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Two Approaches to the Measurement of Pulsed Electromagnetic Fields Incident on the Surface of the Earth

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Abstract

This note discusses two types of sensor platforms for measuring pulsed electromagnetic fields incident on the surface of the earth. One technique uses a flat conducting ground plane located on the ground surface. The other uses a conducting sensor boom leading from the ground surface to the sensor. For both techniques appropriate clear times can be defined which limit the time for which the ideal early-time performance of the sensor platforms applies. The ground plane approach is also considered for its low frequency performance which is the same as its early-time performance depending on a flat ground surface in the vicinity of the ground plane.

I. Introduction

One of the problems in the measurement of electromagnetic fields concerns the position at which the field component (or other related quantity) is to be measured and the electromagnetic geometry (conductors, insulators, etc.) in the vicinity of this position. The various things near the position of interest (other than the sensor itself) which can influence the fields can be there for at least one of two reasons. First there may be materials in the locale of interest before anything is introduced as part of the measurement system; one may be interested in the electromagnetic fields in the absence of the local perturbations. The case considered in this note is the measurement of the fields associated with a wave incident on the surface of the earth as illustrated in figure 1. In such a geometry one may wish to measure the incident fields and desire that the ground or water influence on the fields being measured either be negligible or be of a kind which makes the total fields have some simple and accurately known relation to the incident fields. Such simple operations might include multiplication by a constant factor (frequency independent), time differentiation, time integration, etc. However, for some applications in measuring transient fields one would only need this simple mathematical operation to apply for some finite length of time (a clear time) after the arrival of the pulse at the sensor. In considering the interaction of the incident fields with the ground or water and with other media one might place there to control the field interaction, one will generally need to consider some of the characteristics of the incident fields: the type of wave (planar, spherical, etc.), the angle of incidence, and the polarization.

A second kind of field-distorting objects in the vicinity of the sensor could be structures for physically supporting the sensor, devices for transporting signals from the sensor to recorders, and objects associated with the recording instruments. These would be objects external to the sensor and not considered as part of the basic electromagnetic geometry of the sensor. However, they would be important for the measurement. Such objects can scatter fields which in turn interact with the sensor to produce unwanted noise or error signals. One would then like to configure such objects in their position, choice of materials, use of special scattering reduction devices, etc. so that the scattered fields have minimal influence on the signal from the sensor. Alternatively one may try to include some features of the scattered fields in the measurement and account for their presence as part of the sensor response. Again one would like the resulting signal from the sensor to be some simple mathematical operation (accurately known) on the incident field component of interest.

