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Comments on "Propagation of EM Pulses Excited by an Electric Dipole in a Conducting Medium"

D. Margetis and R. W. P. King

In the above paper,[1] the authors wish to determine the transient electromagnetic field generated in a conducting medium by an impulsive current in a short electric dipole. Their approach and their results, however, seem to be questionable.

To start with, their choice of a delta-function excitation causes serious mathematical difficulties which have been overlooked. Because the spectrum of the delta-function pulse extends over all frequencies with equal Fourier amplitudes, the assumption that the conducting medium, specifically sea water, is characterized by frequency-independent permittivity and conductivity is incorrect. In fact, if relaxation phenomena are taken into account, the permittivity must be complex, with frequency-dependent real and imaginary parts. For the $e^{j\omega t}$ time dependence, the often proposed mathematical model is that of $\epsilon(\omega)$ having a simple pole on the positive imaginary axis, leading to the known Debye formula [1, p. 410], namely

$$\epsilon = \epsilon' - j\epsilon'' = \epsilon_\infty + \frac{\epsilon_s - \epsilon_\infty}{1 + j\omega\tau} \tag{1}$$

while

$$\sigma = \sigma' - j\sigma'' \simeq \sigma_0. \tag{2}$$

At 20 degrees C, the static value is $\epsilon_s = 80\epsilon_0$, the high-frequency value is $\epsilon_\infty = 5.5\ \epsilon_0$, the relaxation time is $\tau = 9.5 \times 10^{-12}$ s, and the d.c. conductivity is $\sigma_0 \simeq 4$ S/m. More complicated formulas for $\epsilon(\omega)$ involve sharp electronic resonances in the range of visible to ultraviolet frequencies [1, pp. 399–400].

The above formulation will result in significant changes in the high-frequency part of the 'exact' solution of Song and Chen, mainly due to the analytic behavior of $\mathrm{Re}\,\epsilon(\omega)$ and $\mathrm{Im}\,\epsilon(\omega)$ in the vicinity of $f = 1/(2\pi\tau) \simeq 17$ GHz. It is expected that including the realistic frequency dependence of $\epsilon(\omega)$ at infinity will eliminate the possibility of a response which is a delta function decaying with distance. Such a pulse does not change its shape, and it is, therefore, not realizable.

In attempting to apply their formulas (15), (20), and (22) specifically to sea water, Song and Chen were unable to carry out the requisite evaluation of integrals containing modified Bessel functions. Instead, they concentrated on the so-called 'late-time approximation' with $t \gg r/v$ and $t \gg \tau_0$, by using asymptotic expressions for the Bessel functions of large argument. This approximation, along with a certain normalization of distance, leads to the pulse forms shown in their Figs. 2, 5, and 6, and the conclusion that the pulse decreases in amplitude as $1/r^3 \sim 1/r^5$ depending on the shape of the antenna excitation current. These results conceal the physically meaningful picture of a complete electromagnetic field which includes the near, intermediate, and far fields and differ in all respects from published results that accurately analyze the propagation of low-frequency pulses in sea water [2]–[5]. By selecting pulses with a narrow bandwidth, centered at some low frequency, relaxation phenomena are not effective and both permittivity and conductivity are constants. Under these conditions, it has been proved [2]–[6] that the propagating pulse changes its shape from the original form of the excitation current to the spatial and time derivatives as the pulse successively moves from the near to the intermediate and then to the far field.

In a recent paper [6], the propagation of an EM field generated by a current pulse with a finite, nonzero rise and decay time was studied analytically. In the limit of zero rise time or zero width or both, such a pulse reduces to a rectangular, exponentially decaying or delta-function excitation, already examined by Song and Chen (Figs. 7 and 8). The complete electric field in the equatorial plane of the dipole has been found to be

$$E_z(\rho, t) = \frac{\mu_0 a h_e I_0}{8\pi t_1} \cdot \begin{cases} 0, & t < 0, \\ \mathcal{E}(\rho, t), & 0 < t < 2t_1, \\ \mathcal{E}(\rho, t) - \mathcal{E}(\rho, t - 2t_1), & t > 2t_1, \end{cases} \tag{3}$$

