Sensor and Simulation Notes

Note 362

August 1993

STANDARD CALIBRATION METHOD for ELECTROMAGNETIC FIELD PROBES

Gary D. Sower
EG&G Special Projects
Albuquerque, NM

ABSTRACT

*This report proposes that a calibration method for electromagnetic field sensors be used wherein **the sensor under test be directly compared, by substitution, to a reference standard sensor.** The use of a reference standard removes any ambiguity in the calibration of the test cell, signal source, and recording instrumentation, in essence calibrating the field to a high accuracy and precision. Broad-band reference standard sensors can be made to a very high degree of precision, with their sensitivity (transfer function) entirely and completely determined by their geometry, making them primary standards for field measurements. The complete transfer function (frequency domain) and impulse response function (time domain) can be determined for these reference standard sensors, thus allowing for deconvolution processes to be used to remove instrumentation and test cell (field) transfer functions from the calibration of the sensors and sensors.*

1. INTRODUCTION

The problem in the calibration of electromagnetic field sensors is that there does not exist a standard technique for the generation of known fields. This results in the situation that presently exists wherein sensors from different manufacturers, or different sensors from the same manufacturer, can give greatly different responses to the same measurement, even though they are both supposedly calibrated and should give identical responses, at least to within the specified calibration and sensor accuracy.

The Introduction to reference [1] contains a particularly appropriate, perhaps even understated, description of the situation:

> In designing electromagnetic-field sensors one is concerned with the question of accuracy. How well does one know the relationship between the electromagnetic field (or its time derivative) and some voltage or current delivered to some terminal into some specified impedance? Here we are considering passive geometric structures (antennas) which (among other things) have accurately calculable quasi-static response parameters. Given the basic parameters in the constitutive equations (μ_0 by definition, ϵ_0 from the speed of light c known to many significant figures), then with the Maxwell equations one can design some such sensors that are "calibratable by a ruler".
>
> One can, of course, expose the sensor to some standard field, current, etc., but this begs the question. What calibrates the calibrator? This is some device which establishes some electromagnetic-field configuration when driven (at one or more terminals) by electrical source(s). A fundamental electromagnetic principle here is reciprocity which relates the response of antennas in transmission and reception (providing non-reciprocal media are not used, the typical case). The accuracy of the transmitting antenna (field producer) and sensor (field receiver) are comparable geometric (ruler) problems. If there is some disagreement between transmitter and receiver, which one is in error? Perhaps both are in error. In principle it is no more difficult to make a standard sensor than a standard electromagnetic source. For both the use of special calculable geometries with error estimates for how well one realizes these geometries is essential.

2. GENERATION OF STANDARD FIELDS

For most of the frequency band of interest, tens of kilohertz to tens of gigahertz, the generation of electric and magnetic fields cannot be separated. The generation of one field component by means of voltages or currents on a conducting structure results in both charges and currents flowing on the structure, related by the continuity equation, which thereby generate all field components. It is therefore best to deliberately generate a known **electromagnetic** field, specifically such that the ratio of the magnetic-to-electric field is well known and constant.

One usual method of calibration is to place the sensor in a transmission line test cell that is designed to propagate the **transverse electromagnetic mode (TEM)**, drive the cell with a known stimulus, and measure the sensor response. This type of cell, known commercially as the "TEM cell" (sometimes as the "Crawford cell"), is sometimes used as a reference standard. This type of calibration is common for the broad-band sensors, the response of which is designed to operate across at least one decade of frequency, perhaps several decades. The ones with the greatest bandwidth are often used for transient measurements.

In the radar and microwave community, the calibration method is to use an open field or an anechoic chamber, with transmit and receive antennas set at various separations, directions, and polarizations. Errors arise from the uncertain calibration of the reference antenna (whichever one, unless they are identical), and from reflections from the ground, walls, and/or antenna support structures. These are usually narrow-band sensors, covering perhaps an octave of frequency.

The use of a transmission line cell for the calibration of EM sensors and sensors is certainly a viable technique of choice, regardless of whether the cell is a TEM cell **[2,3]**, a GTEM cell **[4]**, a two-plate transmission line **[5,6]**, or some other design. The bounded wave nature of transmission-line fixtures is conducive to the properties required for calibration, namely having the desired field response over the desired bandwidth (with appropriately sized structures) and stability of the produced fields.

