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Design, Construction and Calibration of Sensors for HPM Measurements

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1. SUMMARY

The measurement of High Power Microwave (HPM) coupling is an important diagnostic tool in the understanding of HPM interaction with complex structures. The quantities of interest include the electric and magnetic fields both in free space and at (or near) the surface of a body. The sensors used must be small in order to cause minimal perturbation of the ambient field and to function over as wide a bandwidth as possible. In addition, the signal-to-noise ratio (SNR) must be as large as possible. This paper presents an engineering overview of the design and construction of various HPM sensors presently used at the Defence Research Establishment (DREO). Calibration methods for such sensors will also be briefly discussed.

2. PREFACE

Although the operating principles of common electromagnetic sensors are easily found in the literature [1, 2], the details of construction are often omitted. This is particularly true for sensors to be used in the multi-GHz region where the required dimensions are typically only a few millimeters.

In addition, once a sensor has been constructed, there remains the difficulty of accurately establishing it's calibration factor. Ideally, the sensor is "calibrated by ruler". In other words, the response can be established either analytically or numerically such that given a certain physical geometry, the calibration factor is known. However, the fabrication process often introduces deviations from theory which can not be easily discounted. For example, a finite thickness ground plane, a truncated ground plane, co-axial leads or dielectric support assemblies may influence the results of measurement. As a result, it is often more accurate to measure a sensor response. The question of how to establish an accurate electric or magnetic field then becomes an issue.

This paper is intended as an engineering review of the construction and calibration techniques used at DREO and will discuss some of the details mentioned above.

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3. SENSOR TYPES

3.1 Electric Field

3.1.1 Monopole/Dipole

Figure 1 is a schematic representation of one half of a biconical dipole sensor. The 5 mm dipole is tapered at 47° to create a 100 Ω impedance. The top of the electrode is rounded in an effort to minimize the resonance due to the finite height. The base of the electrode is connected to the inner conductor of a 25 cm long, 50 Ω co-axial line which is feed through a square brass tube and is terminated with a modified SMA connector. The dipole is completed with a second assembly which is identical except that it is tapped to receive the 2-56 flat head screws used to hold the unit together. In addition, commercial feed-through or bulkhead SMA connectors are often permanently added to the sensors for two reasons. The first is so the SMA connection on the sensor (which was slightly modified to accept the 0.034" diameter co-axial cable from the dipole) does not vary with time or degrade the contacts of the high quality SMA or 3.5 mm cables used in the lab. The second is so a supporting plate can be attached to the sensor leads.

The response of the dipole described above is shown in Figure 2. This measurement was made in an anechoic chamber using a broadband horn antenna as a source. From this figure it can be seen that the upper –3 dB point of the sensor is at approximately 7 to 8 GHz and that the resonance is above 12.5 GHz (upper limit of the measurement).

3.1.2 Patch Antenna

The operating principles of a patch antenna are discussed in detail in References [3, 4]. At DREO these sensors are used in two modes. In the first, the centrally fed patch is oriented horizontally such that the electric field is perpendicular to the radius as shown in Figure 3. In this mode of operation, the lower frequency pick up is emphasized and the sensor has a very large, relatively uniform response from 100's of kHz to the TM_{01} resonance which is determined by setting n=0 and m=1 in the equation,

$$f_{nm} = \frac{X_{nm} c}{2\pi a_e \sqrt{\varepsilon_r}}$$

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where

$$a_e = a\sqrt{1 + \frac{2t}{\pi a \varepsilon_r}\left(\ln\frac{\pi a}{2t} + 1.7726\right)}\ ,$$

$$X_{nm} = \text{roots of } J_n'(x) = 0\ ,$$

c is the speed of light, ε_r is the dielectric constant, a is the patch radius and t is the patch thickness. The responses of two patch sensors are shown in Figure 4. Both sensors have a 2.5 cm radius but differ in dielectric type and thickness as identified on the plot. From these and other responses (not shown) it has been determined that a thinner dielectric and a higher dielectric constant increases the capacitance of the sensor and, therefore moves the –3 dB point to a lower frequency. Unfortunately, the sensor pick up is also reduced resulting in a poorer SNR.

