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Sensor and Simulation Notes

Note 271

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Sensors for Measurement of Intense Electromagnetic Pulses

Carl E. Baum
Air Force Weapons Laboratory

Abstract

Fast, large-amplitude pulses are encountered in the nuclear electromagnetic pulse (EMP), lightning, various pulse-power machinery, and charged particle beams. In the context of the EMP program various accurate, broad-band sensors have been developed. The principal types of these sensors have been designed to measure electric and magnetic fields, current densities, currents, and voltages. Often it is the time-derivative waveforms that are measured for good accuracy. These sensors are now being applied to the measurement of the fast-transient electromagnetic properties of lightning.

The general design concepts and techniques for such sensors are also applicable in various pulse power machines, where one may wish to measure various impulsive currents and voltages. A more difficult problem occurs when there are pulsed particle beams (γ ray, X ray, neutron, electron, etc.) present. However, some of the important EMP sensor designs were for nuclear-source-region environments, making the concepts generally applicable for such particle-beam environments.

Besides the actual sensors which convert the desired electromagnetic field parameters to voltage and current at a connector (terminal), one must also consider the topology of any conductors (such as cables) attached to the sensor, or of which the sensor forms a part (such as a shield), in designing experiments. In some cases symmetry is also an important consideration.

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Besides the actual sensors which convert the desired electromagnetic field parameters to voltage and current at a connector (terminal), one must also consider the topology of any conductors (such as cables) attached to the sensor, or of which the sensor forms a part (such as a shield), in designing experiments. In some cases symmetry is also an important consideration.

I. Introduction

The measurement of transient and broad-band electromagnetic fields and related parameters is important for various kinds of electromagnetic environments. Although there are some specific differences in the non-EM-field part of such environments the basic EM-field part is common to them all. Often one is aided by the presence of uniform isotropic media in which to measure such fields, and perhaps the presence of highly conducting boundaries near which to measure the fields. However, there can be more difficult media to consider in the cases of the various environments of interest. In the case of the nuclear electromagnetic pulse (EMP) one has the difficult medium of the nuclear source region with nuclear radiation, source current density, and nonlinear and time-varying air conductivity. In the case of natural lightning in the stroke itself (as in the direct strike to an aircraft) there is a nonlinear and time-varying air conductivity (or corona). In pulse-power machinery where media are often stressed near breakdown similar nonlinear and time-varying conductivity phenomena occur. So there are some similarities in the electromagnetic sensor design requirements, and some differences as well.

While the basic concepts of electrically-small antennas for measuring electromagnetic fields are quite old, optimization of these in a transient or broad-band sense is relatively recent. The historical motivation for these developments resides in the nuclear electromagnetic pulse (EMP) program; this aspect has been reviewed in [3]. More recently such sensors have been used for measuring lightning environments [7], including (in some cases) appropriate modifications. EMP simulators [4] have used electrical pulsers [6] as the sources for the simulators proper (or antennas); in this context the electromagnetic sensors of our concern have been often used and even included within the actual pulse-power machinery.

The basic sensor designs have been reviewed in [3]. This paper first summarizes these only briefly. There are, in addition, some special factors to be considered when using such sensors. The topology of the conducting cables must be integrated with the topology of the other conductors in the measurement situation. In some cases one can utilize the symmetry inherent in the sensors combined with symmetry in the fields and/or measurement cables to minimize the effects (noise) of the scattering of certain field components by the sensor and cables.

II. Some Basics

Summarizing some of the basic aspects of electromagnetic sensor design [3], first we have our definition of a sensor as a special kind of antenna with the following properties.

1. It is an analog device which converts the electromagnetic quantity of interest to a voltage or current (in the circuit sense) at some terminal pair for driving a load impedance, usually a constant resistance appropriate to a transmission line (cable) terminated in its characteristic impedance.

2. It is passive.

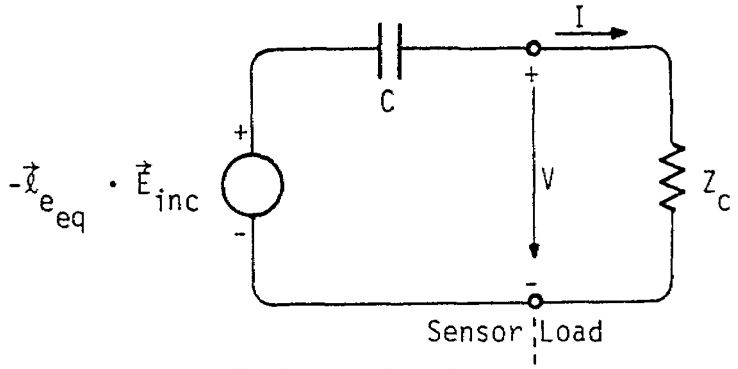
3. It is a primary standard in the sense that for converting fields to volts and current, its sensitivity is well known in terms of its geometry; i.e., it is "calibratable by a ruler." The impedances of loading elements may be measured and trimmed. Viewed another way it is in principle as accurate as the standard field (voltage, etc.) in a calibration facility. (A few percent accuracy is usually easily attainable in this sense.)

4. It is designed to have a specific convenient sensitivity (e.g., $1.00 \times 10^{-3}\ m^2$) for its transfer function.

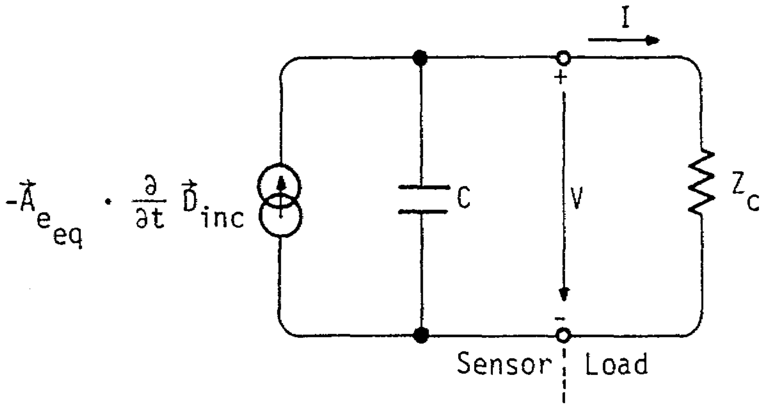
5. Its transfer function is designed to be simple across a wide frequency band. This may mean "flat" in the sense of volts per unit field or time derivative of field, or it may mean some other simple mathematical form that can be specified with a few constants (in which case more than one specific convenient sensitivity number is chosen).

