed to be made complete with the five aforementioned terms, the physical interpretation of these terms is now provided. Consider first the integration along the branch cut associated with the branch point at $\beta = k_1$; the integration path is designated as C_1, where $C_1 = C_1' + C_1''$ (see Fig. 1). In general, all contributions of C_1 play an important role in ascertaining the near and far field behavior of the field in region one. Between the wire and the earth, the contributions of C_1' and C_1'' give rise to incoming and outgoing waves, respectively. Obviously, both wave species are admissible solutions to Maxwell's equations in free-space. More importantly and per the addition theorem of Hankel functions, both wave species must exist due to the displacement of the wire from the origin of the coordinate system. In the far field, however, the contribution of C_1'' is negligible in comparison to the contribution of C_1'. For this situation, only outgoing spherical waves that vary in both azimuth and elevation (i.e., waves that have two degrees of freedom) contribute to the solution, as required by the radiation condition [23]. Note: Whether the waves are incoming or outgoing as observed in the near field or far field, their propagation characteristics are dependent only on k_1. That is, the existence of these waves is independent of the existence of the interface; they exist solely as solutions to Maxwell's equations in unbounded media. (Similar arguments may be stated, but will be omitted, for the radiation mechanism into region two; the mechanism is due to the branch cut associated with k_2.)

When a lossy interface is included in the boundary value problem, Maxwell's equations admit an additional wave species: The cylindrical Zenneck surface wave. This wave is bound to the interface and propagates only along the horizontal plane. Unlike the previously mentioned spherical waves which have two degrees of propagation freedom, the Zenneck surface wave is thus seen to have one (i.e., azimuth). Since the branch cuts associated with k_1 and k_2 give rise to spherical waves in regions one and two, respectively, the branch-cut associated with $k_a = k_1 k_2/\sqrt{k_1^2 + k_2^2}$ must predict the Zenneck wave. This indeed is the case as an asymptotic saddle-point analysis reveals [23]

$$\frac{Q(\phi)}{\sqrt{\rho}}\, e^{+jk_1^2 y/\sqrt{k_1^2+k_2^2}}\, e^{-jk_a\rho}. \tag{14}$$

Here, $Q(\phi)$ is an unspecified function, Im$\sqrt{k_1^2 + k_2^2} < 0$ and (ρ, ϕ) are cylindrical coordinates in the xz-plane (i.e. $\theta = \pi/2$). (Further information on the Zenneck wave and its contribution to the total solution is found in [24].)

The aforementioned wave species (i.e., the spherical wave in region one, the spherical wave in region two and the Zenneck wave) exist independently of the wire. When a wire is introduced, some directional preference will affect the field structure by redirecting some of the electromagnetic energy of the spherical and Zenneck waves into the direction of the wire. Thus, the solution is augmented with two additional guided wave modes. One mode will serve to redirect the energy from the spherical wave; the other will serve to redirect the energy from the Zenneck wave.

The first of these discrete modes is the aforementioned quasi-TEM mode. As $k_2 \to \infty$, this mode reduces to the pure TEM mode of a wire over a perfect conductor. As shown in [25], the field associated with this mode decays rapidly away from the wire in the transverse plane and thus is bound to the wire. That is, there are no directional degrees of freedom of this mode, in contrast to the spherical or Zenneck waves. The redirection of energy from the spherical wave into the quasi-TEM wave is due to the close proximity of the TEM zero to the branch point k_1. For this reason, this mode can be labeled as a "guided radiation" mode.

The second of the discrete modes is the surface attached mode as described in the previous section. For typical earth parameter values, the zero of $D(\beta)$ associated with surface attached mode is in close proximity to k_a. Hence, like the relationship between quasi-TEM mode and the spherical wave, the proximity of this zero to k_a will redirect some of the energy from the cylindrical Zenneck surface wave into the direction of the wire. For this reason, this mode may be labeled as a "guided Zenneck wave" mode. Again, the fields are bound to the wire (but not so tightly bound as those fields associated with the quasi-static TEM mode) and, hence, the directional degrees of freedom have been reduced to zero.

IX. Extensions to the Theory

In 1977, Wait generalized his work on the full wave analysis of propagation along a single wire above a homogeneous half-space to an arbitrary number of wires above an earth with an arbitrary number of layers [26]. This, along with [1], provided the foundation for a host of analyzes associated with multiple wires, stratified media, and external sources.

The first paper using full wave theory to solve the problem of external source excitation of a wire above earth was published by Olsen and Chang [27]. In this work, the source was a plane wave. Shortly thereafter, Wait [28] as well as Olsen and Usta [29] published papers on the excitation of the wire by a vertical dipole. This work has since been followed up by numerous studies of currents induced on wires above earth by lightning and high altitude nuclear electromagnetic pulses [30], [31]. A general theory for wire excitation by arbitrary sources is given in [10].