However, the assumption that the fields within the cells are deterministic and calculable is simply not valid. The "calibrated field" cannot be accurately calculated from the input voltage and the cross-section geometry of the cell. Such calculations assume that the cell is infinitely long, without source and termination connections and the effects associated with such. Reflections and standing waves always exist within a TEM cell, at all frequencies, because it is impossible to build a structure which terminates all frequencies in a perfectly matched load. The cells do not produce electromagnetic fields which can be considered to be standards.

The TEM cell is designed to be a transmission line enclosure which supports transverse electromagnetic (TEM) waves, and hence generates a known field distribution based upon its geometry. The geometrical discontinuities inherent in its design generate reflections, diffraction, mode mixing, *etc.* which significantly perturb the ideal field distribution. In one form, these manifest themselves as spectral nulls, which vary with location and frequency, causing the "calibration" of sensors to give irreducible results. Viewed in another form, the signal introduced into the chamber will bounce around within it, in a manner similar to that of ray optics, with a significant portion of the incident energy eventually dissipated in the walls of the chamber, never reaching either the output load nor the input connector. S_{11} measurements of the input port might thus show a low SWR value across a broad frequency band, but S_{21} measurements will not indicate the same low SWR; the difference between S_{21} and S_{11} is not unity as in a lossless transmission line. Electric and/or magnetic field measurements made along the length of the working volume, similar to standing wave measurements on microwave slotted waveguides, show large standing waves within the chamber, with resulting frequency-dependant peaks and nulls. Furthermore, the characteristics are different for the electric and magnetic fields, indicating that very significant non-TEM modes exist within the cells.

The SWR problem exists for CW measurements. For time domain measurements, which characterize the sensor by its impulse response function, reflections within the test cell do not have to perturb the data, provided that the input section of the cell is electromagnetically "clean." This means that only the TEM wave is propagated within this section without impedance discontinuities and/or scattering structures (including bends and corners in the cell conductors). It also means that the cell is clean for a sufficient distance past the sensor port that reflections do not occur within the sensor response time, and can be gated out of the data waveform.

Comparison of the sensor under calibration to a reference sensor of about the same size and located in exactly the same position within the test cell is essential to the calibration process:

- The sensor undergoing calibration must measure the same field vector as the reference standard sensor.
- The size requirement occurs because of the interaction of the fields scattered from the sensor with the cell conductors, which changes with differently sized conductive elements in the sensors [7].
- The location requirement occurs because of the variation of the electromagnetic fields with position within the cell.

3. TYPES OF MEASUREMENTS

The calibration procedures discussed here are applicable to techniques in both the frequency domain (CW, swept CW, stepped CW, white noise) and in the time domain (impulse, step, damped sine). The results obtained using any one method can be applied to any other by the appropriate mathematical processes (Fourier transforms). The generation of the signals with which to produce the fields (CW signal generator, network analyzer, impulse generator, step generator, random-noise generator) and the measurement of the signals from the sensors (spectrum analyzer, network analyzer, transient digitizer) are relatively straightforward with modern equipment.

Most of the sensors that require calibration are **broad-band**. This may mean anything from an octave in frequency to several decades of useful bandwidth. This implies, for reasons of hardware and personnel utilization optimization (cost), that the calibration process utilize equipment which can automatically cover a multitude of frequencies, rather than a single continuous frequency at a time.

This broadband requirement precludes the use of standard half-wave dipoles as the primary standards. These can, however, be used as single-frequency calibration checks on the broadband reference standard sensors and on the field sensors.

4. SENSOR TYPES

There are four kinds of electromagnetic field quantities that are directly related by the Maxwell equations and constitutive relations, forming a cyclic set of physical quantities as shown in Fig. 1, excluding source terms, from **[8]**. These quantities are the **electric field** (V/m), **current density** including the **displacement current** $\partial D/\partial t$ (A/m^2), **magnetic field** (A/m), and **voltage density** (V/m^2). The first two are **electric dipole** quantities and the last two are **magnetic dipole** quantities. The first and last form **current type** quantities and the middle two form **voltage type** quantities. Sensors are constructed to measure all of these quantities.