A first important category of such sensors is the electric-field sensors. Figure 2.1 shows the basic topology of such a sensor (two separate conductors connected to a terminal pair) and its equivalent-circuit representation (valid for electrically small sensors). The three basic sensor parameters are related as

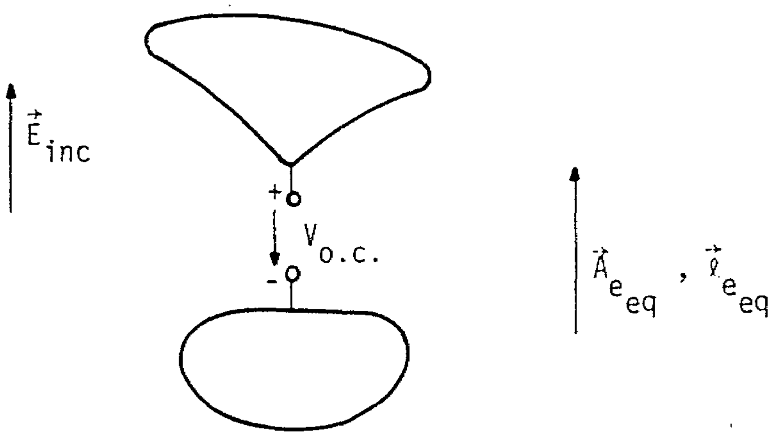
$$\begin{aligned}
\vec{A}_{e_{eq}} &= \frac{C}{\varepsilon} \vec{\ell}_{e_{eq}} \\
\vec{A}_{e_{eq}} &\equiv \text{equivalent area} \\
\vec{\ell}_{e_{eq}} &\equiv \text{equivalent length (or height)} \\
C &\equiv \text{capacitance}
\end{aligned} \tag{2.1}$$



a. Thevenin Equivalent Circuit



b. Norton Equivalent Circuit



c. Electric Dipole Sensor

Figure 2.1. Electrically Small Electric Dipole Sensor in Free Space.

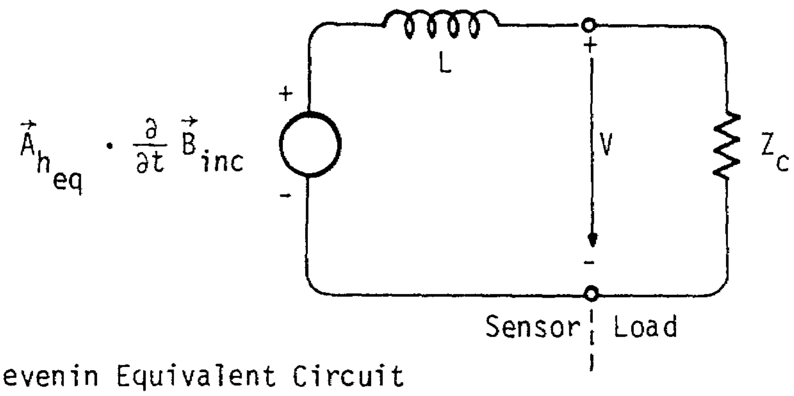
so that only two of the basic parameters are independent. Note that if in addition to the medium permittivity ε there is a conductivity σ, then a conductance G appears in parallel with the capacitance C in the equivalent circuit.

Various types of such sensors have been constructed in standard models. Most common are those operated in short-circuit mode for which the equivalent area in Fig. 2.1B is the relevant sensitivity parameter. Such a sensor measures current density, which in a nonconducting medium ($\sigma = 0$) is just the displacement current density $\partial\vec{D}/\partial t$. In a more general case this is $(\sigma + \varepsilon\partial/\partial t)\vec{E}$. Common models for free space are the HSD (hollow spherical dipole), ACD (asymptotic conical dipole), and FPD (flush plate dipole). In open-circuit form (Fig. 2.1A) the equivalent length is the relevant sensitivity parameter for measuring the electric field $\vec{E}$. An example of this is the PPD (parallel plate dipole).

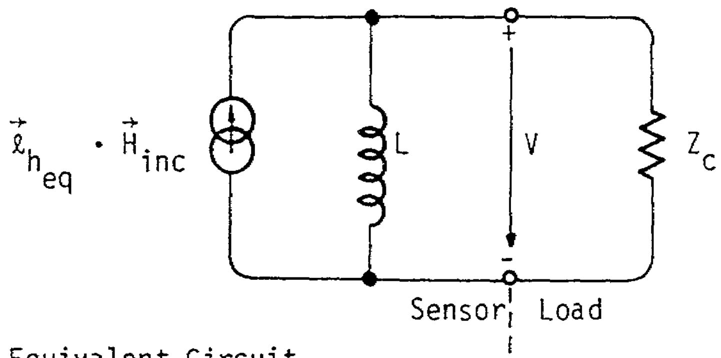
A special case is encountered in source regions with distributed source currents or in regions with nonlinear medium conductivity (such as in the EMP nuclear source region or in the immediate vicinity of a lightning arc). Again current density is easier to measure. The FMM (flush moebius mutual inductance) has been successfully used here, as well as a modified FPD design. Electric field (open circuit) measurements are considerably more difficult due to the requirement to sample the potential in the medium without significantly distorting the electric field in the vicinity of the sensor. With considerable difficulty this has been accomplished for EMP source regions with the PMD (parallel mesh dipole).

The basic parameters of the magnetic-field sensors are indicated in Fig. 2.2. The basic topology of such a sensor is a loop broken to connect to a terminal pair. The basic sensor parameters are related as

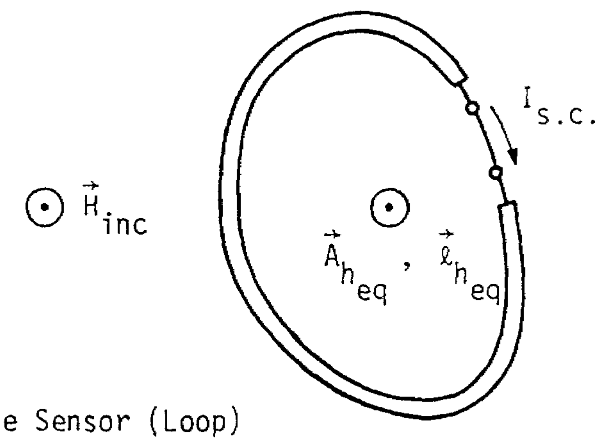
$$\begin{aligned}
\vec{A}_{h_{eq}} &= \frac{L}{\mu}\vec{\ell}_{h_{eq}} \\
\vec{A}_{h_{eq}} &\equiv \text{equivalent area} \\
\vec{\ell}_{h_{eq}} &\equiv \text{equivalent length} \\
L &\equiv \text{inductance}
\end{aligned} \tag{2.2}$$



a. Thevenin Equivalent Circuit



b. Norton Equivalent Circuit



c. Magnetic Dipole Sensor (Loop)

Figure 2.2. Electrically Small Magnetic Dipole Sensor in Free Space.

Again only two of the basic parameters are independent. The medium permeability μ is often that of free space, μ_0.

Various topological techniques involving transmission lines (cables) have been used in constructing the loop windings, giving a great deal of design flexibility. For high-frequency (transit-time-limited) applications the MGL (multi-gap loop) design has been quite successful. For lower-frequency applications the MTL (multi-turn loop) design is appropriate.

In conducting media and source regions it is important to insulate the loop conductors (for bandwidth) and to be careful with the choice of materials (for nuclear radiation transport). The CML (cylindrical moebius loop) design has been most commonly used for this application, although both TML (twin moebius loop) and MHL (multi-turn hardened loop) designs have been added for special applications.