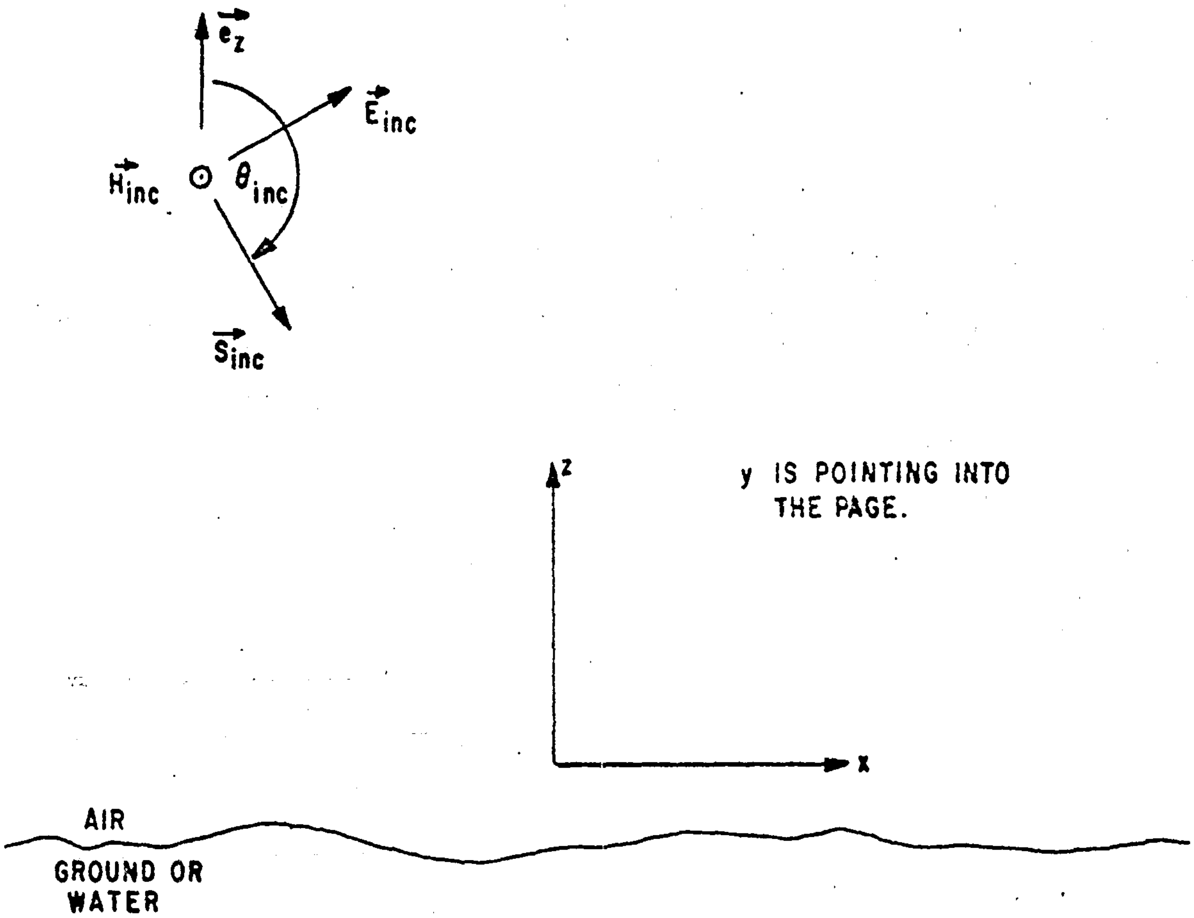


FIGURE 1. ELECTROMAGNETIC FIELDS INCIDENT ON A GROUND OR WATER SURFACE: SIDE VIEW

In this note we consider two approaches to the measurement of pulsed waves incident on a ground or water surface. The first involves the use of a conducting ground plane located on the surface of the earth; the sensor is located on the ground plane and the recording instruments are located under the ground plane. The second approach involves the use of a conducting boom leading from the recording instruments on the ground (or water) to the sensor up in the air; the signal from the sensor would be transmitted over cable (coax, twinax, etc.) to the recording instruments and the cable would be typically run inside the conducting boom for added shielding. Both of these approaches involve the use of conducting bodies added to the measurement geometry to interact with the incident fields in ways which modify the signal from the sensor in some simple manner in its relation to the incident field. In some sense the recording instruments are "hid" from the sensor inasmuch as they do not adversely affect the sensor performance. The major conductors affecting the field distribution are specified in some simple controlled geometry so that the field distribution and the resulting effect on the sensor response can be more easily calculated, at least for the times and/or frequencies of interest. There are various other techniques for measuring fields incident on the earth's surface which one might consider, such as by modulating the sensor signal on some high frequency carrier and telemetering it to a receiver, thereby avoiding a conducting connection while adding other instrumentation errors and complexities. However here we are only considering some techniques which involve the use and/or modification of the whole measurement geometry to interact with the incident fields in some desirable fashion and allow a conducting signal path from the sensor to a physically separate recording system while "hiding" this conducting path in the total measurement geometry. The emphasis in this note is placed on the measurement of pulsed waves incident on a ground surface and the illustrations are pointed in this direction. However, the techniques are also applicable to the case of a water surface as well.

This kind of measurement problem arises in ground-based or water-based measurements from nuclear air bursts or high altitude bursts as well as from some types of nuclear electromagnetic pulse (EMP) simulators. Some early models of such simulators already exist and have been tested using the second approach mentioned above involving a conducting boom. This particular boom is about 30 meters long and the boom and associated support structure have existed for over 6 months. In this note we would then like to record some of the design considerations we used for this kind of electromagnetic sensor platform. The conducting-ground-plane approach can also be used as an alternate scheme for such measurements and we would like to indicate here some of the design considerations for this approach as well.

For simplicity in some of the considerations in this note we let the incident wave as in figure 1 be a plane wave with a Poynting vector

$$\vec{S}_{inc} = \vec{E}_{inc} \times \vec{H}_{inc} \tag{1}$$

directed at an angle θ_{inc} with respect to the unit vector $\vec{e}_z$ in the z direction. For convenience the z axis is pointed away from the ground or water surface and the x axis is chosen so that the x, z plane is in the plane of incidence. While the incident magnetic field $\vec{H}_{inc}$ is shown parallel to the y axis this is not required in the discussion but only illustrated this way. Note that the ground or water surface is generally rough as shown in figure 1 and this feature is also part of the measurement problem. Nominally one might take z = 0 on a flat ground (or water) surface, or better take z = 0 on a flat conducting ground plane if placed there; the coordinate origin ($\vec{r} = \vec{0}$) might be taken at the sensor near or at the center of the ground plane. For the case of a sensor boom the coordinate origin might be taken at the sensor at the end of the boom away from the ground (or water) surface; one might also align the z axis parallel to the boom for scattering calculations. The choice of coordinates is, of course, a matter of convenience.

II. Ground Plane Approach

The first approach we consider involves the use of a conducting plane of finite size on the ground surface as illustrated in figure 2. Some of the design considerations for such a sensor platform are similar to those discussed in a previous note with regard to a conducting sensor platform on a sea-water surface.[1] For purposes of illustration the conducting plane is shown as circular with radius a and with some sensor mounted in the center of this ground plane and on top of it. The conducting plane is made flat and is located on a plane which in some sense makes the best approximate fit to the local ground surface in the vicinity of the conducting reference plane (or sensor platform). Part of the interest in such a measurement technique involves the low-frequency performance of the sensor platform; the low-frequency performance involves the local characteristics of the ground and the local shape of the ground surface. The sensor platform is in electrical contact with the ground and various provisions might be made to assure electrical contact. As shown

1. Capt Carl E. Baum, Sensor and Simulation Note 39, Some Electromagnetic Considerations for a Sea-Water-Based Platform for Electromagnetic Sensors, March 1967.