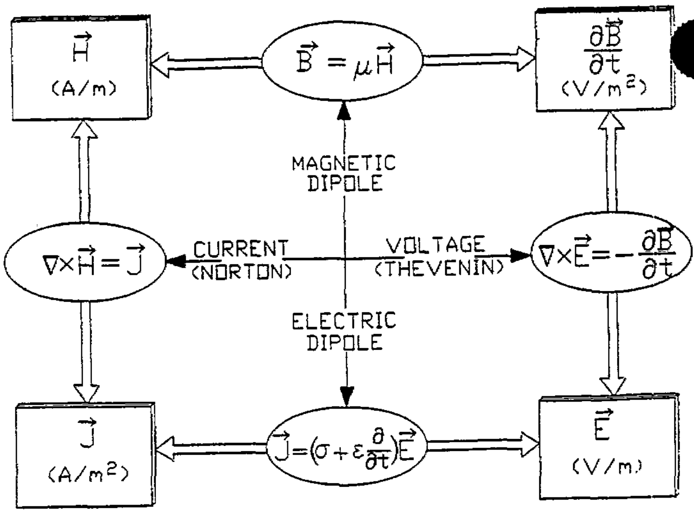


Figure 1. Diagram of Basic Electromagnetic Quantities.

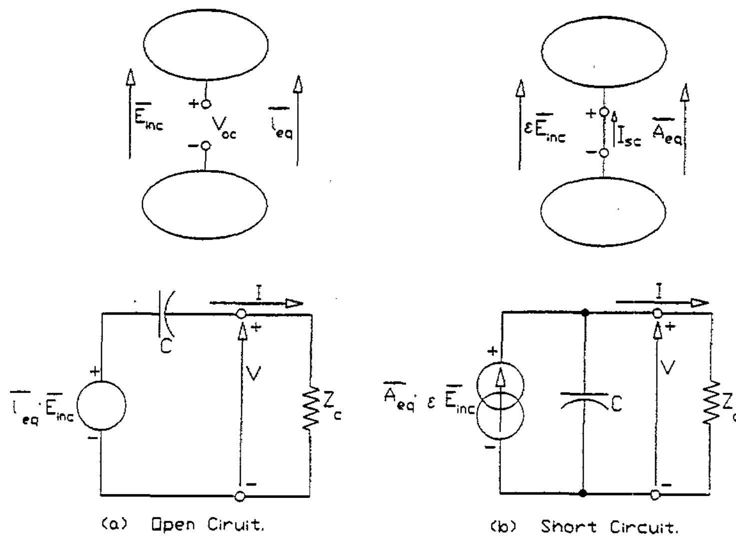


Figure 2. Electric Dipole Probe: Equivalent Circuits.

Electric Dipole

For the measurement of local electric field and total current density quantities, the electric dipole sensor (dipole due to reciprocity between transmission and reception) is used as indicated by Fig. 2. The equivalent circuits are for the case where the sensor is electrically small. The Thevenin and Norton equivalent circuits correspond most conveniently to open-circuit and short-circuit conditions where the magnitude of the load impedance Z_c (50 or 100 ohms) is large or small, respectively, compared to the magnitude of the source impedance $1/sc$ where s is the (Laplace) complex frequency. For open-circuit purposes, the sensitivity is characterized by a constant equivalent length ℓ_{Eeq} (a vector) which samples the incident electric field in a dot product sense. For short-circuit purposes, the sensitivity is characterized by an equivalent area $\mathbf{A}_{Eeq}$ which samples the incident current density (displacement current vector in free space) in a dot product sense (the area of flux intercepted by the sensing elements). ℓ_{Eeq}, $\mathbf{A}_{Eeq}$, and C are defined by the asymptotic form of the response in the electrically small sense. These parameters are not independent but are related by:

$$A_{Eeq} = \frac{C}{\epsilon_0}\,\ell_{Eeq} \ ,$$

with ϵ_0 as the permittivity of free space.

Magnetic Dipole

For magnetic quantities, the magnetic dipole sensor (loop) is used as indicated in Fig. 3. The equivalent circuits are for the case where the sensor is electrically small. The open-circuit and short-circuit again correspond to conditions where the magnitude of the load impedance Z_c is large or small, respectively, compared to the magnitude of the source impedance sL. For open-circuit purposes, the sensor sensitivity is characterized by a constant equivalent area A_{Heq} which samples $\partial \boldsymbol{B}/\partial t$ in a dot product sense (the area of the loop). For short-circuit purposes, the sensitivity is characterized by an equivalent length ℓ_{Heq} which samples the incident magnetic field $\boldsymbol{H}$. These parameters are related by:

$$A_{Heq} = \frac{L}{\mu_0} \ell_{Heq} ,$$

with μ_0 as the permeability of free space. Again, these parameters are defined by the asymptotic form of the response in the electrically small sense.