Current sensors are a special category. An important class relies on an integral form of one of Maxwell's equations as

$$\oint_C \vec{H} \cdot d\vec{\ell} = \int_S \vec{J}_t \cdot d\vec{S} \equiv I_t \tag{2.3}$$

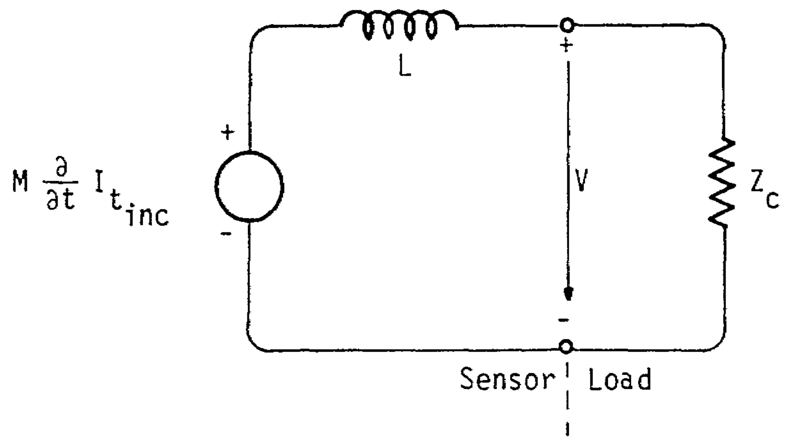
where $\vec{J}_t$ is the total current density passing through the surface S bounded by the contour C. As indicated in Fig. 2.3 the basic sensor concept is to measure the magnetic field (or usually its time derivative) at many places around an area through which the current of interest flows. Appropriately summing (or averaging) these measurements experimentally gives the total current through the area. Note that the total current density is just

$$\vec{J}_t = \nabla \times \vec{H} = \vec{J}_c + \vec{J}_\sigma + \vec{J}_\varepsilon \tag{2.4}$$

including source current density $\vec{J}_c$ (e.g., the Compton current density in an EMP source region), and the conduction ($\vec{J}_\sigma$) and displacement ($\vec{J}_\varepsilon$) current densities which may be even nonlinear in some circumstances. In linear, time-invariant, isotropic media we have

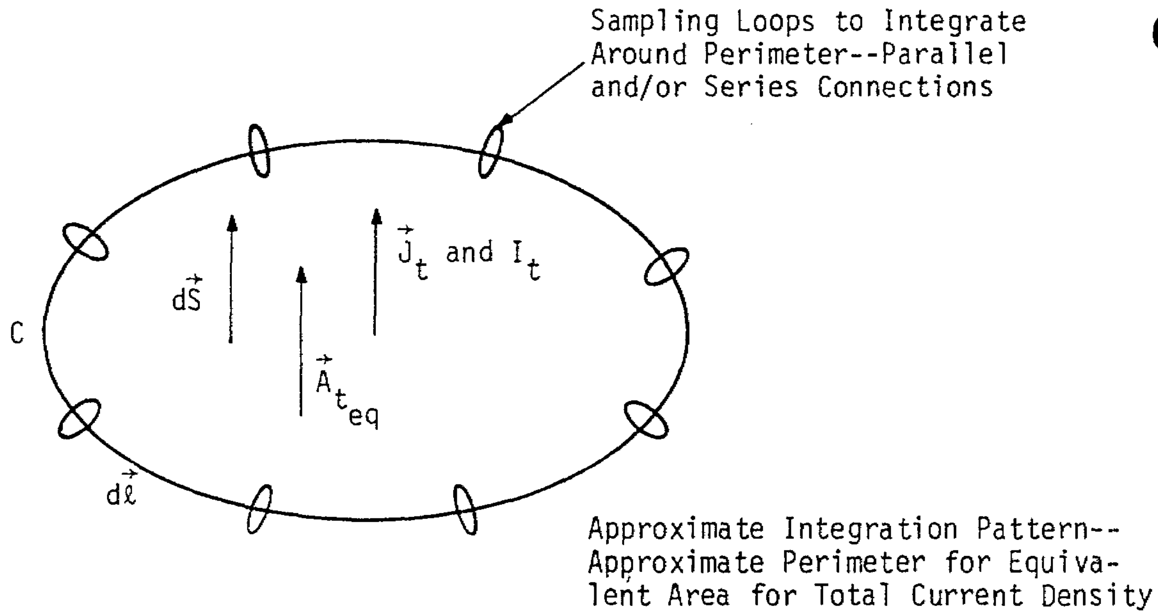
$$\vec{J}_t = \vec{J}_c + \sigma\vec{E} + \frac{\partial}{\partial t}\vec{D} \tag{2.5}$$

$$\vec{D} = \varepsilon\vec{E}$$



$I_{t_{inc}} = \vec{A}_{t_{eq}} \cdot \vec{J}_{t_{inc}}$ for Measurement of Distributed Current Density

a. Norton Equivalent Circuit



b. Inductive Current Sensor (Multiple Loops)

Figure 2.3. Electrically Small Inductive Current Sensor in Free Space.

Since this class of current sensors relies on magnetic field measurements the various loop design techniques are applicable here. However the sensor has to be also designed not to interfere with conduction and displacement current densities of interest. The CPM (circular parallel mutual inductance) is the basic high-frequency design for the time derivative of the total current. At lower frequencies multiturn designs are more appropriate and toroidal magnetic cores are often used. The ICI (inside core I) and OCI (outside core I) are examples of the latter type of design.

In conducting media and source regions this class of sensors also uses the insulation and materials choice as with the magnetic sensors. The basic high-frequency design comes in three versions depending on the location of the slot which lets the magnetic field into the toroid, depending on the topology of how the toroid is built into the conductors in the experiment of concern. There are the OMM (outside moebius mutual inductance), FMM (flush moebius mutual inductance), and IMM (inside moebius mutual inductance). The last type (IMM) is a direct example of the use of such devices in pulse power machinery, since it was developed for measuring electron beam currents inside circular conducting cylinders [8].

Voltage sensors are closely associated with electric-field sensors. Electric-field sensors typically measure the potential (voltage) between two conductors (highly conducting compared to the total medium conductivity) and relate this potential to the electric field through an equivalent length as in (2.1). Here we need only the potential difference itself. However, like an electric-field sensor, voltage sensors have bandwidth restrictions related to the definition of potential. As in Fig. 2.4 one has the voltage as a path integral of the electric field as

$$V = -\int_C \vec{E} \cdot d\vec{\ell} \tag{2.6}$$

where C connects points $\vec{r}_1$ and $\vec{r}_2$ on two separate conductors. However

$$\begin{aligned} &\vec{E} = -\nabla\Phi - \frac{\partial}{\partial t}\vec{A} \\ &\Phi \equiv \text{scalar potential} \\ &\vec{A} \equiv \text{vector potential} \end{aligned} \tag{2.7}$$