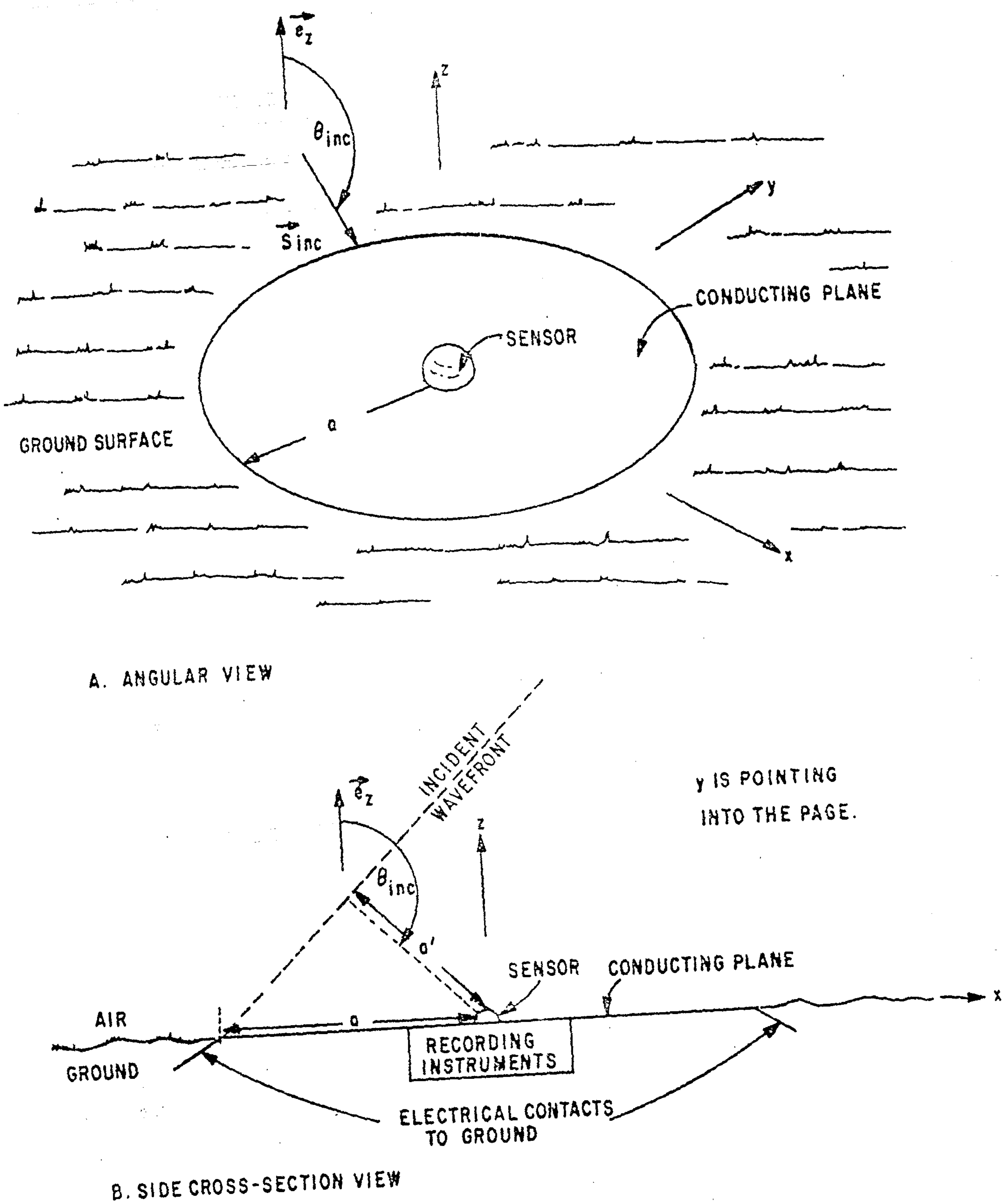


FIGURE 2. CONDUCTING PLANE OF FINITE SIZE AS A SENSOR PLATFORM ON A GROUND SURFACE

in figure 2B one might place conductors in the ground around the periphery of the sensor platform. The local ground surface is not perfectly flat in its natural state, and the ground will in general need to be tailored for the sensor platform; one might also tailor the ground surface near the platform to better approximate a flat surface coplanar with the conducting sensor platform.

The sensor platform or conducting ground plane could be made in various ways; it might consist of continuous metal sheet, metal mesh, wire grids, etc. A sensor platform which is optimized from a practical viewpoint might be a composite of various metal configurations which approximate a perfectly conducting sheet. The highest quality material, say continuous metal sheets or fine metal mesh, would be used in the immediate vicinity of the sensor (or sensors). For positions farther from the center of the ground plane coarser mesh might be used. The outermost portions of the ground plane might even be radial wires.

The recording instruments are located under the sensor platform to give minimum perturbation of the fields in the vicinity of the sensor (or sensors) on top of the platform. The recording instruments might be enclosed in an electromagnetic shield which is connected to the ground plane. Because of the location of the recording instruments plus their shielding one might consider this measurement technique as hiding such equipment from any significant interaction with the fields being measured. Of course as fields penetrate the ground around the sensor platform such fields will propagate to the location of the recording equipment and other associated conductors, etc., and will be distorted by the presence of this equipment. However if the equipment below the ground plane is contained in a volume with all dimensions small compared to a (the characteristic dimension of the ground plane) then the field scattered by this equipment will have only a small effect on the fields in the vicinity of the sensors. Note that we assume that the ground plane is sufficiently highly conducting to prevent any significant penetration of fields through the sensor platform for frequencies of interest. All fields of interest are made to propagate around the sensor platform to reach the opposite side.

For the early-time characteristics of such a sensor platform one can first make a clear time argument. The position vector is[2]

$$\vec{r} = x\,\vec{e}_x + y\,\vec{e}_y + z\,\vec{e}_z \tag{2}$$

2. All units are rationalized MKSA.

where $\vec{e}$ with a coordinate as a subscript is a unit vector in the direction of increasing values of that coordinate. Let the first electromagnetic signal arrive at $\vec{r} = \vec{0}$ (the sensor location) at a time $t = 0$. For a circular ground plane of radius a as shown in figure 2B, when the incident wavefront first reaches the ground plane edge it is a distance

$$a' = a \sin(\theta_{inc}) \tag{3}$$

from the sensor where we are only considering the angle of incidence for $\pi/2 < \theta_{inc} \leq \pi$. The signal from the edge of the ground plane reaches the sensor at a time

$$t_c = \frac{1}{c}(a - a') = \frac{a}{c}[1 - \sin(\theta_{inc})] \tag{4}$$

where the speed of light is

$$c = \frac{1}{\sqrt{\mu_o \varepsilon_o}} \tag{5}$$

and μ_o and ε_o are the permeability and permittivity respectively of free space (and of air to a very good approximation). This time t_c might be called a clear time as it represents the time after first signal arrival for which the fields near $\vec{r} = \vec{0}$ are the same as they would have been if the ground plane were infinitely large. For $0 < t < t_c$ the total fields near $\vec{r} = \vec{0}$ are related to the incident fields as

$$\begin{aligned} H_x &= 2H_{x_{inc}} \\ H_y &= 2H_{y_{inc}} \\ E_z &= 2E_{z_{inc}} \end{aligned} \tag{6}$$

while the remaining 3 components of the total electric and magnetic fields are zero for all times on the ground plane due to the boundary conditions. These results of equations 6 mean that for $0 < t < t_c$ the waveforms for $H_{x_{inc}}$, $H_{y_{inc}}$, and $E_{z_{inc}}$ are just double the incident waveforms in amplitude at the sensor with the same time history while the other field components are zero. This simple result can be rather useful for measuring early-time incident fields.