In the second mode of operation the patch is used at much higher frequencies. A typical response is shown in Figure 5 where the various f_{nm} resonances of the patch can clearly be seen. It is obvious from this response that the sensor cannot be used in this mode without some form of signal processing. If using a network analyzer, the simplest way to do this is to calibrate the sensor response into the reference field measurement and normalize all remaining measurements with respect to this. One advantage of patch antennas is that they can be designed with any commercial software drawing package and fabricated in the same way as printed circuit boards. They can also be designed to conform to a surface.

3.2 Magnetic Field

3.2.1 Loop Probe/Surface Field Probe

The probes used for magnetic field measurements are discussed in detail in References [5, 6]. As depicted in Figures 6 and 7, they may be used in surface field or free field modes and are basically co-axial cables which are formed into a loop. The outer conductor is circumferentially cut at the top (and bottom) of the loop so that the inner conductor will respond to the magnetic field but is shielded from the electric field. The pick-up of these sensors can be modelled by the simple equation

$$\ell\frac{di(t)}{dt} + R\,i(t) = \mu_o A\frac{dH(t)}{dt} \qquad (1)$$

which has time and frequency domain solutions of;

$$i(t) = \frac{\mu_o A}{\ell}\left(\exp(-Rt/\ell) \star \frac{dH(t)}{dt}\right)$$

$$|I(f)| = \frac{2\pi\mu_o A H(f)}{R}\sqrt{\frac{f^2}{1 + (2\pi\ell f/R)^2}}$$

where i is the loop current, H is the magnetic field, $A = \pi a^2$ is the loop area, R is the sum of the radiation and termination resistance, $\mu_o = 4\pi\cdot10^{-7}$ [A/m], r is the wire radius and ℓ is the loop inductance given by

$$\ell = a\mu_o\left[\ln\left(\frac{8a}{r}\right) - 2\right]\ .$$

Comparison of the response measured in a TEM cell to that calculated is shown in Figure 8.

If the radiation and termination resistance in the loop are very small, the value of R in Eq. 1 becomes negligible and the equation reduces to

$$\ell\frac{di}{dt} = \mu_o A\frac{dH}{dt}$$

$$i(t) = \frac{\mu_o A}{\ell}H(t)$$

The advantage of such a sensor is that, like the horizontal patch antenna discussed earlier, this sensor has a very flat response from 10's of kHz into the GHz range or, in other words, the current in the loop is directly proportional to the magnetic field - not it's derivative. Figure 7 depicts a modified ground plane sensor which incorporates a 1 GHz Tektronix current probe in place of the 50 Ω cable. Although this probe significantly reduces the required dynamic range of the measurement, it does not do so by enhancing the pick-up at the lower frequencies but by attenuating the higher frequencies and, as such, decreases the SNR in this range.

4. GENERATION OF FIELDS FOR CALIBRATION

As mentioned previously, it is often difficult to calibrate a sensor using theoretical parameters because of deviations in the simple theory caused by practical considerations in fabrication, calibration and application. As a result, a sensor should be calibrated by measuring its response in a known field. The obvious difficulty is how to establish such a field.

Although there is no means of establishing an exact magnitude, a number of ways exist by which to generate a reasonably well known field value. The Transverse Electromagnetic (TEM) cell [6] is one of these. This device is basically a truncated, rectangular transmission line as depicted in Figure 9 and can be operated from DC to its first resonance determined by the cell dimensions. Unfortunately, the bandwidth is inversely proportional to the size of the cell and, therefore, since a sensor must be much smaller than the septum height or width in order to minimize perturbation of the field, the amount of useful testing which can be done in a TEM cell at high frequencies is very limited.

The other factor to consider is that the field along a cross-section of the cell is not completely uniform but varies according to Figure 10. The sensor calibration must take into account this field variation in addition to the reflections and standing waves which are induced at virtually all frequencies because of the difficulty in inducing and terminating an ideal TEM mode in the cell. This is a result of the geometrical discontinuities inherent to the ends of the cell and is particularly true of very small cells because input connectors, dielectric supports etc. cannot be scaled down to account for the smaller dimensions. In addition, the relative errors in the machining and assembly processes become larger in these smaller cells.