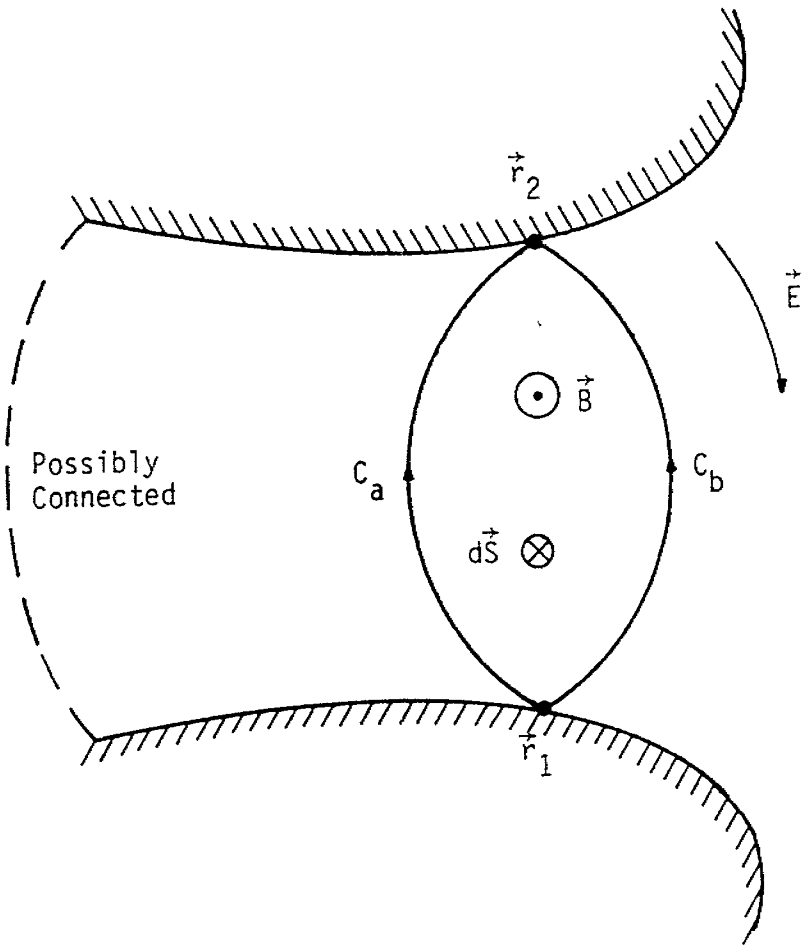


Figure 2.4. Voltage Sensor Definition.

giving (for stationary C)

$$V = \int_C (\nabla\Phi) \cdot d\vec{\ell} + \frac{\partial}{\partial t}\int_C \vec{A} \cdot d\vec{\ell}$$

$$= [\Phi(\vec{r}_2) - \Phi(\vec{r}_1)] + \frac{\partial}{\partial t}\int_C \vec{A} \cdot d\vec{\ell} \tag{2.8}$$

Now, if one has more than one possible contour, say C_a and C_b, then the corresponding voltages, V_a and V_b, are in general different as

$$V_a - V_b = -\int_{C_a} \vec{E} \cdot d\vec{\ell} + \int_{C_b} \vec{E} \cdot d\vec{\ell} \equiv -\int_{C_a - C_b} \vec{E} \cdot d\vec{\ell}$$

$$= \frac{\partial}{\partial t}\int_{C_a - C_b} \vec{A} \cdot d\vec{\ell}$$

$$= \frac{\partial}{\partial t}\int_{S_{a,b}} \vec{B} \cdot d\vec{S} \tag{2.9}$$

$S_{a,b} \equiv$ surface bounded by contour $C_a - C_b$

which is derived from either of

$$\nabla \times \vec{E} = -\frac{\partial}{\partial t}\vec{B} \quad (\vec{B} = \mu\vec{H})$$

$$\vec{B} = \nabla \times \vec{A} \tag{2.10}$$

Typically the contour of concern is near some electrical connection. However, one must be careful (at high frequencies especially) of regarding conductors as equipotentials for voltage measurements. Note that this definition even allows for the measurement of the voltage between two points on the same conductor (e.g., a loop) when $\Phi_a = \Phi_b$.

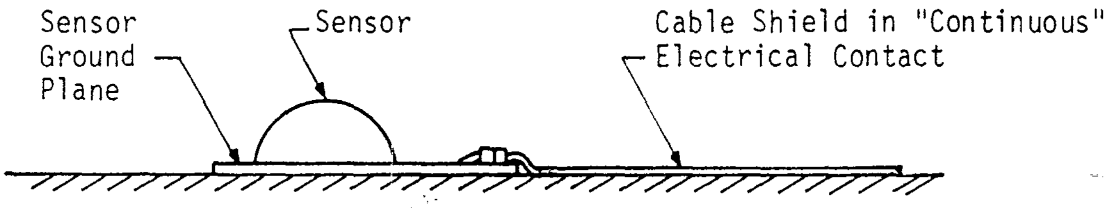
III. Topology of Instrumentation Cabling

The sensor is a fundamental part of an electromagnetic measurement system. However, the signal must be recorded in some way and the signal must be transported from the sensor to the recorder. Assuming that the recorder is distant from the sensor and that the signal is propagated by conducting cables (typically well shielded coaxial or twin-axial cables), one must fit these cables into the experimental configuration without disturbing the electromagnetic quantities of interest. Furthermore, one would like to minimize the current and charge-per-unit length magnitudes on the instrumentation cables to minimize the noise pickup with the recorded signal. This leads to a basic design concept for electromagnetic measurements:

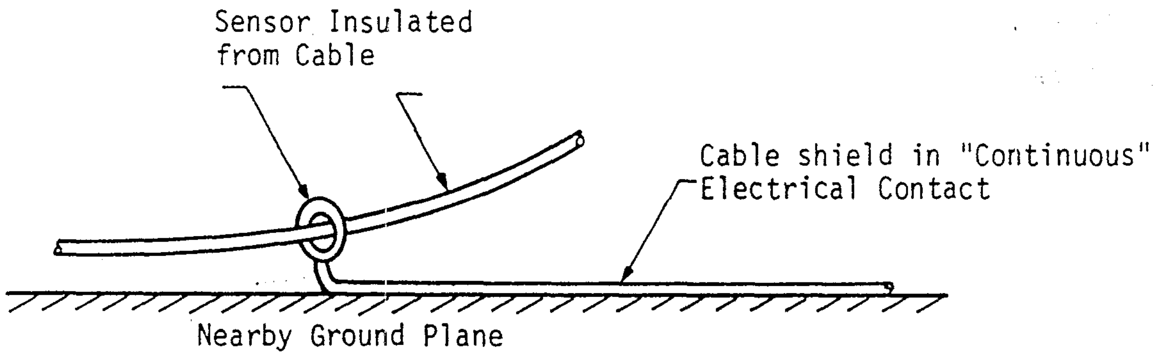
> Make the instrumentation cabling part of or shielded by the conductor topology [11,9] of the experiment.

Consider the case that the sensor is intended to measure an electromagnetic parameter on one of the good conductors present in the experimental configuration. Then this conductor becomes the local ground for the sensor as indicated in Fig. 3.1. Any conducting cable leaving the sensor should not protrude into the (upper) region containing the fields of interest (sampled in the measurement of interest). One can meet this requirement by running the cable shield along the conductor present and with approximately continuous electric contact to it. The cable then behaves (for exterior scattering purposes) as a small perturbation on an already present large conductor. Note that the sensor itself then utilizes this local ground plane as part of the sensor itself in that frequency response, accuracy, and field configuration are strongly influenced by this ground "plane."

