EMISSION AND SUSCEPTIBILITY TESTING IN A TAPERED TEM CELL

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SUMMARY

The use of a tapered TEM cell - anechoic chamber hybrid for radiated emission and susceptibility testing is discussed. The TEM mode is used to simulate a plane wave for susceptibility testing (both CW and pulsed), as with a standard TEM cell. Within the recommended test volume, field uniformity varies with both position (+/- 1 dB) and frequency (+/- 3 dB for dc to 1 GHz). Thus, an overall field uniformity of +/- 4 dB within the recommended test volume is presently achievable. The test volume size may be scaled upwards at the loss of only field strength. For the emission case, test object radiation is modeled with an equivalent multi-pole expansion. The dominant terms of the multi-pole expansion may be determined through a sequence of cell measurements. These dominant terms may then be used to predict test object radiation both in free space and over a ground screen. In this manner time consuming emission measurements, such as those required by FCC Rules Part 15 Subpart J or VDE 0871, may be simulated numerically. Both experimental and theoretical data are presented. The advantages and limitations of this cell design with respect to other popular methods are briefly discussed.

1. INTRODUCTION

The number and scope of technical standards covering electronic equipment radiated emission and susceptibility performance continue to increase. By 1992 all electronics marketed in the European Economic Communities will legally require compliance certification [1]. The EMC engineer is faced with a formidable task in trying to find an effective, economical, all-around, test environment. Popular choices include open field sites and ground planes, anechoic chambers, transverse electromagnetic (TEM) cells, shielded rooms, and reverberation chambers. Each method has certain advantages and limitations [2-4].

This paper discusses an additional alternative consisting of a tapered TEM cell - anechoic chamber hybrid design. The hybrid cell is applicable to both susceptibility and emission testing over a broad frequency range, dc to above a gigahertz. The cell size may be scaled to accommodate small to large test objects (printed circuit boards - equipment racks - automobiles).

The cell may be used to simulate an incident plane wave for performing susceptibility tests. The measurement procedure would be similar to that for a ground screen or an anechoic chamber. The field uniformity varies within the test volume with both position (+/- 1 dB) and frequency (+/- 3 dB, dc to 1 GHz).Thus, an overall field uniformity of +/- 4 dB for frequencies up to a gigahertz is presently achievable. Field strength is a function of input power and location within the cell. Larger cell cross sections require more input power to achieve specific field strengths; however, quite high field levels (100 V/m) can be achieved over reasonable test volumes (0.5 m) with moderate input power (100 W).

Emission testing is more complicated since the device under test (DUT) is radiating into a transmission line. The results can be correlated to an idealized free space or ground plane environment. The approach taken here is to model the DUT as a set of multi-poles. At frequencies where the DUT is small compared to a wavelength, the equivalent electric and magnetic dipole moments usually suffice. This method has been successfully used to predict free space radiation based on measurements in standard TEM cells [5-6]. The great advantage of the GTEM multi-pole approach is that, once the multi-poles are determined, the ground screen simulation is done numerically. Thus, the orientation of the DUT, the height and orientation of the receiving antenna, the separation of the two, and so forth, can all be changed by the computer program. This allows one to simulate VDE 0871 or FCC Part 15 Subpart J radiated emission (RE) tests in a fraction of the time it would take to acquire real data. The accuracy of this approach decreases as the electrical size of the DUT increases. Nonetheless, even for large test objects this approach yields valuable information quickly.

Our paper will review the thinking behind the cell and its basic design (Sec. 2), followed by a discussion of field generation for susceptibility measurements (Sec. 3), emission measurements (Sec. 4), a brief comparison of the hybrid cell to other test environments (Sec. 5), and a brief summary (Sec. 6).

2. CELL DESIGN

A standard TEM cell consists of a section of rectangular coaxial transmission line which propagates a TEM mode. The TEM mode simulates a free space plane wave while the rectangular geometry gives the TEM mode a nearly linear polarization over the test volume. The cell is tapered at each end to mate with standard (50 ohm) coaxial cable. Because the cell acts as its own transducer, no transmitting or receiving antennas are required. A TEM cell is well isolated and thus neither suffers from, nor contributes to any outside interference. The primary TEM cell limitation is the size of the test volume which is inversely proportional to the upper frequency operating limit because of the appearance of higher-order mode induced resonances [7]. TEM cell design and usage is well documented [8].