One means of minimizing the effects of the reflections is to test in the time domain. An impulse test may potentially be designed so that the sensor response can be established before any major reflection has an opportunity to alter the excitation field. This adds an added degree of difficulty to the design of a TEM cell since operation in the frequency domain requires a short cell which maximizes the usable bandwidth (first major resonance is inversely proportional to the cell length). However, operation in the time domain requires that a cell be as long as possible to maximize the temporal separation between the initial field excitation and the reflection from the back taper.

An alternative which avoids this problem is to make use of what is referred to as a GTEM cell [7]. Like a TEM cell, this is also a rectangular transmission line; however, it is essentially only the front taper of the TEM cell which is directly terminated in a resistive load and absorbing material. Since the discontinuities in the cell have been removed, the associated resonances are also gone. However, the cross-sectional field uniformity is still similar to that of Figure 10 and must be accounted for. The situation is aggravated by the fact that the septum is tapered and off-centered in the working volume.

The response of the DREO GTEM cell (1 m long) is shown in Figure 11. The dimensions of this cell are much larger than an equivalent bandwidth TEM cell thus allowing much larger sensors to be tested (or alternatively, a small sensor to perturb the ambient field much less). The primary disadvantage of this cell is that the field magnitude rapidly deviates a few dB both spatially and with respect to frequency. Fortunately, there are no deep nulls in the field values and the response of a sensor can be numerically recovered without any significant difficulties.

Finally, a method which essentially eliminates the possibilities of resonances entirely is to calibrate in an anechoic chamber or an open field site with a standard gain horn antenna as a source. Here too the unwanted reflections from nearby surfaces must be kept under control. One can improve the measurements by using time domain gating.

5. SUMMARY

An overview of the various types of electromagnetic sensors used at DREO has been presented with an emphasis on the engineering aspects of sensor design. The electric field is generally measured with a dipole/monopole, however the patch antenna is available as an alternative under certain circumstances. The primary sensor for the magnetic field is a single turn loop used either in free space or on the surface of a structure. A brief discussion of calibration requirements using TEM and GTEM cells, anechoic chambers and open field test site has also been presented.

6. ACKNOWLEDGMENT

The authors wish to thank R. Apps and A. Walsh for their assistance with sensor assembly and testing.

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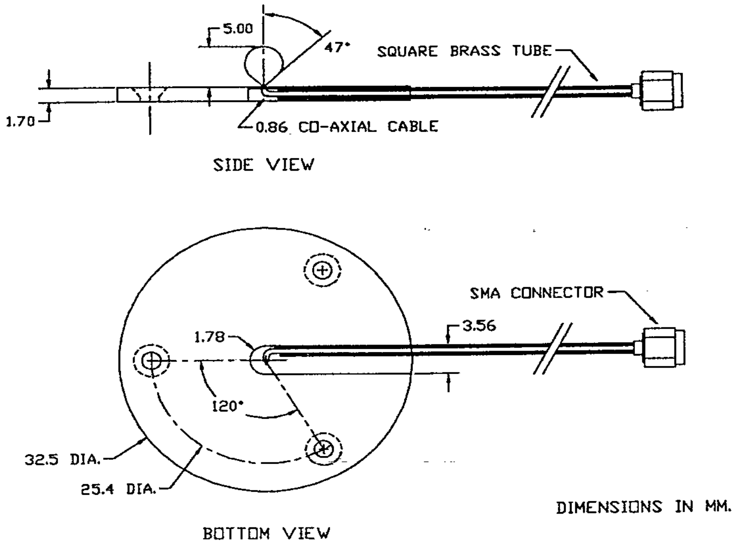

Figure 1: Schematic representation of one half of a dipole. The electrode is 5 mm long and is rounded to minimize the inherent resonance. The other half of the dipole is identical except that it is tapped to receive the assembly screws.