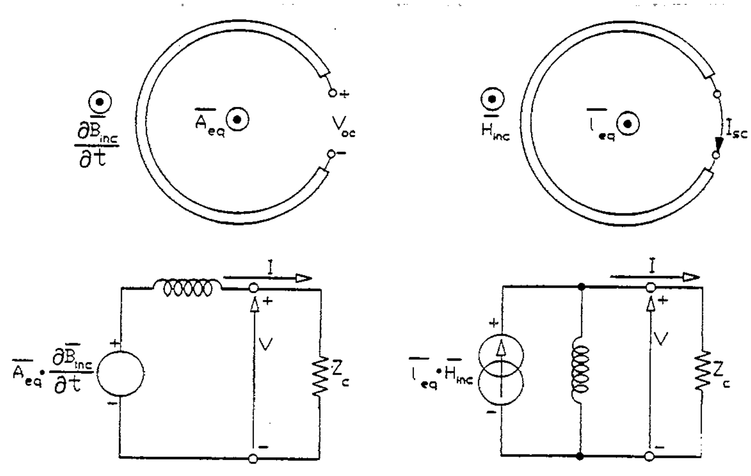


Figure 3. Magnetic Dipole Probe: Equivalent Circuits.

The equivalent area can be accurately calculated for several versions of electric and magnetic field sensors. The equivalent length in general cannot be calculated to the same degree of accuracy. The capacitance can be accurately calculated for a few types of electric field sensors, allowing for the equivalent length to be accurately known only for these types. Likewise, the inductance can be accurately calculated only for a very few types of magnetic field sensors; unfortunately these types are generally of high inductance and therefore of limited bandwidth. It is therefore generally true for broadband sensors that the derivative sensors which utilize an equivalent area to sample a current or charge density are more accurate than those sensors which directly sample the fields by an equivalent length.

5. REFERENCE STANDARD SENSORS

In most branches of metrology, calibration is performed by comparison of the object under calibration to some primary standard, usually by the use of transfer or reference standards. The calibration of electromagnetic sensors and sensors should therefore utilize some form of primary or reference standard sensor for the measurement of the electric or magnetic field. Such a sensor should not itself require a field for calibration, but should be calibrated in some other (non-electromagnetic) manner, traceable to NIST and international standards.

Two general methods are applicable to the measurement of field strength, see **[9]**, from which is quoted:

> One method consists of measuring the received power or open-circuit voltage induced in a standard receiving antenna by the EM field to be measured, and then computing the field strength in terms of the measured power or voltage and the dimensions and form of the standard receiving antenna. The other method consists of comparing voltages produced in an antenna by the field to be measured and by a standard field, the magnitude of which is computed from the type and dimensions of the transmitting antenna, the net power delivered to the transmitting antenna (or its current distribution), the antenna separation distance, and the effect of the ground. For the standard receiving antenna method, there are special requirements for the antenna and the power or voltage measuring equipment. Field-strength measurements are often made using commercially available meters that have been calibrated in a known field determined by either of the two above methods, A calibration service is maintained by the National Institute of Standards and Technology for field strength meters in the frequency range of 30 Hz to 30 GHz. For information, write to the National Institute of Standards and Technology, Electromagnetic Fields Division, 325 Broadway, Boulder, CO 80303, USA.

The first of these methods, the standard receiving antenna (reference standard sensor) is the preferred method because it relies on the intrinsic self-calibration properties of the standard sensor and not on the field strength of some transmitting antenna or test cell, which is inherently much less accurate.

A reference standard sensor is defined as a special kind of transducer (antenna) with the following properties:

> It is an analog device which uses one of the Maxwell equations to convert the electromagnetic field vector of interest to a voltage or current signal across a specified load impedance.
>
> It rejects all other electromagnetic field quantities. The signal is generated in the sensing element by a vector dot product between the incident field component and the sensor equivalent area vector, which is aligned along its axis of rotational symmetry. Orthogonal field components are therefore not sensed. The sensors are also designed so that signals generated by the other field (in particular electric field pickup on a magnetic sensor loop) are canceled within the sensor.