For our example in figure 2 we have chosen a circular ground plane with the sensor at its center for simplicity. If, however, one is interested in maximizing t_c for a given direction of incidence while minimizing the area of the ground plane, then for an incident plane wave one might make the shape of the ground plane such that the signals from all points on the edge of the ground plane arrive at the sensor at the same time t_c. To see what this might imply set

$$t_c \equiv \frac{b}{c} \tag{7}$$

where b is some characteristic dimension. Let the sensor be at $\vec{r} = \vec{0}$ and a plane wave be incident at angle θ_{inc} with $\vec{S}_{inc}$ parallel to the x, z plane as above. If the first signal arrives at $\vec{r} = \vec{0}$ at a time $t = 0$ then at other positions on the x, y plane the first signal arrives at a time

$$t_o = \frac{x}{c} \sin(\theta_{inc}) \tag{8}$$

The transit time from a point on the x, y plane to $\vec{r} = \vec{0}$ is just

$$t_1 = \frac{1}{c} [x^2 + y^2]^{1/2} \tag{9}$$

Setting

$$t_c = t_o + t_1 \tag{10}$$

to make all arrival times from some perimeter on the x, y plane equal to t_c gives an equation for the perimeter as

$$b = x \sin(\theta_{inc}) + [x^2 + y^2]^{1/2} \tag{11}$$

This can be manipulated to give

$$[x \cos(\theta_{inc}) + b \tan(\theta_{inc})]^2 + y^2 = b^2 \sec^2(\theta_{inc}) \tag{12}$$

which is the equation of an ellipse with major axis of length $2b/\cos^2(\theta_{inc})$ and minor axis of length $-2b/\cos(\theta_{inc})$. The sensor position $\vec{r} = \vec{0}$ is at a focus of this ellipse.

One disadvantage of an elliptical ground plane is the lack of rotational symmetry about the z axis and the associated increased complexity of calculations applying for $t > t_c$. Thus if one would like to use the ground plane for times large compared to t_c a circular ground plane with the measurement location in the center (on top) might be a good approach.

Next consider some of the things affecting the low-frequency performance of the finite ground plane as a sensor platform. If the first signal from the incident plane wave reaches $\vec{r} = \vec{0}$ at $t = 0$, then for $t > t_c$ we may expect some distortion of the fields at $\vec{r} = \vec{0}$ due to the presence of the ground around and beneath the sensor platform. An incident plane wave does not reflect from the ground surface to produce simple resulting fields as in equations 6 for all frequencies as does a perfectly conducting plane. The reflection coefficients for a plane wave incident on a finitely conducting half space depend on polarization, angle of incidence and frequency or time.[3] Note, however, that in the low-frequency limit the results of equations 6 do apply and these are the only resulting field components at the surface of a uniform finitely conducting half space. Nonuniformities could distort the fields at the ground surface so one might be concerned about the distribution of permittivity, permeability, and conductivity under the ground surface in the locale of interest. Neglecting such nonuniformities, then for sufficiently low frequencies the ground reflection characteristics go to the results of equations 6 and the skin depth in the ground is large compared to a, so that the sensor platform does not significantly distort the field distribution around it (since its boundary conditions are consistent with allowing only H_x, H_y, and E_z). Thus in the cases of both early times (or high

3. Capt Carl E. Baum, EMP Theoretical Note 25, The Reflection of Pulsed Waves from the Surface of a Conducting Dielectric, February 1967.

frequencies) and low frequencies (or late times for appropriate waveforms) the field distribution at $\vec{r} = \vec{0}$ has only 3 field components with the simple relations to the incident fields as in equations 6. This observation lends hope to being able to use such a sensor platform for all frequencies or characteristic times in waveforms of interest with perhaps some limitations on ground plane size, ground electrical parameters, and acceptable deviation from the simple results in equations 6 across some wide frequency band of interest.

There are various characteristics of the ground one might consider when designing a ground plane platform to operate for characteristic times greater than the clear time. Let the ground have permittivity ε, permeability μ (normally approximately μ_o), and conductivity σ. The relative dielectric constant is

$$\varepsilon_r \equiv \frac{\varepsilon}{\varepsilon_o} \tag{13}$$

In the high frequency limit the ground reflection is dominated by ε_r, but for typical values (say a few to twenty or so at high frequencies) the high frequency reflection is rather sensitive to θ_{inc} and polarization. In any event the reflection does not match the simple form in equations 6.

The relaxation time of the ground is

$$t_r = \frac{\varepsilon}{\sigma} \tag{14}$$

where, if ε and/or σ are frequency dependent, some typical values are used. For radian frequencies $\omega >> 1/t_r$ the displacement current density in the ground dominates the conduction current density, while for $\omega << 1/t_r$ the conduction current density is dominant. From reference 3 we see that for $\omega << 1/t_r$ the reflection coefficients of the ground surface tend to give the results for the total fields at the ground surface as in equations 6. In the time domain this means for characteristic times in the pulse large compared to t_r then in a limiting sense equations 6 hold. Thus t_r is a characteristic time for the ground to begin to act as a perfect reflector. Since t_c is a characteristic time for the early-time performance of the ground plane and t_r is a characteristic time for the late-time performance of the ground, then one might like to make $t_c >> t_r$ and see if the early-time ground plane and late-time ground characteristics might blend together to give the performance as in equations 6 for all times or frequencies of interest.

One might consider some typical values for ground parameters to see what numbers are involved. As a first case let

$$\varepsilon_r = 10 \;, \qquad \sigma = 10^{-2} \text{ mho/m}$$
$$t_r \simeq 9 \text{ ns} \tag{15}$$

These might be typical numbers. Suppose we wanted $t_c \simeq 90$ ns for a 10 to 1 ratio. This would make a a little less than 30 m. As a second case let

$$\varepsilon_r = 10 \;, \qquad \sigma = 10^{-4} \text{ mho/m}$$
$$t_r \simeq .9 \;\mu\text{s} \tag{16}$$

If one tried to make t_c about 9 μs then a would be a little less than 3 km, i.e. a little large. Thus the practical implications of making $t_c >> t_r$ depend on σ. For large a, however, one might make most of the ground plane consist of widely spaced wires, recognizing that one does not need a fine grid for portions of the ground plane far from the sensor. The present case where we are concerned with typical soil parameters differs markedly from the sea-water case discussed in reference 1 where the relaxation time is much smaller making it much easier to achieve $t_c >> t_r$ by the platform size.