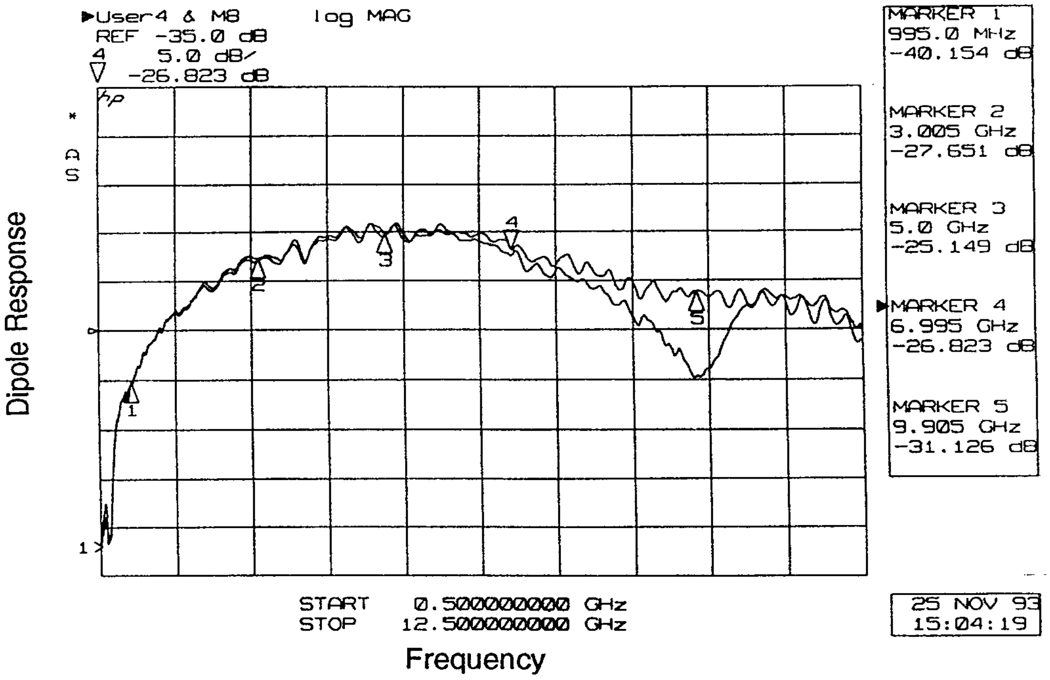

Figure 2: Response of the dipole depicted in Fig. 1. The measurement was made in an anechoic chamber with a standard gain horn antenna as a source. Although both sensors are physically virtually identical, there is clearly a difference in the response.

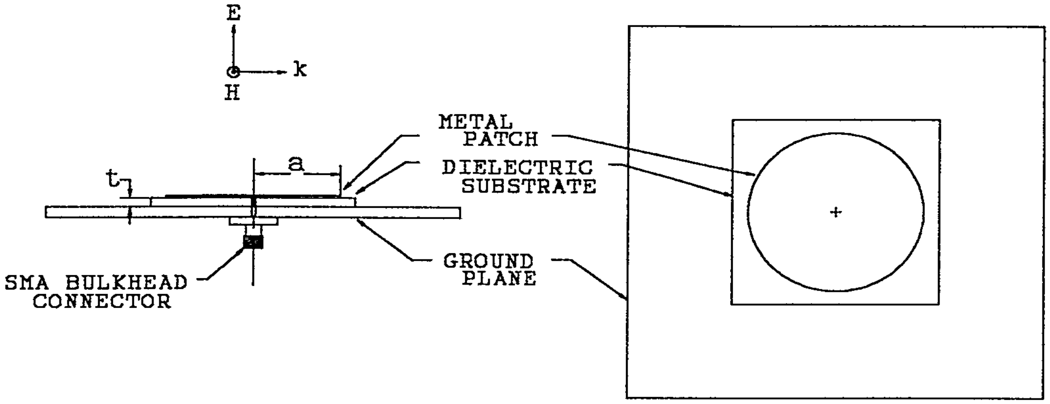

Figure 3: A schematic representation of a patch antenna. The radius of the (in this case) circular patch is "a" and the thickness of the dielectric is "t". In order to emphasize the lower frequency response, a central feed point has been chosen.