It has a minimum perturbation on the incident electromagnetic field in that it extracts a minimum of power from the field and produces a minimum scattered field. This is in contrast to a normal electromagnetic receiving antenna which is designed to intercept as much power as possible from the field.

As a primary standard, it has a minimum of field enhancing/excluding support structures, such as ground plates. It is a laboratory standard and may be delicate due to its lack of robust features.

It is passive. No electronics, either active or passive, are incorporated within the sensor so that its calibration is unaffected by such. Signal conditioning devices are separate entities which can be calibrated by conventional methods.

Its sensitivity is determined only by its geometry, as mathematically related to the Maxwell equations. In this sense it can be considered to be a primary standard because its sensitivity is traceable to the international standard meter. It is "calibrated by a ruler," and is thus inherently more accurate than any calibration system.

It is designed to have a specific, convenient sensitivity. The sensitivity of the standard sensors is an area vector with dimensions of square meters. For convenience this sensitivity is usually expressed as a round number, such as 1×10^{-4} m^2.

Its transfer function is simple across a wide frequency band. For most of the sensors this means that the output signal is proportional to the time derivative of the incident field, from DC up to the specified upper bandwidth of the sensor.

It is optimized to have the largest possible bandwidth. This is done by minimizing both the sensing element reactance and transit times. The high-frequency rolloff is also designed so that it is "maximally flat", giving the fastest risetime with minimum overshoot and ringing (optimum pulse fidelity).

The roll-off with frequency at the ends of the sensor bandwidth can be accurately characterized. For a true primary standard, this response should be representable by an analytical formula in both the time domain and the frequency domain.

Fortunately, it is possible to make such sensors, both for electric and magnetic fields, which are "calibrated by a ruler", that is, their sensitivity is determined strictly by their geometry and is thus traceable to the International Meter. Many references **[10-23]** describe sensors in the form of electric and magnetic dipoles which have sensitivities that are mathematically calculable from their shape, size, and Maxwell's equations. In actual practice, such sensors have small errors due to field perturbations from their mechanical structures. These errors can be bounded by worst-case calculations of the field enhancement or exclusion, and can typically be made acceptably small **[1,22]**.

In addition to an accurate knowledge of the sensitivity of the reference sensor, it is desirous to know the characteristics of its frequency rolloff at both ends of its bandwidth; in the time domain this is equivalent to knowing its impulse response function. This has been determined to an accuracy of about 1.0 percent (0.1 db) for one of the electric dipole sensors referenced above, the Asymptotic Conical Dipole (ACD) **[12,19,23]**. The absolute accuracy of this commercially-available sensor is less than two percent (0.2 db) across its entire usable bandwidth; laboratory standards can be made with significantly more accuracy. The Phillips Laboratory (Kirtland Air Force Base, NM 87117) is presently developing primary standard Asymptotic Conical Dipole D-dot sensors (ground-plane versions) with an absolute accuracy of less than 0.1 percent (0.01 dB), with dimensions traceable to NIST. These will allow the production of **transfer standard** ACD sensors (ground-plane) with absolute accuracy of 0.5 percent and production ACD sensors of accuracy 1.0 percent. It will also allow for the development of transfer standard magnetic field sensors of 0.5 percent accuracy (ground-plane).

The magnetic sensors can be compared to the electric field sensors in a test cell, provided that the field is TEM only for the duration of the measurement. This can be accomplished with a cell which has a very "clean" input section so that no reflections occur from the sides of the cell. The clean section must extend beyond the sensor port so that an adequate clear time exists between the incident field and the first reflection from the end of the cell (termination). This technique only works in the time domain, using impulse transfer function measurements. The concept of a clear time does not extend to the frequency domain.

Sensors are presently made which cover the frequency range up to about 10 GHz. Extending the frequency range to 40 GHz will require the manufacture of sensors that are a factor of four smaller in dimensions, The inherent accuracy of these smaller sensors will be less than that of the larger ones because of the relative fabrication and assembly errors.