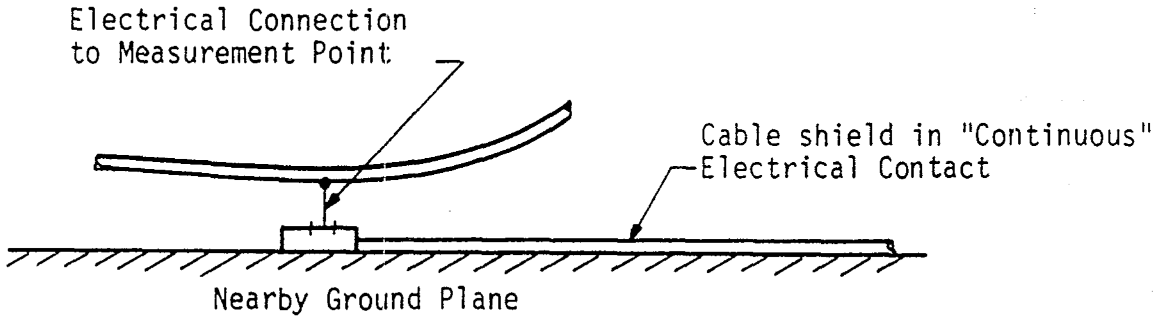
Continuing, the cable transports the signal from the sensor along the large metal conductor to somewhere else, where something is done to the signal. This somewhere else may have, perhaps, an oscilloscope or other recorder in a screen box (also well grounded to the original conductor) or perhaps some modulator which converts the signal to another frequency band and telemeters the signal to another location for demodulation and recording (as in Fig. 3.2A). Note that one must have frequent connections to the original conductor from sensor through screen box [5]. The spacing between connections should be less



a. Field Sensor: electric (surface charge density) or magnetic (surface current density)

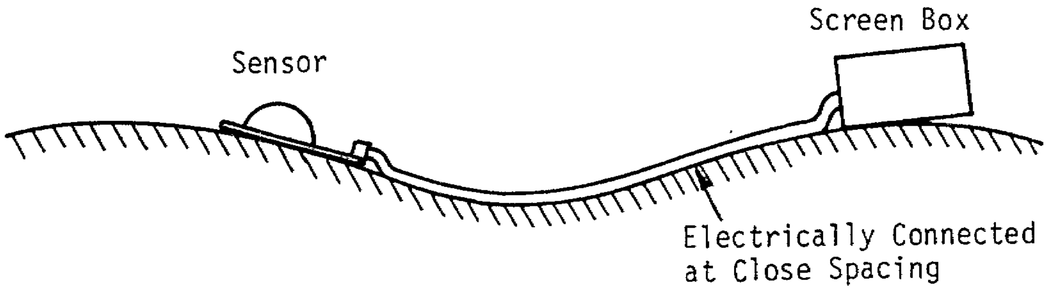


b. I or ∂I/∂t Sensor

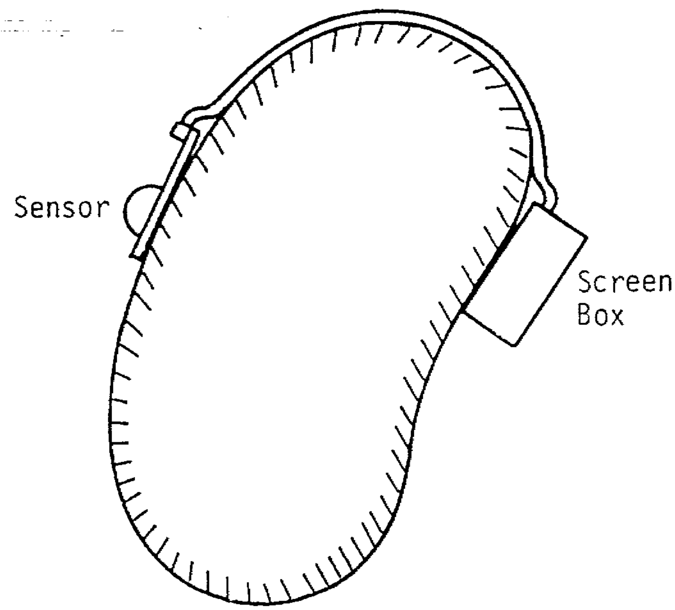


c. V or ∂V/∂t Sensor

Figure 3.1. Local Sensor Grounding Topology.



a. Conforming measurement conductors to experiment conductors



b. "Shadowing" sensor from screen box

Figure 3.2. Continuous Topological Grounding of Sensor/Transmission/ Recorder Conductors

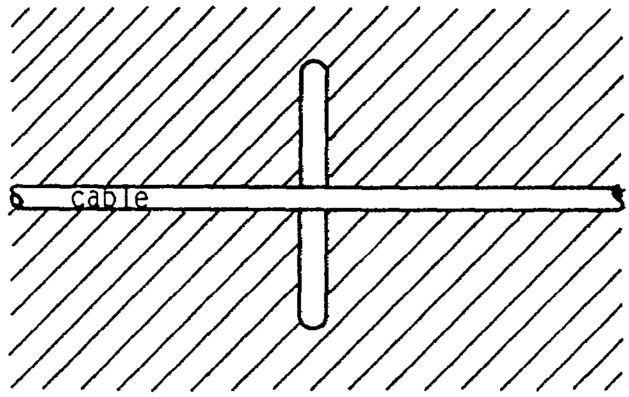
than a half wavelength at the highest frequencies of interest. In special places, such as near the sensor, as well as the sensor "ground plane" itself, it is good practice to increase the number of electrical connections to the original conductor.

In some cases one can further improve the measurement by locating larger objects, such as a screen box, at larger distances from the sensor to minimize the influence of the electromagnetic scattering from such objects to the sensor. As illustrated in Fig. 3.2B, one might position such objects in a place where the scattering to the sensor is shadowed by the original conductor. An example might be the positioning of sensor and screen box on opposite sides of an aircraft fuselage or wing.

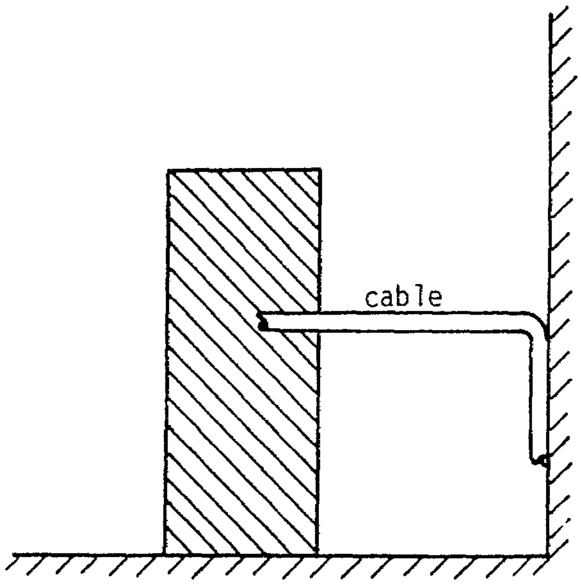
To further illustrate the above points, Fig. 3.3 shows unacceptable cable routing. Perhaps there is a long slot in the original conductor; the cable should be routed around it instead of across it. Perhaps one is measuring a signal in an equipment rack; one should avoid the temptation of jumping the cable from the rack to another structure (e.g., a wall); one should follow the rack conductors until (if and when) they electrically connect to other conductors (e.g., floor, conduit, etc.).

One can go a step further in some cases by using the original conductor of interest as a shield. Figure 3.4A shows the case that the original conductor of interest is locally approximately planar and serves as a shield in that the field(s) of interest on one side are large compared to the fields on the other side. Then on this other side instrumentation cables can be routed with minimal effect on the experiment and minimal noise pickup in the cables. The sensors are any that are mounted on (or near) ground planes with the cable now being fed through (with electrical connection to) the local ground plane.