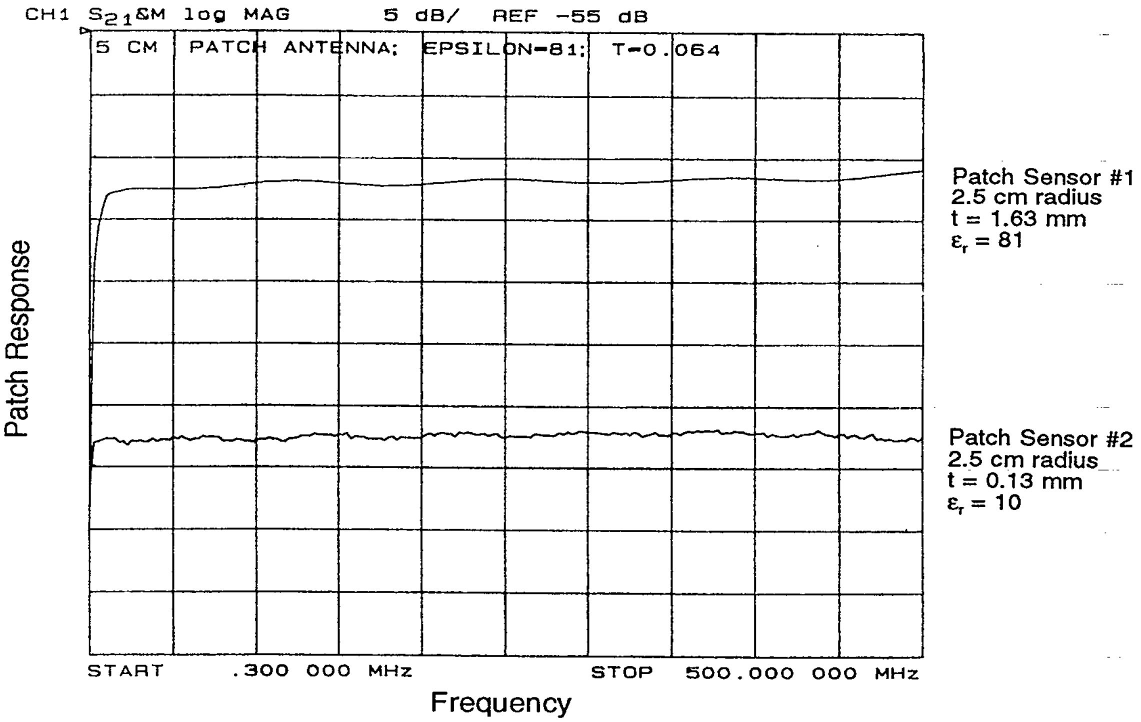

Figure 4: The response of two patch antennas. Although the -3 dB point occurs at a lower frequency for patch #2, approximately 20 dB of sensitivity must be sacrificed to achieve this.