The sensors are constructed with coaxial cables inside of them, both 50 ohm and 100 ohm semi-rigid cable used depending upon the particular model. The highest frequency sensors are necessarily small (so that the sensing elements are electrically small), which dictates the use of small cables. These small cables have more loss than the larger ones, particularly at the higher frequencies at which they are used. This loss can be factored out of data acquired by these sensors, either by a cable compensator circuit of analytical calculations of the acquired data.

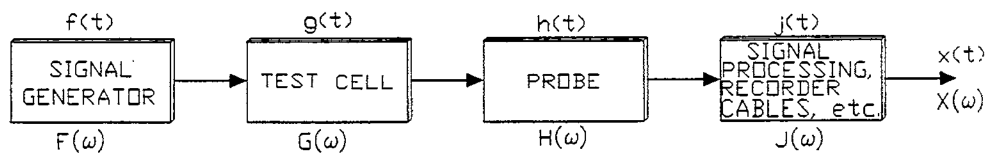
The sensors have been described as more accurate than any system could be made in which to calibrate them. Their accuracy is limited only by the machining and assembly tolerances of their construction, by the exclusion of transient magnetic fields from conductors of magnetic field sensors, and by small field enhancements from ground plates and from dielectric support structures. The tolerances can be made much smaller than one percent. The enhancement effects for the ACD have been measured to an accuracy of about one percent, for which the sensitivity is compensated. They are presently about 2 to 10 percent for the MGL models. The capability now exists to measure these enhancements more accurately.

Electromagnetic fields cannot be generated which are accurate enough to calibrate the sensors. However, extremely repeatable fields from pulse to pulse and over long periods of time are possible. With such, the sensors can be directly compared to each other or to modifications in the enhancement factors, with an inherent accuracy significantly less than one percent.

6. DECONVOLUTION

For very accurate measurements, the perturbations to the data by the measurement system can be removed by deconvolution techniques [24,25]. The **transfer function response** of the entire data system, including the reference standard sensor, is first determined. This total transfer function is the product of the individual transfer functions of each piece of hardware: the signal generator, the test cell (for the particular location of the sensor), the reference standard sensor, and the recording instrumentation, as detailed in Fig. 4. The transfer function of the reference standard sensor is known *a priori*, and is divided out of the total transfer function to give the measurement system transfer function. Data are then taken with the sensor undergoing the calibration in the system, giving a new total transfer function. Dividing by the *a priori* system transfer function obtained above yields the transfer function calibration of the sensor.

This process also works with data taken in the time domain. The recorded result in the time domain is that of the convolution of the **impulse response function** of each piece of equipment. When Fourier transformed into the frequency domain, it is the transfer function response. The above process is then performed in the frequency domain to obtain the transfer function calibration of the sensor. This is then reverse transformed to obtain the time-domain impulse response function calibration. This deconvolution process is easy to describe and understand, but difficult to achieve in practice; much effort has gone into its practical realization.



$$x(t) = f(t) * g(t) * h(t) * j(t) \xrightarrow{FFT} X(\omega) = F(\omega) + G(\omega) + H(\omega) + J(\omega)$$

For Reference Probe, $h(t) = r(t)$ and $H(\omega) = R(\omega)$
These are known and well behaved. Measure $X_1(\omega)$

System Response: $S(\omega) = \dfrac{X_1(\omega)}{R(\omega)}$

With Unknown Probe, $h(t) = p(t)$ and $H(\omega) = P(\omega)$
Want to find $p(t)$ and $P(\omega)$ Measure $X_2(\omega)$

Probe Response: $P(\omega) = \dfrac{X_2(\omega)}{S(\omega)} \xrightarrow{IFFT} p(t)$

$S(\omega)$ must be well behaved (no spectral nulls)

Figure 4. Transfer Function Tree of Probe Calibration.

7. SENSOR TYPES

The above discussion on reference sensors and test cells is equally applicable to free-field sensors and ground-plane sensors. The calibration of the free-field versions is inherently more difficult because of the problem of getting the signal out of the test cell without significantly perturbing it with the cable or signal transmitter connected to the sensor.

For the ground-plane versions, the signal connector or cable can be made to penetrate the cell floor in some acceptable manner. The attachment of the sensor ground plate to the cell wall or floor can be made in a way commensurate with the sensor design. The following discussion is equally applicable to electric-field and magnetic-field sensors.