In addition to higher-order modes, there are other reasons why the standard TEM cell design is difficult to scale upwards. First, the overall size of the cell becomes prohibitive when compared to the usable test volume because of the two tapered sections. Second, transmission is distorted due to differences in the propagation lengths on the inner and outer conductors. This distortion will be appreciable (> 1 ns) for cells designed to have test chambers greater than 1 m in height (assuming 45 degree tapered sections).

A solution to the last two problems is to utilize only the cell taper. This will yield equal propagation lengths on any conductor and keep the overall size of the cell to a minimum. The result is the tapered TEM cell depicted in figure 1. It consists of a section of flared rectangular coaxial transmission line terminated with a matched load. The flare angle (20 degrees total) is more gentle than in a standard TEM cell which reduces the space savings somewhat. The inner conductor is also vertically offset to create a larger usable test volume as opposed to the typical symmetric configuration. This has a neglible effect on field uniformity. The dimensions are chosen to give a 50 ohm characteristic impedance. The design criteria for such tapered cells have been presented previously [9].

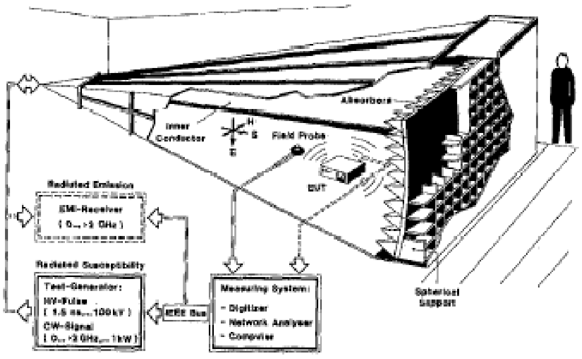

Fig. 1. A tapered TEM cell - anechoic chamber hybrid (GTEM cell).

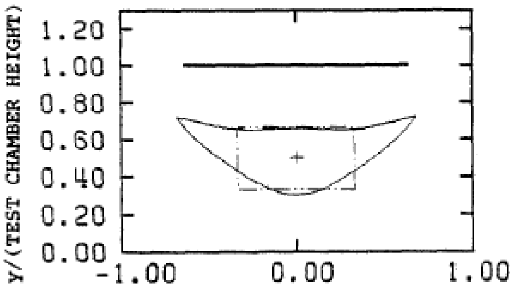

Fig. 2. The test volume resulting from a 1 dB TEM mode field uniformity criterion. The usual "one-third-the-transverse-dimensions" recommended test volume is also indicated (the rectangle).

The flare termination is critical since it must provide a good match over a very broad frequency range. The termination operates on two principles. At lower frequencies, resistive elements are used to create a distributed 50 ohm match. At higher frequencies, RF absorber is used to attenuate the incident wave, as would be done in an anechoic chamber. The transition between these two regimes depends on the size of the cell and absorber, but generally is between 100 MHz and 400 MHz. Cells have been constructed with test chamber heights of 1.5 m (ABB model GTEM1500) and 0.5 m (ABB model GTEM500) respectively. The GTEM designation is to emphasize that these are **gigahertz TEM cells.**

3. FIELD UNIFORMITY, FIELD STRENGTH, AND SUSCEPTIBILITY TESTING

GTEM cells can be used to generate a precise incident field for susceptibility testing. Swept measurements into to GHz frequencies can be done quickly since no antenna changes are involved. The field strength can be accurately controlled.

As mentioned, the TEM mode simulates a free space plane wave. An ideal planewave has electric and magnetic field components which are invariant in the transverse plane. The TEM mode in a GTEM cell primarily consists of vertical electric and horizontal magnetic field components; but these do vary as a function of position in the cell. We define position dependent field uniformity of the TEM mode as the deviation of these values from that of a reference position value, typically, the center of the lower cell chamber. Using +/- 1 dB as the field uniformity criterion, the resulting test volume is the "smile" shape shown in figure 2. Also indicated is the usual recommended test volume [8] which consists of a third the lower chamber height and width. As may be seen, these two volumes essentially coincide. Thus, the recommended test volume closely defines a +/- 1 dB field variation. It should be noted that this figure assumes the TEM mode propagates in an uniform cross section. In fact, as maybe seen from figure 1, the TEM mode propagates as a spherical wave front. Thus,figure 2 (and figure 3 to follow) is really a projection. The projection effect has been analyzed but is excluded here for brevity. Because of the shallow flare, the projection introduces variations of less than +/- 0.1 dB.