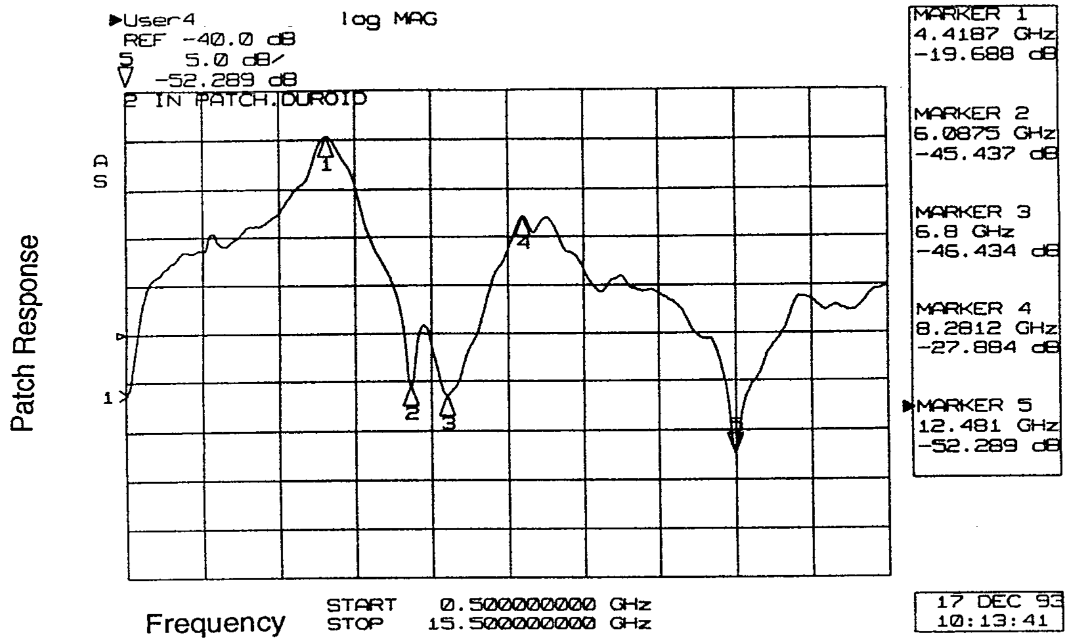

Figure 5: Typical response of a patch antenna. The resonances are due to the various TM_{nm} modes of the patch and make some form of signal processing a necessity.

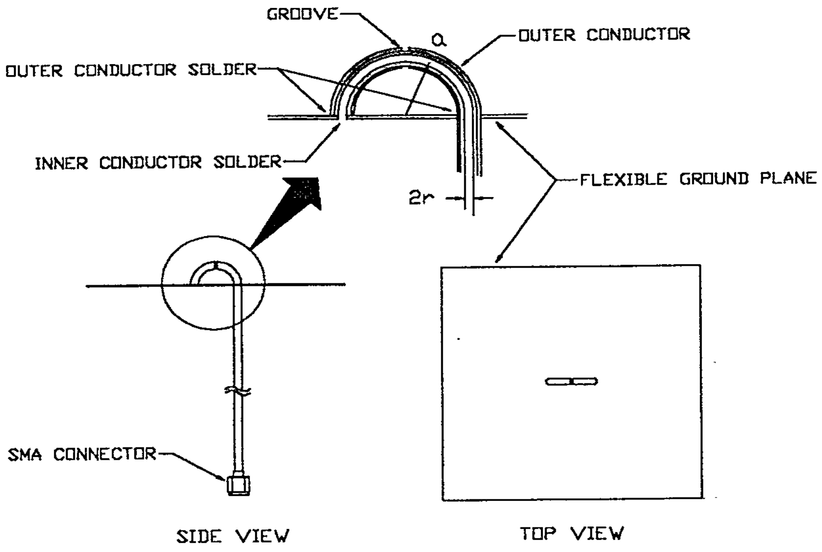

Figure 6: A schematic representation of a surface field probe. This probe responds to a magnetic field but is shielded from the electric field.

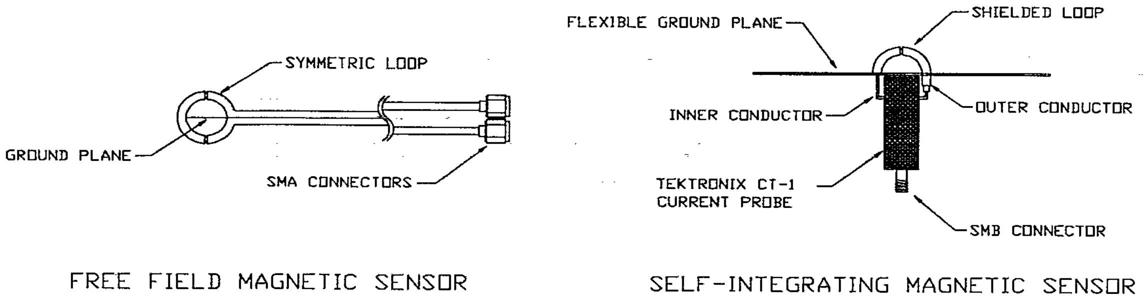

Figure 7: Variations of the surface probe in Figure 6. The first is a free-field version and the second replaces the 50 Ω co-axial cable with a low resistance current probe thus creating a flat response over a larger bandwidth.

