On Measuring Electromagnetic Surface Impedance—Discussions with Professor James R. Wait

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***Abstract*—Electromagnetic (EM) surface impedance, defined as the ratio of the horizontal electric field to the horizontal magnetic field perpendicular to the plane of incidence, has been used in geophysics since the early 1950s for subsurface earth mapping. Traditionally, the electric field component has been measured using a staked voltage probe. In 1989, Wu and Thiel suggested that an insulated wire dipole without the stakes was a more reliable measurement technique. Wait responded to this paper and the discussion continued until Wait's last comments were published in 1999. In this paper, the final arguments are summarized. The major conclusion reached is that either technique can be used provided caution is exercised, particularly at higher frequencies.**

***Index Terms*—Electromagnetic (EM) measurements, EM scattering, impedance boundary conditions, near fields, nonhomogeneous media.**

I. Introduction

By examining the relationship between two orthogonal field components of a plane electromagnetic (EM) wave incident on the surface of the earth, it is possible to gain information about the subsurface depth-conductivity profile beneath the point of measurement [1]. When the source of the field is a vertically polarized transmitter (z direction), the field components used are the horizontal electric field component E_x measured in the plane of incidence and the horizontal magnetic field component H_y measured perpendicular to the plane of incidence. This ratio is called the surface impedance Z_s and is given by

$$Z_s = E_x/H_y. \tag{1}$$

From this, geophysicists define the "apparent resistivity" ρ_a defined by

$$\rho_a = |Z_s|^2/\omega\mu_0 \tag{2}$$

where ω is the angular frequency of the radiation and μ_0 is the magnetic permeability of free-space. Maps of apparent resistivity can be used to locate geological structures such as faults, ore veins, and aquifers and environmental problems such as soil salinity, ground water pollution plumes, and buried objects.

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When the radiation source is not linearly polarized or the earth's subsurface is laterally anisotropic, then the surface impedance must be defined as a 2×2 matrix Z, where

$$Z = \begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{bmatrix} \tag{3}$$

and $Z_{mn} = E_m/H_n$ for $m = x, y$ and $n = x, y$.

This method of mapping the earth's subsurface was initially developed from the telluric method of geophysical mapping where voltage probes were used to measure the potential difference at different points across the earth's surface. It was realized that the main driver for these earth currents was ionospheric currents and so a method of normalizing measured data was achieved by measuring the associated magnetic field components [2], [3]. Since the 1950s the technique has been applied to many frequency bands (10^{-4} to 10^5 Hz), through the use of both naturally occurring and artificial radiation sources [4].

In 1989, it was suggested that the use of a voltage probe (i.e., a center-fed insulated wire staked at both ends) might compromise surface impedance measurements and that the alternative measurement made by using a completely insulated wire dipole lying on the earth's surface is more reliable [5]. This prompted comments from Prof. Wait and responses from the authors [6]–[9]. At this time there appeared to be no definitive method, either experimental or theoretical, of resolving the issue satisfactorily. With the advent of the finite-difference time-domain (FDTD) method of numerical analysis of propagating plane waves, further work was conducted and published [10], and this prompted further comments [11]–[14].

It is the purpose of this paper to review this quite fundamental discussion and to draw out both the points of agreement and any remaining points of disagreement. In order to achieve this, the discussion is divided into a number of key points.

II. Major Arguments

A. The Loop Theory

In a first course on the subject of antennas, students are introduced to the basic radiating structures of an elemental electric dipole or current element (called a Hertzian dipole) and an elemental magnetic dipole or current loop [15]. Prior to this, students are introduced to the generation of electric fields using a potential difference applied to the plates of a capacitor and to magnetic fields generated by circulating current. To obtain maximum electric field induction, a straight wire conductor must be

located parallel to the electric field lines. To obtain maximum magnetic field induction, a loop of wire must be located in the plane perpendicular to the magnetic field lines. This elementary analysis suggests that in order to detect an electric field one needs a straight conductive wire and to detect a magnetic field, one needs a loop of conductive wire.