If the field uniformity criterion is relaxed to +/- 2 dB then the volume shown in figure 3 results. The +/- 2 dB test volume would allow for much larger test objects and encompasses the whole of the usual recommended test volume. In both these figures the lower chamber center has been used as the reference point; but other points might just as well have been chosen with similar results, closer to the floor, for example.

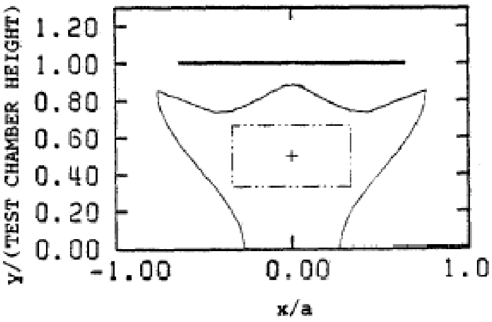

Fig. 3. The test volume resulting from a 2 dB TEM mode field uniformity criterion. The usual "one-third-the-transverse-dimensions" recommended test volume is also indicated (the rectangle).

In addition to field uniformity in the transverse direction, there are variations in the propagation direction as well. The TEM mode propagates according to exp(jkr) and attenuates as 1/r where r is the distance as measured from the cell apex. This behavior is consistent with a spherical plane wave.

It should also be noted that introducing a DUT will certainly perturb the cell characteristics as well as the incident field. Limiting the DUT size to the recommended volume should mean minimal changes to the cell transmission line parameters [8,10]. Field perturbations occur in any test environment when a DUT is present, even in an ideal free space. Thus, field perturbations in a TEM cell should be normalized to those for the equivalent DUT exposed to a free space plane wave. It is anticipated that these normalized perturbations will not be large, but further work clearly remains in this area. The above discussion applies to the TEM mode. However, there will also be field variations as a function of frequency because of possible termination mismatch and the appearance of resonances associated with higher-order modes.The present termination design provides for a very low VSWR (< 1.4) over the prescribed frequency range (< 18 GHz). However, it should be emphasized that VSWR is not a good indicator of field uniformity since this depends primarily on the excitation of higher-order modes. Thus, we presently would not stress VSWR as a primary figure of merit, but rather as a diagnostic and tuning aid. In addition, the termination absorber results in a low Q cavity. Thus, higher-order modes are only weakly excited and are not highly resonant. The result is a very uniform field versus frequency. Figure 4 shows data for the relative vertical electric (upper curve) and horizontal magnetic (lower curve) fields from 1 Mhz to 1.8 Ghz on a 10 dB/div scale. The fields were measured with sensors located in the floor of a cell (0.8 m chamber height) and offset from the center to avoid field symmetry cancellations. The variations are within +/- 3 dB. Similar results have been obtained for larger cell cross sections. It is expected that the fields are well behaved further into the GHz range but our current sensor capability precludes checking this at present.

Together, the position variations (+/- 1 dB in the recommended test volume) and frequency variations (+/- 3 dB up to 1 GHz) give an overall field uniformity of +/- 4 dB.

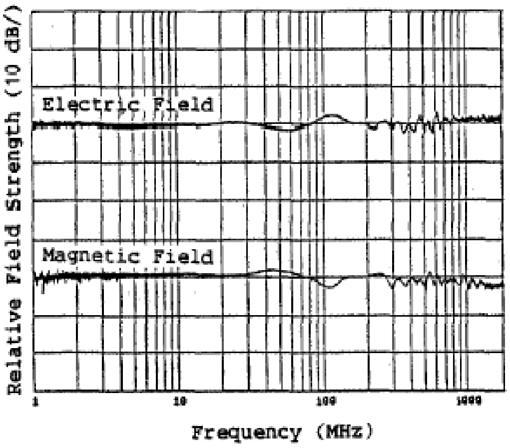

Fig. 4. Relative field strength as a function of frequency for the dominant TEM mode components (vertical electric and horizontal magnetic) as measured at the floor of a GTEM cell (0.8 m lower chamber height).