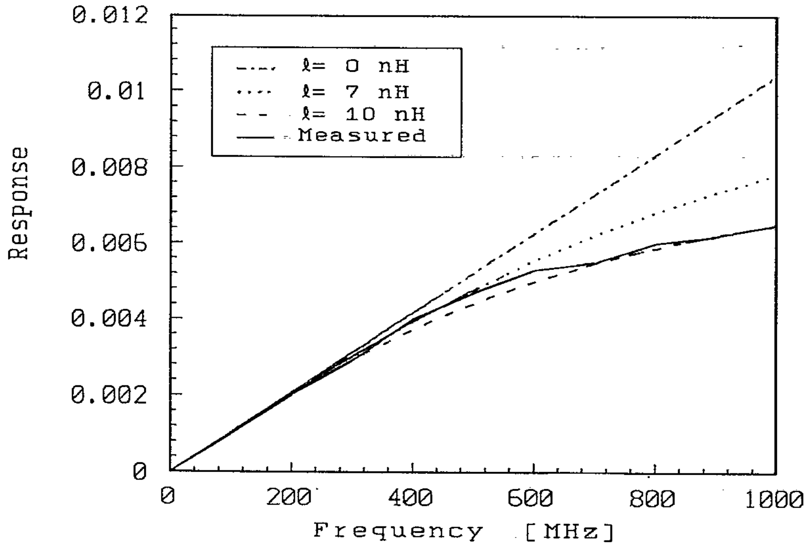

Figure 8: The response of the field probe depicted in Figure 6 when tested in a TEM cell. The inductance, ℓ, of the probe is calculated to be approximately 8 nH.

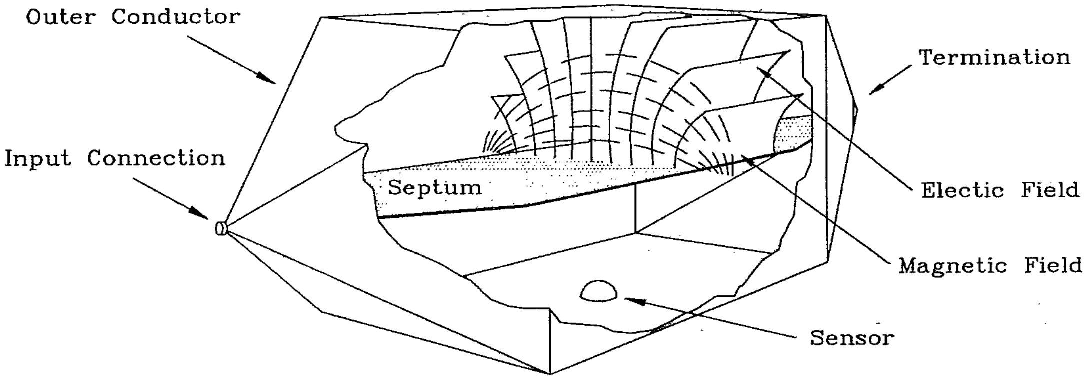

Figure 9: A schematic representation of a TEM cell and its associated fields.

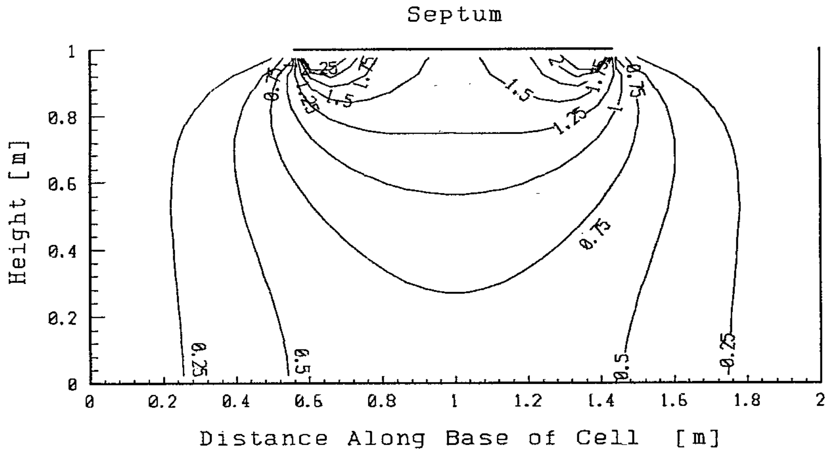

Figure 10: Variation in the vertical electric field in the lower half of a 100 Ω TEM cell. The field level at the base of this cell, as calculated for the static case using Finite Difference, is 65% of the nominal voltage/height value.