Another characteristic time of the measurement geometry is a diffusion time for the magnetic field to significantly penetrate under the conducting plane by propagating through the ground around and beneath it. As discussed in reference 1 the magnetic field distribution in the vicinity of the ground plane is distorted because of the penetration of the magnetic field into the ground to some depth while the magnetic field penetration into the ground plane itself is comparatively very small. An effective depth for such penetration into the ground after some time t for a step function (u(t)) magnetic field is

$$d = \sqrt{\frac{4}{\pi}\,\frac{t}{\mu\sigma}} \tag{17}$$

as long as $t >> t_r$. One might expect the magnetic field distortion to get worse as d increases toward the characteristic dimension a of the ground plane. However, for sufficiently large t or small ω the magnetic field can completely diffuse under the ground plane and the distortion of the field go away because of the boundary conditions on the ground plane being consistent with the low-frequency field distribution near the ground surface as in equations 6. With a being a characteristic ground plane dimension then one might define a characteristic diffusion time for the ground plane from equation 17 as

$$t_d \equiv (\text{constant})\mu\sigma a^2 \tag{18}$$

where the dimensionless constant might be best determined as appropriate for detailed calculations. For ω of the order of $1/t_d$ one might expect this field distortion to be most significant. Also the electric field distortion may in general be somewhat different from the magnetic field distortion. In order to minimize the adverse effects of such field distortion on the measurement one might wish to choose the ground plane geometry and sensor location in some optimum fashion. Perhaps a circular ground plane with sensor or sensors near the center is a good choice but the answer to such questions lies in more detailed calculations beyond the scope of this note.

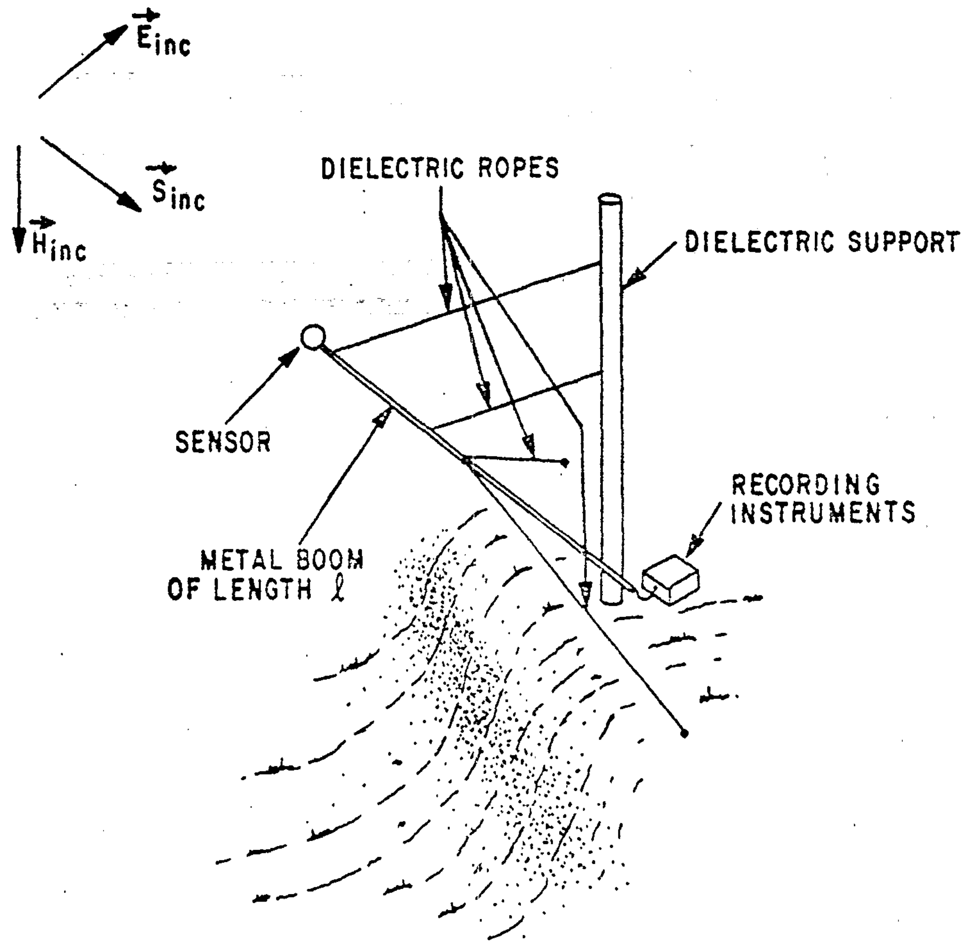
While the ground-plane approach to measuring fields incident on the ground surface shows some promise across the frequency spectrum there are still numerous problems of the boundary-value type to be solved to quantitatively resolve some of the questions and arrive at some optimum design. One would like to know how closely the fields at some position on the ground plane might be made to follow the ideal characteristics of equations 6 for all frequencies and times of interest. Furthermore one would like to know the sensitivity of the results to the ground electrical parameters and their homogeneity which may be unknown to some extent and variable over long time spans; one would like the measurement to be insensitive to such uncertainties. In addition one would like to know the effects of variation in the electrical contact of the conducting plane to the ground as well as the effects of the rough (not truly flat) ground surface. As can be readily seen there are many problems which might be usefully considered.

III. Conducting Boom Approach

The second general technique we wish to consider might be called a conducting boom approach. In this approach the sensor is elevated above the ground (or water) surface to give a clear time between the first signal and first ground reflection to arrive at the sensor. As in the previous section we denote this clear time as t_c. For this conducting boom approach, however, we are only considering times for $t < t_c$ where $t = 0$ is taken as the time of first signal arrival at the sensor. A conducting boom, typically metal, of length ℓ is connected to the sensor and leads in a straight path to the recording instruments located on the ground surface. The signal cable(s) leading from the sensor to the recording instruments are made electrically part of the boom so that there is only one long slender conductor to scatter the incident fields associated with the wave we are trying to measure. If the metal boom is a hollow conducting tube, then with appropriate electrical seals at both ends of the boom the signal cables can be placed inside the boom for added shielding. One might try to have no conductors leading to the sensor and telemeter the measured waveform to the ground via a modulated carrier. However, if one wishes to use conducting signal cable to transmit the signal because of its simplicity and accuracy and design around the field scattering introduced, then enclosing the cable in a strong but slender conducting boom does not qualitatively change the scattering problem.