Besides measuring local surface current and charge densities one might also measure such integral quantities as current and charge per unit length on or in cylindrical conductors as indicated in Fig. 3.4B and 3.4C. Suppose, as in Fig. 3.4B, one wishes to measure the current and/or charge per unit length on a circular conducting cylinder (such as a pipe or tube). Then one can insert appropriate sensors which preserve the electrical continuity (and hence shielding of the interior). By leaving a shielded passage through the center the instrumentation cables from various such sensors can be routed

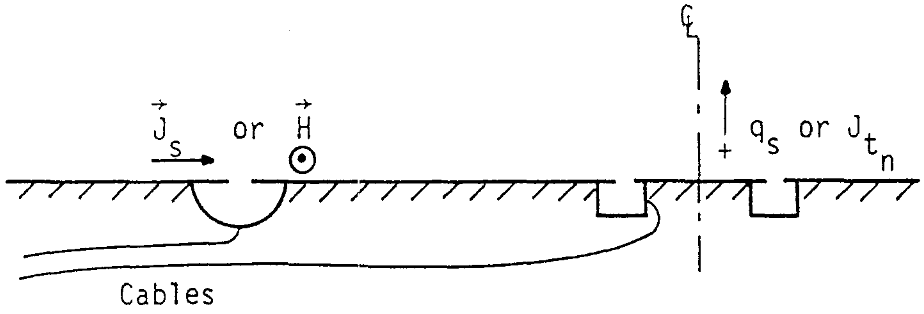


a. Crossing slot or other aperture

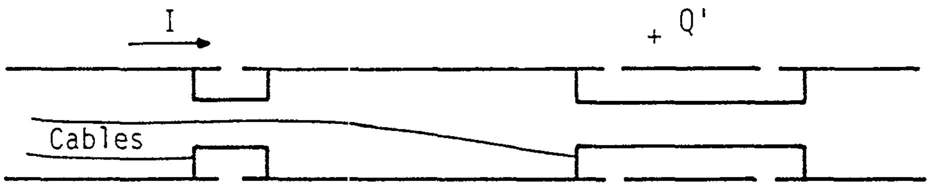


b. Jumping from one structure to another

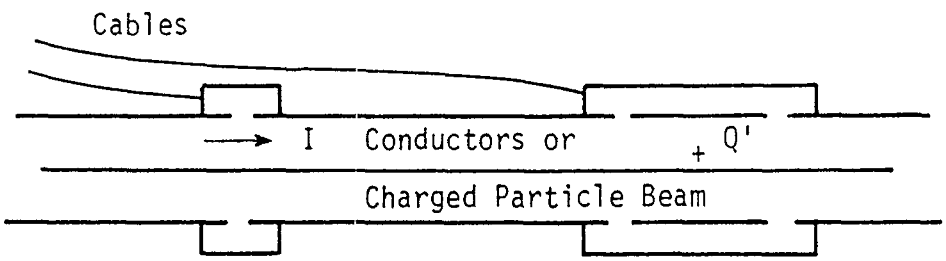
Figure 3.3. Unacceptable Cable Routing



a. Cabling behind ground plane



b. Cabling inside



c. Cabling outside

Figure 3.4. Cabling Shielded by Conductors of Experiment Topology.

through other such sensors to the recorders (or telemetering devices) without disturbing the measurements by these other devices.

Figure 3.4C illustrates the complementary problem in which the electromagnetic fields of interest are inside the conducting pipe. There is some current and associated charge per unit length propagating along or near the axis of the pipe. This may be via a conductor (as in the center conductor of a coaxial cable) or via energetic charged particles coming from some particle accelerator. Sensors can be built for this application which preserve the electrical continuity of the pipe, and thereby allow the instrumentation cables to leave by various routes from the pipe.

IV. Symmetry Considerations in Sensors and Instrumentation Cabling

Suppose now that one wishes to measure electromagnetic parameters at positions removed from the conductors in the experiment. What does one do with cables from the sensor? Symmetry of the sensor, cabling, and/or electromagnetic-field configuration can be used to minimize the errors associated with instrumentation-cable scattering. This leads to another basic design concept for electromagnetic measurements:

Configure the sensor and cabling such that

a. the cabling is orthogonal to the incident electric field (minimizes the scattering) and/or

b. the large field components scattered by the cabling exterior are orthogonal to the sensor response characteristics (sensor symmetry with respect to cabling).

Of course one may also choose to remove this cable scattering problem by removing the cable (such as by telemetering the data from the immediate vicinity of the sensor).

Symmetry is a powerful concept in that it allows one to make useful statements concerning some of the properties of a physical system, even a very complex one, without detailed calculation (whether analytical or numerical, recognizing accuracy limitations). If one had a highly conducting circular cylinder (boom) as the outer conductor of the cable or a conduit enclosing one or more cables, one might consider the two dimensional pure-rotation group C_∞ [10]. As in Fig. 4.1 such a sensor boom might have coordinate systems with origin at the sensor. Cylindrical coordinates (Ψ',ϕ',z') would have the z' axis as the axis of rotation for the circular cylindrical boom. C_∞ symmetry leads to $\cos(n\phi)$ and $\sin(n\phi)$ terms (integer n) for an infinite set of separate terms in the electromagnetic-field expansion in the presence of this boom.

The sensor, however, may not in general possess C_∞ symmetry with respect to the z' axis because of various other requirements in its design. Fortunately the main results of interest are achieved with a lower order symmetry, namely reflection (or planar) symmetry [10]. Consider planes containing the z' axis (e.g., the $x'z'$ and $y'z'$ planes) and note that these are symmetry planes for the conducting boom, and that some number of such planes (typically 2) can be symmetry planes of the sensor as well.

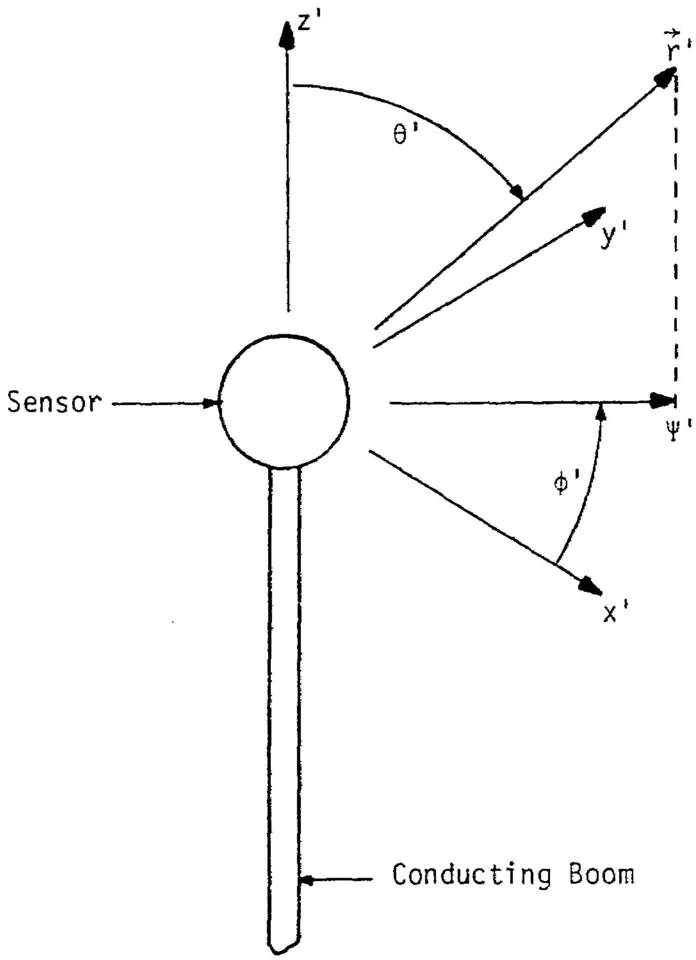


Figure 4.1. Coordinates for Sensor Boom.