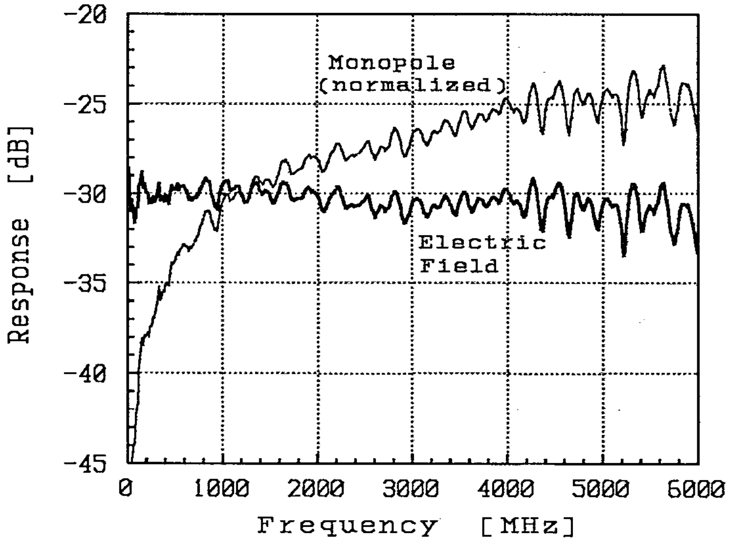

Figure 11: The E-field response of a 1m long GTEM cell as measured by a short monopole. Although the magnitude varies a few dB both spatially (not shown) and with frequency, there are no deep nulls in the response.

DISCUSSION

G.S. BROWN
It seems to me that your talk was primarily concerned with problems associated with very wideband fields measurements. Are there any problems associated with the high power levels attendant with HPM ?

AUTHOR'S REPLY
Yes, it is feasible that one could create a field which is intense enough to generate an arc in or around a critical component of a sensor. A good example of this is patch #2 in figure 4. This sensor is constructed by anodizing an aluminium plate to create the dielectric material (which is inherently thin and porous). As the field strength of a uni-polar pulse is increased, the peak value in the sensor response tends to become non-linear. It is speculated that this is a result of arcing between the top plate and ground plane through the dielectric*. In principle, the same response may be observed (at different field strengths) in a sinusoidal pulse.
(* original observations made by M. Kekez and J. Durr of the NRC in Canada)

P. ZWANBORN
1/ Could you please comment on the fact that your antenna factor decreases if you downsize your sensor.
2/ Have you taken into account that you obtain a mirror image of your sensor when inserted inside a TEM-cell. How does that influence your calibration ?

AUTHOR'S REPLY
1/ In general, a sensor bandwidth is inversely proportional to its dimension and its response is proportional to this dimension. Therefore, as a sensor bandwidth is increased, the magnitude of the response will decrease. This will result in a poorer SNR in the measurement.
2/ A TEM cell can be considered to be a coaxial line and as such, any sensor placed inside it will act as a perturbation in the impedance and cause a reflection to oscillate within the cell. The way we avoid (or minimize) this is to try to keep the sensor less than one tenth of the size at the septum to outer conductor spacing.This should be considered a "rule-of-thumb" and I don't have numerical data to quantify the effects.

A. TAYLOR
Have you investigated temporal dispersion with frequency - ie are high frequencies delayed with respect to low frequencies ?

AUTHOR'S REPLY

No, we have not investigated temporal dispersion.

M.P. CLARKSON

Has phase calibration of the sensors been looked at ?

AUTHOR'S REPLY

My oral response to this question was that we had not investigated the phase response at the various sensors. However, this comment was erroneous because I had mistakenly interpreted the question. We have not looked at a phase calibration in the range of a sensor where the response is very non-linear (ie where a sensor is very resonant). However, in the linear portions the phase response is generally as linear and uniform as the magnitude of the response.