In making a surface impedance measurement, one needs to measure both E_x and H_y independently. The proposition put by Wu and Thiel [5] was that the staked ends of the voltage probe made an electrical contact with the earth, which completed the loop circuit and so the voltage probe will respond to the magnetic field component in addition to the potential difference between the two contact points in the earth. To support this argument, Wu and Thiel compared and analyzed the responses from three probes over a 24-h period; a small ferrite-cored loop antenna (used as a magnetic field reference), an insulated wire dipole and a staked voltage probe, using a very-low-frequency (VLF) vertically polarized transmitter as a source. The output of the staked probe was clearly larger than that from the insulated dipole and it was suggested that the staked probe had responded to a combination of both the electric field and the magnetic field, the "loop" being formed when the conductive path of the voltage probe was completed through the conductive earth.

Wait [6] responded by explaining that the electric and magnetic fields are directly coupled and so the effects cannot be additive; they are simply one and the same measurement. Wait [6], [11] went on to explain that the voltage probe does measure the magnetic field with an equivalent loop area of h/γ, where h is the separation distance between the stakes and γ is the complex propagation coefficient in the earth below the probe.

Adding to this discussion was the question relating to the use of stakes in a nonconducting ground layer (e.g., ice or permafrost) [7], [8], [12]. Specifically, if the stakes did not make good electric contact because the surface layer of the earth was highly resistive, it would be impossible to make reliable staked measurements. The problem was similar but not identical to the case of a highly resistive contact in a staked probe [16]. In this case, the difference between an excellent contact (i.e., the contact resistance is very much less than the input impedance of the receiver) and an extremely poor contact (the contact resistance is very much greater than the input impedance of the receiver) is a factor of two [16]. One can conclude that when the dipole is grounded by stakes, the current distribution along its length is uniform and, when it is insulated, the current distribution is triangular with the current on the ends being zero and maximum in the center. This accounts for the factor of two, and was verified in the FDTD analysis [10]. This also accounts for the difference in response observed by Wu and Thiel [5].

Another factor thought to play a role, was the possible presence of an air gap between the horizontal wire and the earth's surface in the case of the staked voltage probe. The air-cored single loop, thus formed, would respond to the magnetic field. In the FDTD analysis [10], it was apparent that the air gap for a voltage probe was important and the true surface impedance could only be reliably calculated if this additional voltage was subtracted from the total detected voltage. The possibility of this being of significance in practice was analyzed [12] and found not likely to be significant.

An additional argument concerned the separate detection of both the electric and magnetic field components using the same antenna. In a plane wave, the two field components are intimately related and so one cannot claim that an antenna is responding to both the electric and magnetic field contributions. They are one and the same. Thus, Wait [6] argued that while the staked voltage probe does respond to the electric field, it also acts as an equivalent loop antenna with area h/γ. Both yield precisely the correct surface impedance. Wu and Thiel [7] commented that even in the case of a plane wave in free-space, there are additive electric and magnetic field effects, usually referred to as "dipole mode" and "circulating mode" [17]. This is particularly important in accurate direction finding when using loop antennas. When the loop is electrically very small, then this effect is also very small.

Another argument relates to the fact that the electric field probe lies in the near field of the earth currents. In the near field of a current carrying conductor, the relationship between the electric and orthogonal magnetic field is not that of free-space. For example, in the case of the near fields of a Hertzian dipole at short distances r from the radiating elements, the ratio between E_θ and H_ϕ is [15]

$$\frac{E_\theta}{H_\phi} = \eta_0 \frac{\dfrac{1}{(k_0 r)^3} + \dfrac{j}{(k_0 r)^2} - \dfrac{1}{k_0 r}}{\dfrac{j}{(k_0 r)^2} - \dfrac{1}{k_0 r}} \tag{4}$$

where $k_0 = 2\pi/\lambda_0$, λ_0 is the free-space wavelength and $\eta_0 = 120\pi$ ohms. The ratio is within 5% of the free-space value η_0 at distances greater than $0.5\lambda_0$. Thus, when making measurements in the quasistatic field region (i.e. at distances where $r < \lambda_0/2\pi$), the relationship between the fields varies significantly with distance. This may also be the case when making measurements on the earth's surface, where the measurement location is very much inside the quasi-static region for earth currents flowing on and near the surface. This point was emphasized by Zonge and Hughes [18] when discussing the high-frequency distortion problems associated with poor contact resistance due to the "capacitive pickup" along the dipole cable. They noted that a high-contact resistance may result in high-frequency signal distortion, which can be solved by using preamplifiers at the position of the stakes and running a shielded low-impedance cable to reduce the time constant of the dipole [16]. It therefore becomes important to discuss the role of the receiver input impedance.