Reflection symmetry, say group R, is illustrated by Fig. 4.2. The coordinate system in Fig. 4.2A has chosen our symmetry plane of interest as the xy plane which lets us define

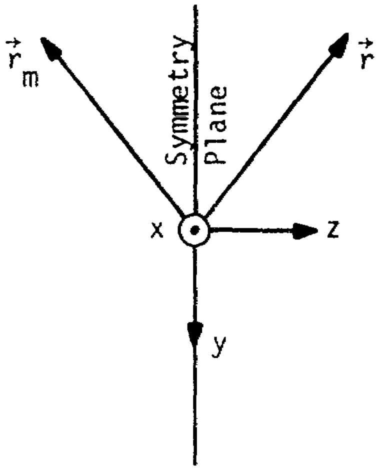
$$\begin{aligned}
\overleftrightarrow{R} &\equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{pmatrix} \equiv \text{reflection matrix} \\
&= \overleftrightarrow{R}^{-1} \\
\vec{r} &\equiv x\vec{1}_x + y\vec{1}_y + z\vec{1}_z \equiv \text{position or coordinates} \\
\vec{r}_m &\equiv \overleftrightarrow{R} \cdot \vec{r} \equiv \text{mirror position or mirror coordinates} \\
&= x\vec{1}_x + y\vec{1}_y - z\vec{1}_z
\end{aligned} \tag{4.1}$$

The function of the reflection matrix is to map each position into its "mirror image" through the symmetry plane. Having this symmetry plane apply to a sensor and boom means that whatever is at $\vec{r}$ is at $\vec{r}_m$ also; this whatever being typically conductors and insulators, at least as far as external scattering is concerned. This applies to tensor parameters such as permittivity, conductivity, and permeability (where used); such tensors are reflected from $\vec{r}$ to $\vec{r}_m$ by a similarity transformation using $\overleftrightarrow{R}$. This type of symmetry analysis is considered in much greater detail in a previous paper [1].

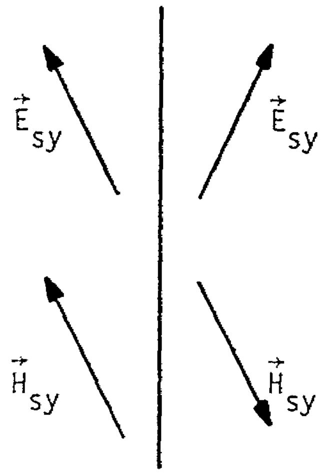
With respect to such a symmetry plane one can decompose electromagnetic fields, potentials, etc. into two uncoupled parts which we term symmetric (subscript sy) and antisymmetric (subscript as). For some of the common quantities we have

$$\begin{aligned}
\vec{E} &= \vec{E}_{sy} + \vec{E}_{as} && \text{(electric field)} \\
\vec{J} &= \vec{J}_{sy} + \vec{J}_{as} && \text{(current density)} \\
\vec{\rho} &= \vec{\rho}_{sy} + \vec{\rho}_{as} && \text{(charge density)} \\
\vec{H} &= \vec{H}_{sy} + \vec{H}_{as} && \text{(magnetic field)}
\end{aligned} \tag{4.2}$$

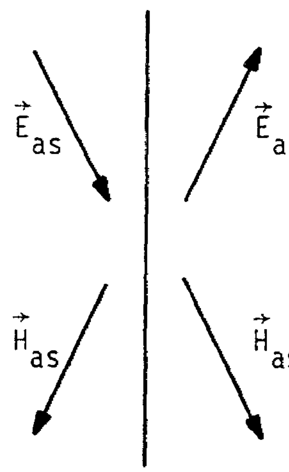
The construction of the symmetric and antisymmetric parts uses combinations of the fields at $\vec{r}$ and $\vec{r}_m$ [1].



a. Coordinates and mirror coordinates



b. Symmetric fields



c. Antisymmetric fields

Figure 4.2. Electromagnetic Symmetry with Respect to a Plane.

The symmetric part reflects as indicated in Fig. 4.2B. Note that the electric type vectors have tangential components continuous through the plane while magnetic type vectors have the normal component continuous. Specifically we have

$$\begin{aligned}
\vec{E}_{sy}(\vec{r}_m) &= \overleftrightarrow{R} \cdot \vec{E}_{sy}(\vec{r}) \\
\vec{J}_{sy}(\vec{r}_m) &= \overleftrightarrow{R} \cdot \vec{J}_{sy}(\vec{r}) \\
\rho_{sy}(\vec{r}_m) &= \rho_{sy}(\vec{r}) \\
\vec{H}_{sy}(\vec{r}_m &= -\overleftrightarrow{R} \cdot \vec{H}_{sy}(\vec{r})
\end{aligned} \tag{4.3}$$

The antisymmetric part reflects with exactly opposite signs as

$$\begin{aligned}
\vec{E}_{as}(\vec{r}_m) &= -\overleftrightarrow{R} \cdot \vec{E}_{as}(\vec{r}) \\
\vec{J}_{as}(\vec{r}_m) &= -\overleftrightarrow{R} \cdot \vec{J}_{as}(\vec{r}) \\
\rho_{as}(\vec{r}_m) &= -\rho_{as}(\vec{r}) \\
\vec{H}_{as}(\vec{r}_m) &= \overleftrightarrow{R} \cdot \vec{H}_{as}(\vec{r})
\end{aligned} \tag{4.4}$$

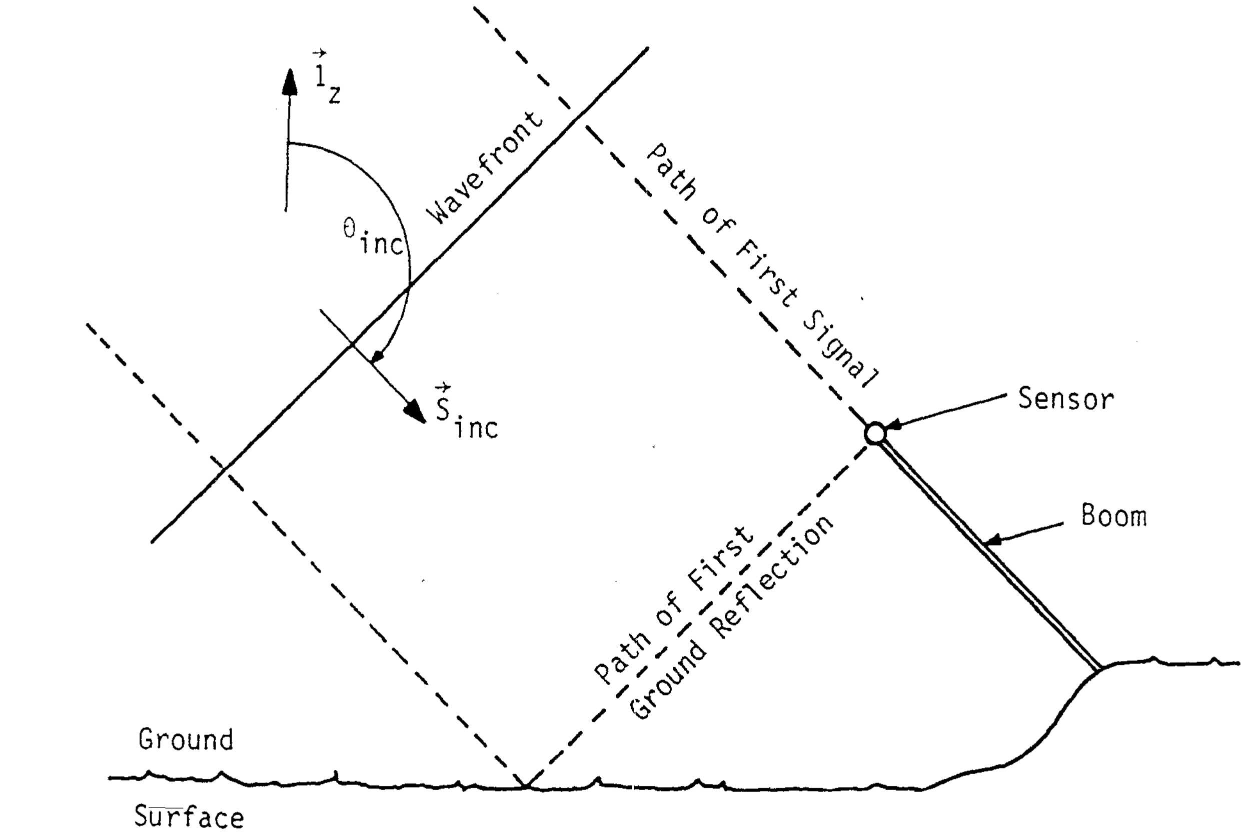
In this case normal components of electric type vectors are continuous through the plane as are tangential components of magnetic type vectors.