where

$$\mathcal{E}(\rho, t) = \frac{e^{-R^2}}{t\sqrt{2t}} \left\{ \frac{1}{2R^3}[F(Z) - F(R)] + \frac{\Omega}{R^2} G(Z) - \frac{2\Omega^2}{R} F(Z) \right\}, \tag{4}$$

$$F(Z) = \mathrm{Re}\,[e^{Z^2} \operatorname{erfc}(Z)]; \quad G(Z) = \mathrm{Im}\,[e^{Z^2} \operatorname{erfc}(Z)], \tag{5}$$

$$Z = R + i\Omega; \quad R = \frac{a\rho}{\sqrt{2t}}; \quad \Omega = \sqrt{\omega_p t}, \tag{6}$$

$$a = \left(\frac{\mu_0 \sigma}{2}\right)^{1/2} = 1.585 \times 10^{-3}\ \mathrm{m}^{-1} s^{1/2} \tag{7}$$

and $\tau_p = 1/\omega_p$ is the rise time, $2t_1$ the width and $I_0/2t_1$ the amplitude of the normalized excitation pulse, $2h_e$ is the length of the dipole, and $\rho = \sqrt{x^2 + y^2}$ is the radial distance from the source.

Due to the low-frequency approximation, the above solution does not include the Sommerfeld precursor, which is an extremely weak signal traveling with the velocity of light and, therefore, of no practical significance in propagation in sea water. The above solution is consistent with the 'late-time approximation' of Song and Chen. In fact, in the double limit $\omega_p \to +\infty$, $t_1 \to 0^+$, (3) reduces to their (31), derived with an impulsive current excitation.

From (4), it is obvious that the complete field includes terms proportional to $[F(Z) - F(R)] \cdot 1/R^3$, $\Omega G(Z) \cdot 1/R^2$, and $\Omega^2 F(Z) \cdot 1/R$ corresponding to the near, intermediate, and far fields, respectively. This is a consequence of the use of the parameter $R = R(t)$. For fixed time $0 < t < 2t_1$, the field spatial dependence changes from $1/\rho^3$ to e^{-R^2}/ρ^2 as the pulse moves from the near ($R \ll 1$) to the far field ($R \gg 1$). This situation changes dramatically in the limit $\omega_p \to +\infty$, $t_1 \to 0^+$, or both [6].

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[1] J. Song and K.-M. Chen, *IEEE Trans. Antenn. Propagat.*, vol. 41, pp. 1414–1421, Oct. 1993.

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Finally, as pointed out in [6], the derivation of their (31) as a limiting case of the above (3) clearly shows that the 'late-time' response to the nonrealistic delta-function excitation may be attributed to its low-frequency part of the spectrum and, therefore, to a physically realizable pulse as well.

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Authors' Reply

Kun-Mu Chen and Jiming Song

We would like to make a few points in response to the comments of Margetis and King:

1) We are aware that the conductivity and permittivity of sea water is frequency dependent. We made the approximation of constant conductivity and permittivity for two reasons: First, the exciting impulse current contains all the frequency components from zero to ∞. The high frequency components of the excited EM field decay very rapidly, however, and only the low frequency components have significant value in the late-time period away from the antenna. Thus, the former was ignored. For the low frequency band, the conductivity stays nearly constant and the permittivity effect can be neglected because the displacement current is negligible compared to the conduction current. The second reason for the assumption of constant conductivity and permittivity is that with this assumption we are able to obtain an exact solution for the EM field excited by an impulse current. This is the impulse response of the system, and with this solution we can obtain the EM field excited by any form of antenna current through convolution theorem. Our major goal is to find an optimal form of antenna current pulse which can excite a maximum EM field in the conducting medium.
2) Our results reduce to well-known existing results for some special cases. In fact, the results of Margetis and King given in their comment can be derived by the convolution of the late-time approximation of our results with their excitation current.
3) To identify the EM field excited by a current pulse as a sum of near, intermediate, and far zone field may not be appropriate because the excited EM field contains all the frequency components.

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Correction to "Determination of Lines of Constant Phase in the Near-Field of a Metallic Cube and an Airplane"

Erich Kemptner

In the previously mentioned paper[1] there is a reversal in Fig. 6. The upper right picture corresponds to the back face of the cube (face III), and therefore it has to be marked with (c). In return, the lower left picture corresponds to the right face (face II), and so it has to be marked with (b).

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