B. The Input Impedance Theory

There is a significant difference between the input impedance of the staked voltage probe and the insulated wire dipole. Both are very dependent on the local conductivity of the earth. In the case of the staked voltage probe, the real part of the impedance is affected by the conductivity of the earth and, in the case of an insulated dipole, the reactive part of the impedance is affected by both the conductivity and the proximity of the earth's surface. The ability of the input impedance of the receiver to accommodate very large changes in input impedance in some cases is clearly important. If the input impedance of the staked probe is

too low, then the earth currents are distorted and the measured values will be incorrect. The location of the insulated antenna on the ground will affect the input reactance, although it is estimated that the variation is likely to be relatively small in practice if the wire is sufficiently long and flexible. Similarly, the earth contacts in the case of the staked probe, are very important. It has been shown experimentally by Zonge and Hughes [16] that poor ground contacts can lead to incorrect readings with a very significant error in addition to other sources of error such as electrode polarization [19]. Low noise instrumentation amplifiers with an input impedance of greater than $10^{12}\Omega$ are now commonly available so that these problems can be minimized.

C. The Tilt Angle Error Theory

Wait [6], [8], [11], [13], [20] was concerned that an insulated dipole antenna lying on the surface may be susceptible to the effect of the very large vertical electric field component present in typical situations. The electric field wave tilt W is defined by the ratio of the horizontal electric field component E_x to the vertical electric field component E_z and is given by [21]

$$W = \frac{E_x}{E_z} = \frac{\eta_1}{\eta_0} \frac{\left(1 - \frac{k_0^2}{k_1^2}\sin^2\theta\right)^{1/2}}{\sin\theta} \tag{6}$$

where

η_1 intrinsic impedance of the earth;
k_1 wave number in the earth;
θ angle of incidence.

At VLF, this vertical electric field can be up to 1000 times greater than the horizontal electric field component when the ground is highly conductive (i.e., $\sigma = 1$ S/m at 20 kHz). At much lower frequencies, the conductivity of the earth can have much lower values with the same effect (for example $\sigma = 0.001$ S/m at 20 Hz).

While care must be exercised in making measurements with an insulated antenna, when the antenna wire is sufficiently flexible, coupling into the very strong vertical electric field is not likely to yield significant errors [12].

D. Contact Area Theory

When a conductive, semi-infinite half-space is covered by an insulating layer, no treatment of the stakes will achieve an adequate contact. Clearly, the upper layer forms part of the total earth plane and must form part of the measurement so that driving the stakes through this insulating layer will remove its contribution to the overall surface impedance measurement. Another consequence of this strategy is to allow the significant magnetic field coupling into the total response of the probe. This argument becomes obvious when that insulating layer is air. The effect of stake length on the staked probe configuration was briefly investigated as part of the FDTD analysis [10]. The penetration depth of the stakes into the ground had little effect for a uniform half-space, but in the case of the insulating upper layer, the effect was quite significant. This is because excellent electrical contact is made once the stakes have made direct contact with the lower earth half-space. Thus, it appears that the contact surface area of the stakes with the ground can affect the contact resistance. This is not a problem if the input impedance of the detector is sufficiently high. However, the penetration depth of the stakes through an insulating layer is critical to the results of the measurement. The effects of near-surface structures have been referred to as "static shift" [18] and can cause significant interpretation difficulties.

III. Conclusion

In the final analysis, it appears that both the staked probe and the insulated dipole yield reliable measurements of the horizontal electric field. The principal difference between the two results under ideal circumstances lies in a simple factor of two; the staked probe will yield twice the voltage compared to an insulated wire of the same length. The susceptibility to electromagnetic noise, the reliability of making repeatable measurements, the influence of the strong vertical electric field component, and the reliance of a high-input impedance detector system are all important considerations in attempting horizontal electric field measurements, particularly at frequencies greater than 20 kHz.

Finally, in an experimental science, the proof lies in the proven application and there is sufficient support for both techniques (for example see [18] and [23]).

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