The first work on noninfinite wires above earth using the complete spectrum was presented in [32]. Again, the results were found to be in agreement with the expected asymptotic behavior of the input conductance as $h \to \infty$.

The first use of full wave theory for a wire above a two-layer medium was presented by Kuester and Chang [29]. By considering a wire at the surface of a grounded dielectric slab, they studied the modes, which might propagate on a narrow microstrip [33]. This work was later extended to a more realistic microstrip by modeling the conductor as a set of closely spaced parallel wires [34].

Rather than placing the wires parallel to one another, Young and Wait provided the formal solution for the crossed wire case and couched that solution in terms of two integral equations; the equations manifested both the self and mutual coupling impedances of the wires [35]. A TEM closed-form approximation for the coupling was provided in a followup paper [36].

Although the Carson approximation is satisfactory for most propagation problems in power engineering, the full wave theory is necessary for a complete analysis of corona-generated electromagnetic interference, which is detectable at frequencies up to 1 GHz. Olsen and several of his students analyzed this by modeling corona as spatial distribution of randomly excited dipoles on a multiconductor power line and solving for the associated electromagnetic noise fields surrounding the power line [37], [38]. The full wave theory was necessary to explain the observed decay rate of these fields away from the power line.

It is perhaps fitting that this paper concludes with a mention of an extension to Prof. Wait's work, which is an application to power systems. This is because Prof. Wait's first paper [39] was entitled, "Detection of overheated transmission line joints by means of a bolometer," and was written while he was employed at Hydro-Electric Power Commission of Ontario, Toronto, Canada. Although Prof. Wait's career was largely outside of the field of power engineering, his work in electromagnetic theory has led to some fundamental advances in the same area where he made his first contribution to the professional literature.

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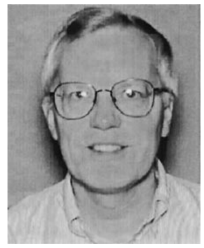

Robert G. Olsen (S’65–M’73–SM’85–F’92) received the B.S. degree in electrical engineering from Rutgers University, New Brunswick, NJ, in 1968, and the M.S. and Ph.D. degrees in electrical engineering from the University of Colorado, Boulder, in 1970 and 1974, respectively.

He has been a Faculty Member of the Electrical Engineering Department, Washington State University, Pullman, since 1973. During that time he has been a Visiting Scientist at GTE Laboratories, Waltham , MA, ABB Corporate Research, VBsterIs, Sweden, and EPRI, Palo Alto, CA. He has also been a Visiting Professor at the Technical University of Denmark, Lyngby. His research interests include electromagnetic interference from power lines, the electromagnetic environment of power lines, electromagnetic compatibility, and electromagnetic scattering.

Dr. Olsen presently serves as Chair of the IEEE Power Engineering Society Corona Effects Fields Working Group, as Associate Editor of the IEEE TRANSACTIONS ON ELECTROMAGNETIC COMPATIBILITY, and as U.S. National Committee representative to CIGRE Study Committee 36 (Electromagnetic Compatibility). He is past chair of the IEEE Power Engineering Society AC Fields Working Group.

Jeffrey L. Young (S’79–M’89) received the B.S.E.E. degree from Ohio Northern University, Ada, in 1981, and the M.S.E.E. and Ph.D. degrees from the University of Arizona, Tucson, in 1984 and 1989, respectively.

He was formerly a Doctoral Fellow and Staff Engineer with the Hughes Aircraft Company, Tucson, AZ. He is currently with the Department of Electrical Engineering, University of Idaho, Moscow, as an Associate Professor. His research interests include electromagnetic wave propagation in complex media, modern numerical methods in electromagnetics, and high-speed interconnecting circuits.

Dr. Young is an Editor of the *Antennas and Propagation Magazine* as well as a Member of URSI Commission B.

David Chang (S’65–M’67–SM’76–F’86) was born in Hubei, China, in 1941 and became an American citizen in 1967. He received the B.S.E.E. from National Cheng-Kung University, Taiwan, in 1961, and the M.S. and Ph.D. degrees in applied physics from Harvard University, Cambridge, MA, in 1963 and 1967, respectively.

After serving a distinguished career at the University of Colorado at Boulder as Faculty Member, Chair of the Electric/Computer Engineering Department, and Director of the NSF Industry/University Cooperative Research Centerfor MIMICAD from 1967 to 1992, he joined Arizona State University, Tempe, as Dean of Engineering and Applied Science. In 1994, he became the ninth President of Polytechnic University, Brooklyn, NY. He is active in research and has published over 300 technical papers in conference proceedings and technical journals.

Dr. Chang has served as President of the IEEE Antennas and Propagation Society and as Associate Editor of the IEEE TRANSACTIONS ANTENNAS AND PROPAGATION. In addition, he was chair of the United States National Committee of URSI from 1993 to 1996.