There are two methods of attaching the connector to ground plane sensors: it can be located above the ground plane, attached to the ground plate as shown in Fig. 5a, or it can be located below the ground plane, attached to the back side of the ground plate as in Fig. 5b. The first method is the more common because the sensor can be put on a test object without modifications to the object. The second method requires a hole in the test object at the measurement point; this method usually gives a better measurement of the field because it perturbs the environment less(field scattering), and because the signal cable (usually) is exterior to the field environment and is thus not susceptible to coupling pickup. The reference standard sensors are of this type.

With the signal cable inside of the test environment, care must be taken that the cable does not perturb the ambient environment and that it does not pick up significant signals that couple into it. In particular, the cable must not form ground loops with the existing conducting body of the test object, nor must it form a large electrical antenna. The best method of routing such a cable is to electrically bond it to the existing metal structure as often as possible, for which copper tape with conducting adhesive is commonly used. Another successful method is to load the exterior of the cable with ferrite beads, which present a high impedance to electrical currents flowing over it. For calibration purposes, the cable should exit the test cell at the first opportunity, such as with a short service loop to a bulkhead connector as in Fig. 5.

For certain types of electromagnetic field sensors which include signal processing electronics, the output signal may propagate over an electrically isolated (fiber optic) path or a high impedance cable. The field perturbation and signal interference are minimized with these sensors.

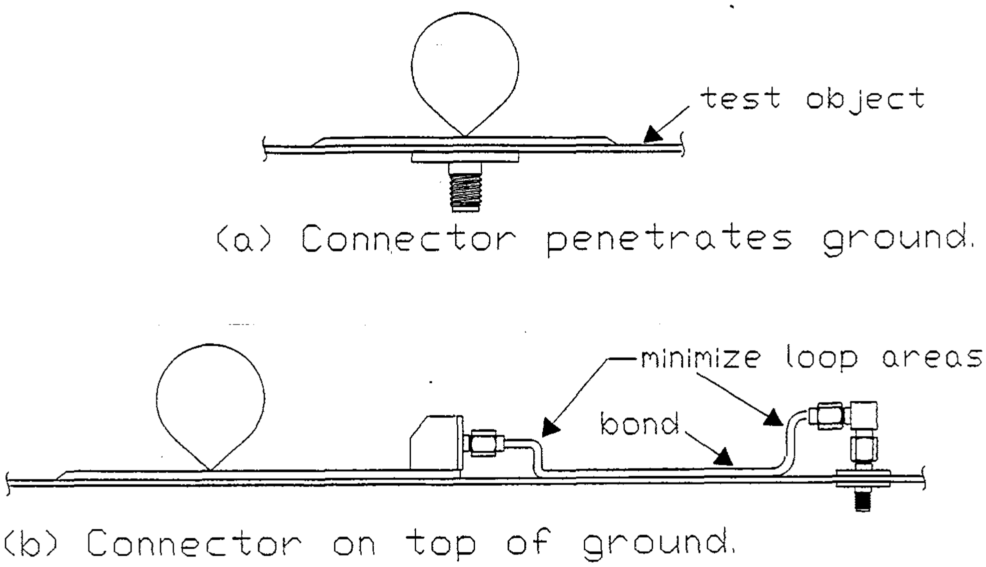


Figure 5. Ground Plane Probe Connections.

8. ERRORS

Errors associated with the sensor calibration process include the following:

1. Accuracy of Primary Standard Sensors . . . . 0.1% (0.01 dB)
   Fabrication and assembly of the sensor sensing element(s).

2. Transfer Standard Sensors . . . . 1.0% (0.1 dB)
   Characterization of enhancements . . . [about 0.5% (0.04 dB)]
   Comparison to Primary Standard Sensor [about 0.5% (0.04 dB)]

3. Reference Sensors (commercial) . . . . 2.0% (0.2 dB)

4. Characterization of electromagnetic field in user test cell. [Depends upon user instrumentation accuracy and stability]

6. Calibration of sensor in test cell. Depends upon:
   - User instrumentation accuracy and stability.
   - Accuracy of location of reference sensor vs sensor.
   - Relative size of reference sensor vs sensor.

REFERENCES

[1] C. E. Baum, "Accuracy Considerations in the Design of B-Dot and I-dot Sensors," SSN 344★, June 1992.