Also of interest is the field strength at the reference point (lower chamber center) as a function of the lower chamber height. Figure 5 shows the results for three different input powers. 10 kW is sufficient to create high field levels (200 V/m) over very large chamber heights (up to 3.5 m). More standard laboratory equipment (100 W source) can generate field levels of 100 V/m up to chamber sizes of almost 1 m.

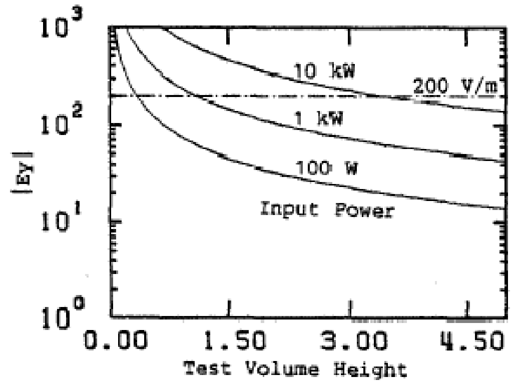

Fig. 5. Vertical electric field strength as a function of the lower chamber height for various input powers.

Figure 6 shows an example of the type of susceptibility data that may be quickly obtained. A commercially available fiber optic link receiver (1.2 kHz to 1 GHz) was exposed to a 20 V/m incident field. Figure 6 shows the noise level both with and without the incident field present. The radiation induced noise level is 5-10 dB and could lead to data transmission errors. Such quick diagnostics can be invaluable in tracing measurement error sources.

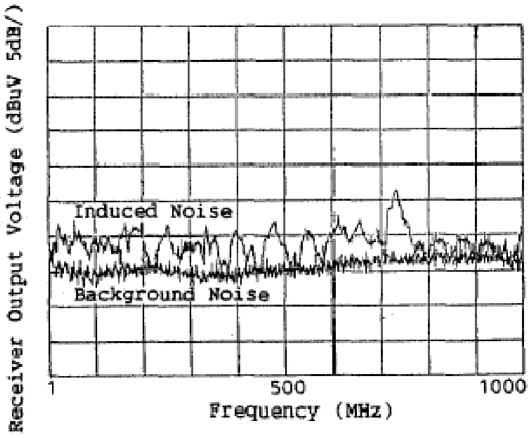

Fig. 6. Noise level change for a broadband optical fiber link when exposed to a 20 V/m incident field.

4. EMISSION TESTING

GTEM cells, like any indoor facility, are very convenient environments for emmission testing. They are well isolated from background noise and TEMPEST secure, as opposed to open area test sites. No antennas are needed and swept frequency measurements to 1 Ghz can proceed uninterrupted. However, GTEM cell measurements result in voltage data (radiated by the DUT and measured at the cell apex) whereas most emission measurements are designed to measure either the radiated electric or magnetic field directly. Consequently, in order to compare data some correlation needs to be established.

The problem has been considered before for standard TEM cells [5-6]. The basic idea is to represent the DUT in terms of a multi-pole expansion. For test objects small when compared to a wave length, only the leading terms of this expansion need be retained. These are the electric and magnetic dipole moments which produce equivalent radiation at observation points not too close to the DUT. Since most unintentional radiators will not be highly directive, these equivalent dipole moments give meaningful results even for objects which are no longer electrically small.

This basic approach has been adapted to the GTEM cell where only a single output voltage is available, as opposed to a standard TEM cell which is a two port device. A sequence of GTEM measurements are used to determine the magnitudes of the electric and magnetic dipole moments. Once found, these may be used to predict how the DUT will radiate in free space or over a ground screen. In particular, we may simulate VDE 0871 or FCC Part 15 Subpart J qualification measurements. The required GTEM measurements take little time and may be automated. Some DUT rotations are involved. In comparison,ground screen measurements are time consuming, as well as being subject to electromagnetic and weather ambients. The analytical details are omitted here but may be found in [5-6,11].

In order to test the correlation, various radiating devices have been tested; first in a GTEM cell and then on the ABB Baden rooftop ground screen. The test objects to be discussed here will be a self-contained spherical dipole, a pocket calculator, and a desktop personal computer.