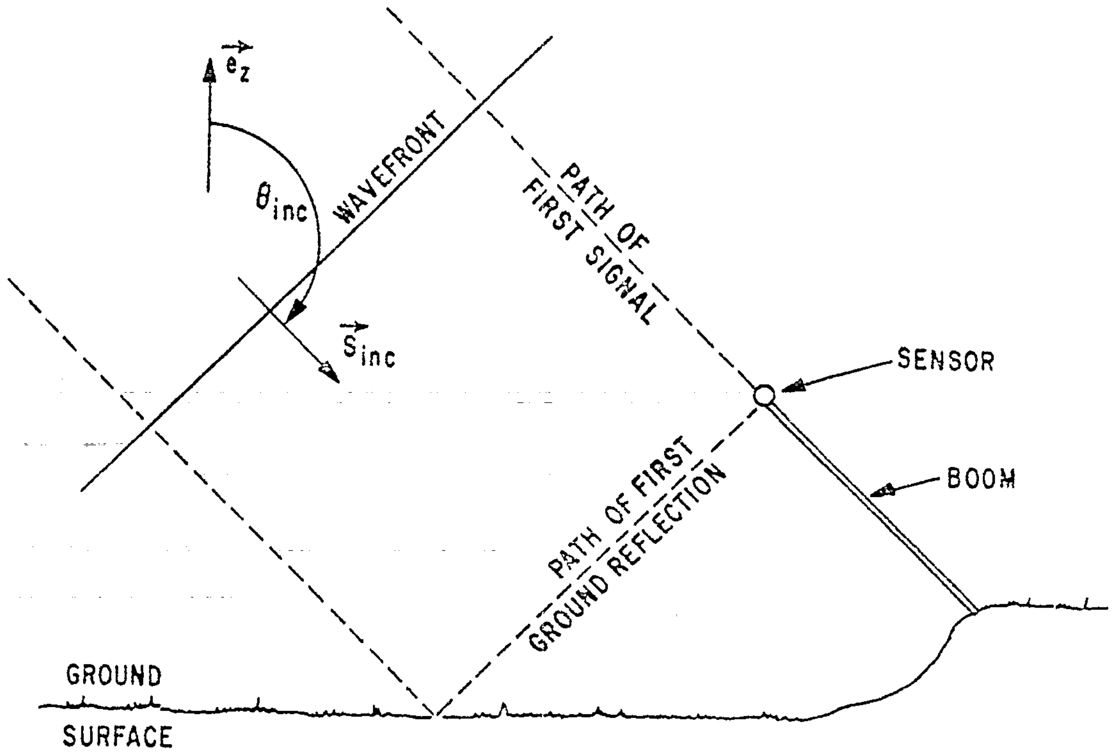
Figure 3 shows a conducting-boom installation. Note that the sensor and boom need to be supported by some mechanical supports which give negligible perturbation to the incident fields, at least as reach the sensor for $t < t_c$. As shown in figure 3 there might be a main dielectric vertical support (such as a telephone pole) together with dielectric ropes leading to the boom in some fashion which allows for convenient changes in the boom orientation, including lowering it to the ground. There are various other arrangements of dielectric supports and guides that one might use (e.g. balloons). Note that as shown in figure 3 the sensor boom is mounted on top of a hill or on the edge of a cliff or other steep ground falloff from the base of the boom. The local ground contour can be used to maximize the clear time t_c for some angle of incidence θ_{inc} other than vertical so that $\theta_{inc} < \pi$. For use with various θ_{inc} a sensor-boom facility can make use of both boom length ℓ and the local ground contour to maximize t_c. Besides fixed installations one might also have portable sensor booms to take to various test sites where appropriate EMP simulators have been temporarily installed. Such portable booms might be installed on the roofs of instrumentation vans and the recorders placed inside the vans. However, one might expect greater difficulty in building large boom systems if they must also be portable.

To illustrate the influence of the ground contour near the sensor boom consider the examples illustrated in figure 4. Let a plane wave be incident at some angle θ_{inc} with respect to $\vec{e}_z$ with $\pi/2 < \theta_{inc} < \pi$. Note in figure 4A that the first reflection to reach the sensor does not come from the base of the

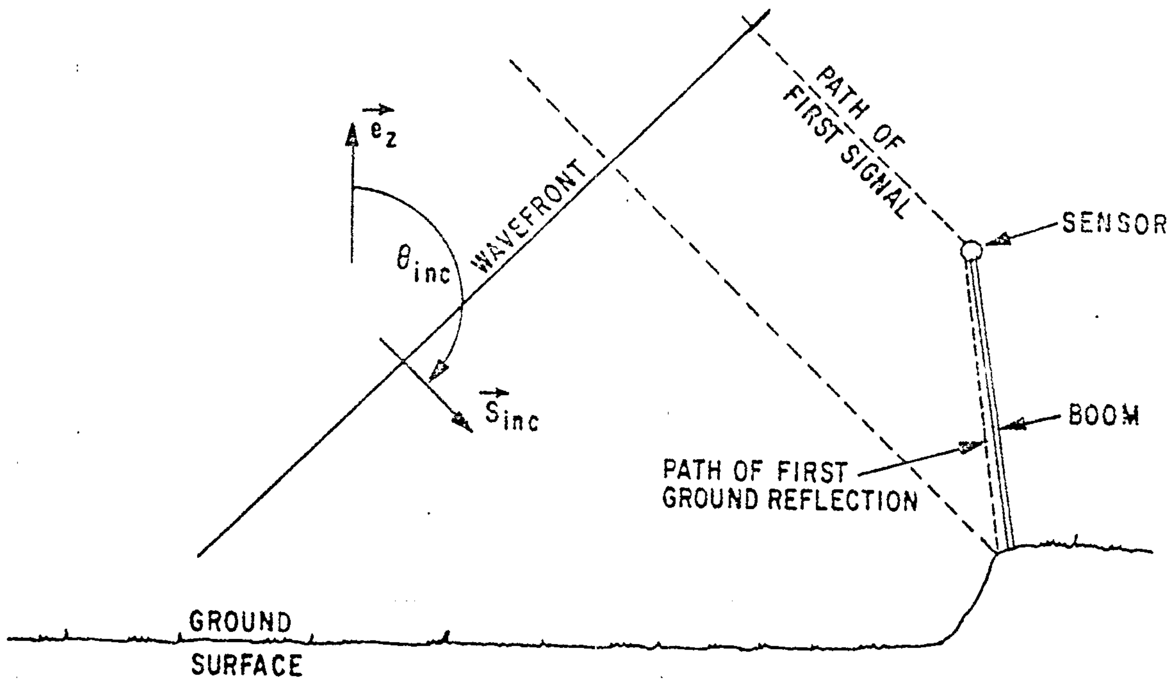


AS SHOWN, THE BOOM MIGHT BE MOUNTED ON TOP OF A HILL OR CLIFF.