[2] M. L. Crawford and J. L. Workman, "Using a TEM Cell for EMC Measurements of Electronic Equipment," NBS [NIST] Tech Note 1013, April 1979.

[3] M. L. Crawford, "Options to Open-Field and Shielded Enclosure Electromagnetic Compatibility Measurements," 70M1, 4th Symposium and Technical Exhibition on Electromagnetic Compatibility, Zurich, March 10-12, 1981.

[4] D. Königstein and D. Hansen, "A New Family of TEM-Cells with Enlarged Bandwidth and Optimized Working Volume," 7th International Zurich Symposium and Technical Exhibition on Electromagnetic Compatibility, March 3-5, 1987.

[5] C. E. Baum, "Impedances and Field Distributions for Parallel Plate Transmission Line Simulators," SSN 21*, June 1966.

[6] T. L. Brown and K. D. Granzow, "A Parameter Study of Two Parallel Plate Transmission Line Simulators of EMP Sensor and Simulation Note 21," SSN 52*, April 1968.

[7] R. W. Latham, "Interaction Between a Cylindrical Test Body and a Parallel Plate Simulator," SSN 55, May 1968.

[8] C. E. Baum, E. L. Breen, J. C. Giles, J. O'Neill, and G. D. Sower, "Sensors for Electromagnetic Pulse Measurements Both Inside and Away from Nuclear Source Regions," IEEE Trans. Antennas Propagate., Vol. AP-26, No. 1, January 1978; IEEE Trans. EMC, Vol. xx, No. xx, February, 1978.

[9] IEEE Std 291-1991, IEEE Standard Methods for Measuring Electromagnetic Field Strength of Sinusoidal Continuous Waves, 30 Hz to 30 GHz

[10] C. E. Baum, "Maximizing Frequency Response of a B-Dot Loop," SSN 8, December 1964.

[11] C. E. Baum, "The Multi-Gap Loop in Nonconducting Media," SSN 41, May 1967.

[12] C. E. Baum, "An Equivalent-Charge Method for Defining Geometries of Dipole Antennas," SSN 72, January 1969.

★ SSN is the abbreviation for "Sensor and Simulation Note," one of a series of publications by the Phillips Laboratory, formerly the Air Force Weapons Laboratory (AFWL).

[13] C. E. Baum, "Parameters for Electrically-Small Loops and Dipoles Expressed in Terms of Current and Charge Distributions," SSN 74, January 1969.

[14] C. E. Baum, "Electrically-Small Cylindrical Loops for Measuring the Magnetic Field Perpendicular to the Cylinder Axis," SSN 78, March 1969.

[15] C. E. Baum, "The Single-Gap Hollow Spherical Dipole in Nonconducting Media," SSN 91, July 1969.

[16] R. W. Latham and K. S. H. Lee, "Capacitance and Equivalent Area of a Spherical Dipole Sensor," SSN 113, July 1970.

[17] H. Whitehead and R. W. P. King, "The Loop Antenna as a Sensor," IEEE Trans. Antennas Propagate., pp. 291-297, May 1964.

[18] C. E. Baum, "A Figure of Merit for Transit-Time Limited Time-Derivative Electromagnetic Field Sensors," SSN 212, December 1975.

[19] G. D. Sower, "Optimization of the Asymptotic Conical Dipole Sensor," SSN 295, October 1986.

[20] R. A. Lawton, "New Standard of Electric Field Strength," IEEE Trans. Inst. and Meas., Vol. IM-19, No. 1, February 1970.

[21] C. E. Baum, "From the Electromagnetic Pulse to High-Power Electromagnetics," Proc. IEEE, Vol. 80, No. 6, June 1992.

[22] C. E. Baum, " Some Further Considerations for the Circular Parallel Plate Dipole," SSN 86, June 1969.

[23] G.D. Sower and K.M. Gheen, "Use of B-Dot and D-Dot Sensors for the Measurement of High-Power Microwave Oscillators," Conference on HPM, Livermore CA, October 1989.

[24] S. M. Riad and N. S. Nahmen, "Application of the Homomorphic Deconvolution for the Separation of TDR Signals Occurring in Overlapping Time Windows," IEEE Trans. Inst. and Meas., Vol. IM-25, No. 4, December 1976.

[25] S.M. Riad, "The Deconvolution Problem: An Overview," Proc. IEEE, January 1986.