The spherical dipole consists of two hemispheres separated by a small gap and powered by an internal comb generator. Versions have been constructed using 10, 16, and 20 MHz clocks. Harmonics of usable signal strength are generated up to 1 GHz for the 10 and 20 MHz models.

Figure 7 shows the results for the 20 MHz version as measured on the ABB Baden roof top ground screen. Only the data points at 20 MHz multiples have meaning; the lines merely connect points. The frequency range was 30 MHz to 1 GHz to simulate VDE or FCC RE qualification frequencies. The horizontal electric field was measured 1, 2 ,3 and 4 m above the ground screen. The separation was 10 m. The dipole was oriented for maximal coupling. The vertical electric field was similarly measured, although the data will not be presented here. These data indicate what would be received if the spherical dipole were subjected to a full VDE or FCC radiated RE qualification test.

We next placed the spherical dipole in the GTEM cell, determined the equivalent dipole moments (primarily a single electric component as expected), and predicted the ground screen data for the same parameters chosen in Figure 7. The results are given in figure 8. The measured (fig. 7) and predicted (fig. 8)data agree very well except at frequencies where the ground screen background noise was comparable to the desired signal. There is, however, a large difference in the time necessary to obtain the two curves. The GTEM data requires < 2 hrs to obtain, inculding set up, measurements, reorientation of the radiator, etc. The noise level in a GTEM cell for the equipment used in this experiment is on the order of 1 uV and the individual harmonics are readily seen using the swept frequency mode. The ground screen data required almost 3 days to obtain including set up and measurement. The main difficulty is that the background noise is so great that data points must be obtained via manual tuning using very narrow bandwidths.

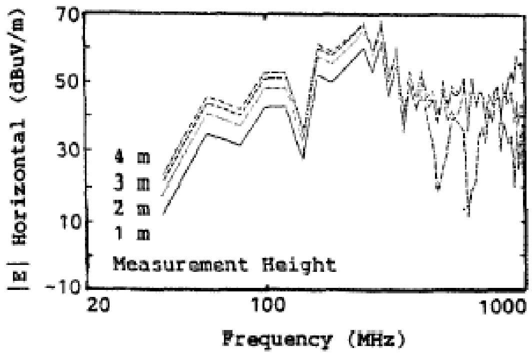

Fig. 7. Horizontal electric field radiated by a self-contained spherical dipole (20 MHz comb generator) as measured above the ABB Baden rooftop ground screen. The receiving antenna (10 m separation) was varied in height from 1-4 m.

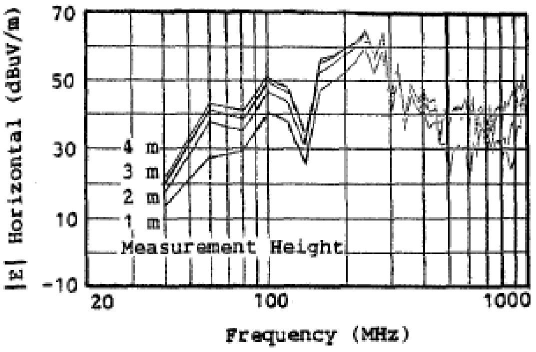

Fig. 8. Horizontal electric field radiated by a self-contained spherical dipole (20 MHz comb generator) as predicted from GTEM cell measurements. The parameters are chosen as in fig. 7.

An alternative to determining the full set of equivalent dipole moments is to measure only the DUT total radiated power in the GTEM cell. This further reduces the GTEM measurement time and necessary data storage. The total power may then be used to generate an upper bound to the expected DUT radiation as follows. We assume that the DUT gain is no better than that of a dipole. Thus, the DUT radiation should be bounded by that of a dipole radiating the same total power and oriented for maximum coupling. This will be either a horizontal or vertical dipole depending on whether the horizontal or vertical electric field is desired. The maximum electric field for a simulated sweep of the receiving antenna may then be determined. The results are simple correlation curves relating the maximum electric field |Em| for either the horizontal or vertical case to the total power P_0 measured in a GTEM. An example is shown in figure 9 for a 10 m DUT to receiving antenna separation. These "worst case" data may be compared to radiated emission limits and the expected compliance of the DUT quickly determined.