Consider now the scattering of an electromagnetic wave from a conducting plane. Note that the antisymmetric part has zero tangential electric field and as such is not scattered by the conducting plane. Only the symmetric part is scattered. Considering some plane containing the z' axis in Fig. 4.1, the antisymmetric fields have little scattering from a cable or boom of small cross section. It is the case of an electric field parallel to the cable which has a large scattering. An incident electric field with a large z' component constitutes a large symmetric part with respect to all planes containing the z' axis. Minimization of boom (or cable) scattering means having an antisymmetric field distribution with respect to two planes containing the z' axis (e.g., the x'z' and y'z' planes).

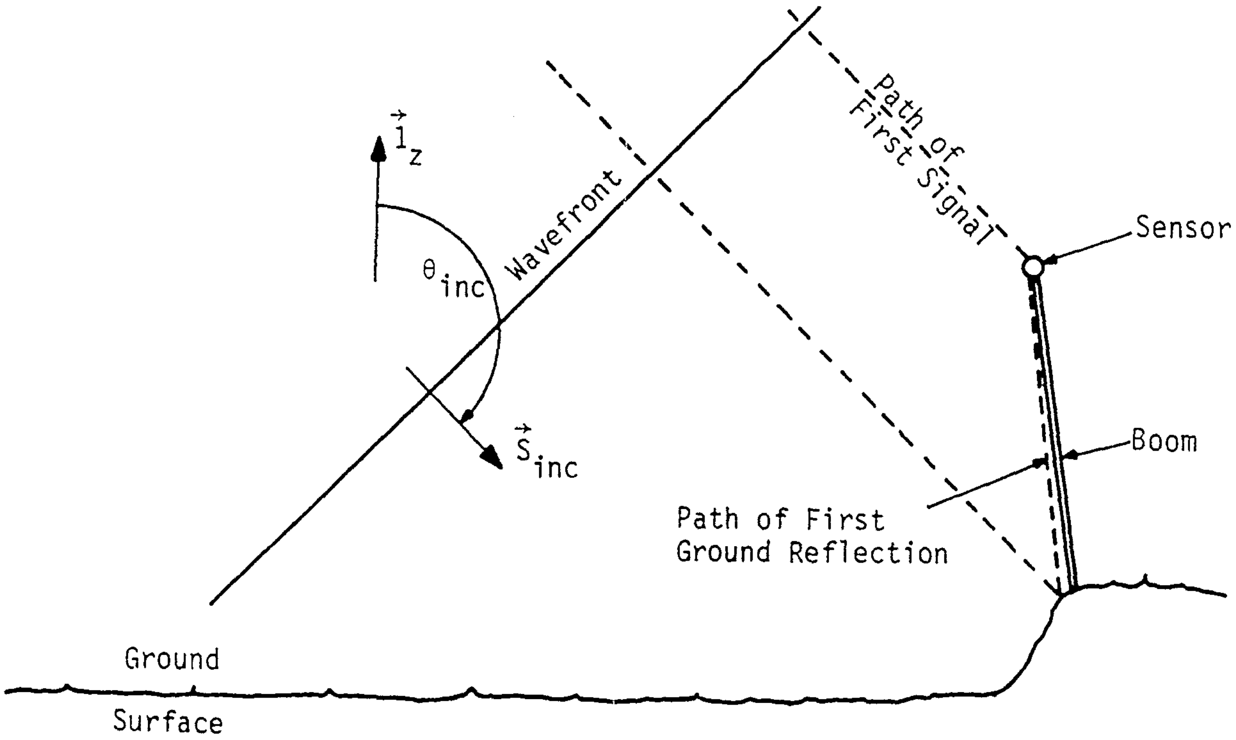
Enforcing the sensor to have two symmetry planes containing the z' axis also helps. Say there is an incident electric field with a z' component. One may still try to measure the x' and y' components and use sensor symmetry to ideally have no response to the z' component. However, since the scattering of a z' incident electric field is so large near the sensor one may still encounter signal-to-noise problems because of construction tolerances which introduce small distortions of the sensor from the desired symmetry.

In the case of the magnetic field the situation is somewhat better. The incident z' electric field produces a large charge near the end of the boom and on the sensor. However, the same position is also a current minimum (for net axial current) which implies a relatively small scattered magnetic field from the boom in the vicinity of the sensor. It is thus generally possible to measure all three components of the incident magnetic field in the usual dot product sense at the end of a boom. For the electric field only two components are possible in this sense, and with some signal-to-noise restrictions depending on the relative amount of z' incident electric field present and sensor precision in its symmetry.

Note that we have been only considering sensor and boom symmetry. One should also consider other scatterers which may be present. Figure 4.3 shows a sensor and boom mounted on the earth, say to measure the fields from an airborne EMP simulator [2]. In general this other scatterer (in this case the local earth topography, conductivity, etc.) may have no symmetry plane in common with the boom. However a transient wave has its leading edge propagate with the local speed of light in the media of concern. This allows one in many cases to have a measurement valid for a period of time (the "clear time") before reflections from these other scatterers can arrive at the sensor. During this "clear time" the foregoing symmetry analysis is still applicable.



a. On axis incidence



b. Off axis incidence

Figure 4.3. Modes of Operation of Sensor Boom.

V. Summary

Much is now known concerning the design of sensors for accurate measurement of electromagnetic-field parameters. These special antennas come in many varieties and can be used to measure various types of electromagnetic environments including those of EMP, lightning, pulse-power machinery, charged particle beams, etc.

Besides the techniques for design of such sensors one must properly integrate them into each experiment. Fundamental to such an integration are the concepts of electromagnetic topology and symmetry of the sensor and/or fields with respect to scattering conductors such as sensor cables.

For many details the reader may consult the references of this paper and [3].

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