FIGURE 3. CONDUCTING BOOM AS A SENSOR PLATFORM ON A GROUND SURFACE



A. ON AXIS INCIDENCE



B. OFF AXIS INCIDENCE

FIGURE 4. MODES OF OPERATION OF SENSOR BOOM

boom; it comes from the ground surface away from the base of the boom and generally toward the wave source (while still being on the ground surface). Then by having the ground surface at a lower level on this side of the base of the boom the first reflection will arrive later in time. Note in figure 4B that with the sensor boom in a more upright position the first reflection from the ground to the sensor comes from a position closer to the base of the boom. In raising the sensor position like this t_c may be increased but the boom is no longer parallel to $\vec{S}_{inc}$.

Figure 4 shows two configurations of the sensor boom relative to $\vec{S}_{inc}$; the boom can be parallel to $\vec{S}_{inc}$ as in figure 4A or not parallel as in figure 4B. This has some bearing on the performance of the conducting boom as a sensor platform because of the scattering of the incident wave by the conducting boom. Without going into detail there are several points to consider in minimizing adverse effects on the sensor signal due to the presence of the conducting boom. These considerations are also dependent on which type of field and which component of that field is being measured.

Consider first magnetic field measurements. First the net current on the boom considered as a single rod goes to zero at the sensor end except for the small current which can go onto the sensor. To first order the magnetic field at the sensor due to the boom current is then zero. The sensor is at a position where the magnetic field scattered from the boom is minimum (in magnitude). There are other higher order scattering modes associated with no net current along the boom but these are less significant. Second the scattered magnetic field associated with the net boom current is an axially symmetric magnetic field. Refer to figure 5 where primes are used to designate coordinates referred to the boom with $\vec{r}\,' = \vec{0}$ as the sensor location and the boom centered on the negative z axis. The principal scattered $\vec{H}$ has then only a ϕ' component which is independent of ϕ'. The sensor can be designed symmetrically with respect to the z' axis so that it does not couple to this scattered ϕ' component of the magnetic field while measuring the incident $H_{x'}$, $H_{y'}$, or $H_{z'}$. Third by making $\vec{E}_{inc}$ perpendicular to the boom the net current on the boom is zero at all positions along its length (at least before ground reflections reach the boom). For this configuration the principal scattered magnetic field mode is zero. To ensure $\vec{E}_{inc}$ perpendicular to the boom one might choose $\vec{S}_{inc}$ parallel to the boom; this would even allow the polarization to rotate with time while still maintaining $\vec{E}_{inc}$ perpendicular to the boom.

The electric field measurements have a more significant problem associated with the boom scattering. First, while the current induced on the boom is at a null at the sensor end, the charge per unit length on the boom (say a cylindrical rod) is

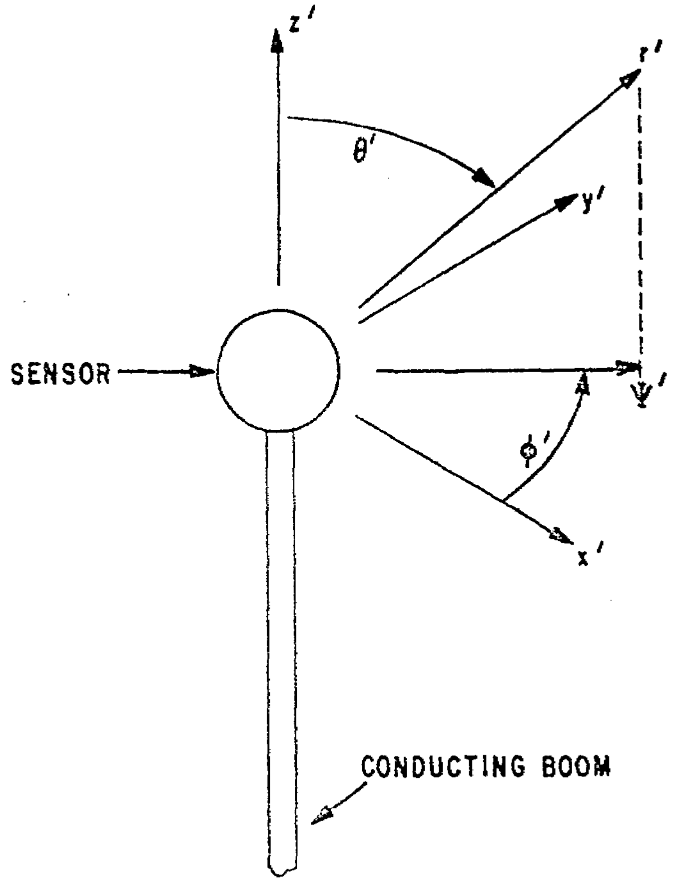


FIGURE 5. COORDINATES FOR SENSOR BOOM

maximized at the sensor end. The sensor is then at a position where the scattered electric field generally has a maximum magnitude. Second this principal electric field scattering mode is also axially symmetric about the z' axis with only Ψ' and z' components, both independent of ϕ'. One could make an electric field sensor which was symmetrically placed with respect to the z' axis and measured the incident $E_{x'}$ or $E_{y'}$ differentially so as to have no net coupling to the principal scattered electric field mode. However, the scattered field could give a large common mode signal and one would have to be sure it wasn't significantly affecting the measurement. Note that the principal scattered electric field can be much larger in magnitude near the sensor than the incident electric field. In trying to measure the incident $E_{z'}$ the scattered $E_{z'}$ has the same direction across the entire sensor and is then invariably picked up with the incident $E_{z'}$. Only a sensor designed to measure a component of $\vec{E}$ perpendicular to the z' axis can, assuming adequate symmetry, be unresponsive to the main axially symmetric electric field scattering mode. Of course, one might try to measure the z' component of the combined incident and scattered electric field, but if the result is to be related to the incident electric field then one must understand the relation of the sensor output to the incident wave. The boom itself is then an important part of the sensor and its shape will have to be controlled to give the desired electromagnetic response. Third by making $\vec{E}_{inc}$ perpendicular to the boom the principal electric field scattering mode is not excited (within the clear-time limitation). Again to ensure $\vec{E}_{inc}$ perpendicular to the boom one might make $\vec{S}_{inc}$ parallel to the boom so that the polarization of $\vec{E}_{inc}$ could even rotate with time while still keeping $\vec{E}_{inc}$ perpendicular to the boom.

There is then a significant difference in the boom scattering as it affects electric and magnetic field measurements at the end of the boom. This scattering is significantly more favorable to measurement of a component of the incident magnetic field than a component of the incident electric field. In both types of measurement the influence of the scattered field on the measurement can be minimized by appropriate sensor symmetry with respect to the z' axis and by aligning the sensor boom parallel to $\vec{S}_{inc}$. However a configuration with the sensor boom parallel to $\vec{S}_{inc}$ does not necessarily give the maximum clear time t_c. On the other hand one may have to take extra care and perhaps sacrifice clear time for good measurements of the incident electric field perpendicular to the boom axis. As mentioned before, the boom changes $E_{z'}$ in the vicinity of the sensor in a manner that makes a measurement of the incident $E_{z'}$ depend on the boom for the basic sensitivity of the sensor; the scattered field is inherently part of the measurement. Note that for our illustrations we have used an incident plane wave for simplicity. However typical waves of interest might be spherical (at least for the leading edge) as might be generated by some pulse-radiating antenna with a somewhat localized source region. The discussion above concerning the field scattering by the boom still applies for the cases that this scattering is made to have negligible effect. For the case of measuring $E_{z'}$ where the scattered field is an integral part of the measurement one may need to consider the difference in response to the spherical instead of plane wave if the radius of curvature of the incident wave is not sufficiently large in the vicinity of the sensor.

One thing this discussion points out is the effect of the fields scattered from the boom and the need for sensor symmetry with respect to the boom. These considerations point to many possible detailed calculations of the boundary-value-problem variety. These would include various boom geometries such as semi infinite perfectly conducting cylinders with various end caps, a set of coaxial perfectly conducting cylinders of different radii to form a boom of varying radius, a circular perfectly conducting cone of very small half cone angle, etc. Also one might consider various sensor geometries, such as a sphere, etc., mounted on the end of the boom as part of the total scattering problem. Of course, one would like such calculations for all appropriate directions of incidence and polarization.

Referring again to figure 5 where we use the primed coordinates based on the sensor boom one can define a "clear volume" of space based on the clear time t_c which we define as in equation 7 in the form

$$t_c \equiv \frac{b}{c} \tag{19}$$

where $b > 0$ is some characteristic distance. Assume there is some transient point source located at $(x', y', z') = (0, 0, d)$ which emits a wave at $t = -d/c$ so that the signal reaches the sensor at $t = 0$. At $t = t_c$ scattered fields can reach the sensor from anywhere on a surface with the sum of the distances to both source and sensor equal to $d + b$. This defines a surface as

$$[(z' - d)^2 + \Psi'^2]^{1/2} + [z'^2 + \Psi'^2]^{1/2} = d + b \tag{20}$$

which can be manipulated to give

$$\left[\frac{2}{d+b}\right]^2\left[z' - \frac{d}{2}\right]^2 + \left\{\left[\frac{d+b}{2}\right]^2 - \left(\frac{d}{2}\right)^2\right\}^{-1} \psi'^2 = 1 \tag{21}$$

which is the equation of a special type of ellipsoid known as a prolate spheroid. This surface defines the volume around the sensor and point source which must include no ground and this surface just touches the ground for the clear time for ground reflections to be just t_c. In the optimum case that the first reflection comes from the base of the sensor boom with the sensor boom aligned with the point source then the characteristic distance b is just 2ℓ and the clear time is $t_c = 2\ell/c$. In the limiting case that $d \to \infty$ so that the spherical wave becomes a plane wave the surface equation becomes

$$\psi'^2 = 2bz' + b^2 \tag{22}$$

which is the equation of a circular paraboloid with the sensor at the focus. In the prolate spheroidal case both the source and the sensor are at the focii. We have considered the case that the sensor boom is parallel to $\vec{S}_{inc}$ and used coordinates based on the boom to define a clear-time surface. One might let the boom be oriented at some angle with respect to $\vec{S}_{inc}$ as discussed before. In this case we can still define a clear-time surface as above provided we regard the coordinates, say with double primes, as being fixed by the sensor and the direction of wave incidence at the sensor; $\vec{r}'' = \vec{0}$ would be the sensor position and the z'' axis would point at the wave source from the sensor.

IV. Summary

Thus we have at least two general approaches for the problem of measuring pulsed electromagnetic fields incident on the surface of the earth. One of these has the sensor(s) on a conducting ground plane located on the ground surface; the other is a conducting sensor boom leading from the ground surface to the sensor. Both of these techniques use the sensor platform to "hide" signal cables and/or recording instruments in the sensor geometry. The sensor geometry is used to scatter the incident fields in a known and controlled manner so that the fields at the sensor can be related to the incident fields in a known manner with a relation which is ideally trivial within some desired accuracy. For both techniques a clear time can be defined as a time to which the early-time response of the platform can be used; the early-time responses are ones fitting ideal relations for field scattering to the sensor.

The ground plane approach makes the resultant fields on the ground plane zero for certain field components. For both early times and low frequencies the remaining field components are doubled over those in an incident plane wave; for early times this applies to more general forms of incident wave as well. The ground plane approach may be applicable to a broad range of frequencies depending on ground electrical parameters and their homogeneity, the conducting plane size and shape, and the type of electrical contact between the conducting plane and the ground.

The sensor boom approach relies on the distribution of the scattered fields produced by the boom as they appear in the vicinity of the sensor. The scattering characteristics of the boom make the boom end considerably more favorable to measuring the incident magnetic field than the incident electric field. This technique attempts to make the scattered fields have no significant influence on the sensor response so that the sensor only responds to the incident field. However a sensor on the end of the boom sensitive to the incident electric field parallel to the boom will also see the scattered electric field which can be much larger than the incident electric field; sensor symmetry does not help here. Thus an electric field measurement for the component parallel to the boom would have to include the boom itself as part of the sensor geometry and control the boom geometry to achieve some desired response characteristic. Note that the sensor boom technique is only intended to apply for times before the clear time.

This note has included qualitative discussions of various aspects of the performance of these two types of sensor platforms. Many calculations are needed for a detailed understanding of their performance as sensor platforms to optimize their designs.