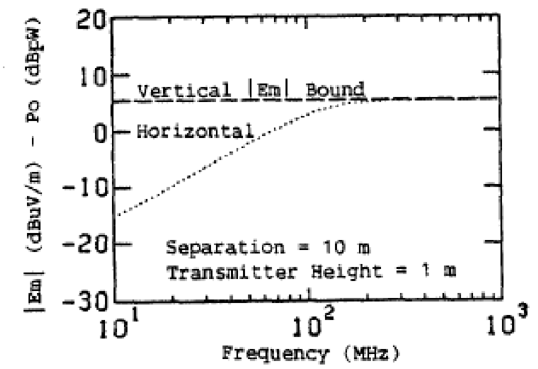

Fig. 9 Correlation curve between the predicted maximum electric field |Em| (horizontal or vertical) over a ground screen (10 m separation) and the total radiated power P_0 measured in a GTEM cell.

Figure 10 shows the results of such data against VDE 0871 B RE limits for two test objects; a 16 MHz clock spherical dipole and a pocket calculator. As may be seen the spherical dipole radiation is expected to be well above the VDE limits over a significant part of the frequency range. This is expected because the dipole is designed to be an efficient radiator. On the other hand, the pocket calculator shows very low radiation levels. In fact, only three significant data points could be located in the very sensitive GTEM cell. The predicted ground screen data is well below the compliance levels. This also is expected since the calculator carries a label indicating full compliance. Again, it should be emphasized that this data may be obtained very quickly with standard laboratory equipment (and some software).

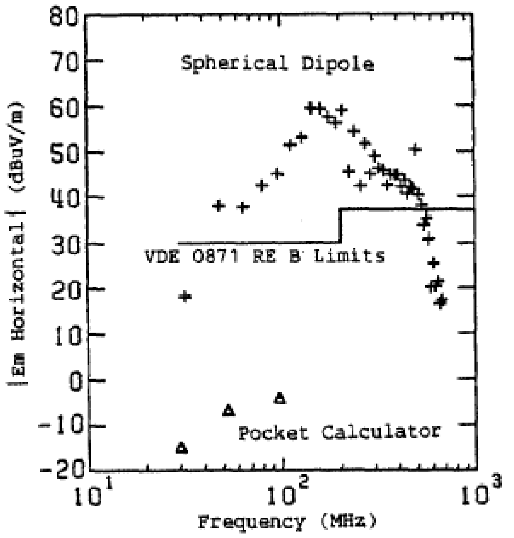

Fig. 10 Predicted maximum horizontal electric field for a self-contained spherical dipole (16 MHz comb generator) and a pocket calculator based on total radiated power measured in a GTEM cell. The VDE 0871 RE B limits are shown for comparison.

A third DUT considered is a desktop computer which also carries a VDE 0871 B compliance label. Total power was measured in the GTEM cell and worst case radiation based on the above dipole model was predicted. The results are shown in figure 11, for both the horizontal and vertical electric field. At frequencies below 100 MHz, the maximum predicted horizontal electric field is slightly less; above this frequency the two curves merge. The data indicate compliance. Only a few points approach the VDE 0871 B RE limits, but it should be remembered that figure 11 represents a worst case envelope. Actual data should be less. An attempt was made to measure the PC on the ABB Baden Rooftop ground screen (VDE compliant as per VDE 0877 Part 2) but the background noise was too severe, as shown in figure 12. Only a few points could be distinguished from the noise.

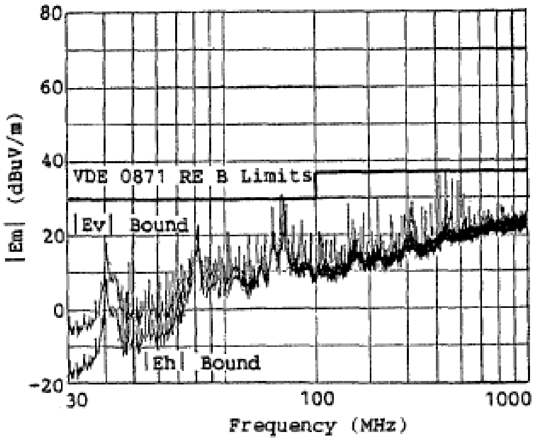

Fig. 11 Predicted maximum horizontal and vertical electric field for a desktop personal computer based on total radiated power measured in a GTEM cell. The VDE 0871 RE B limits are shown for comparison.

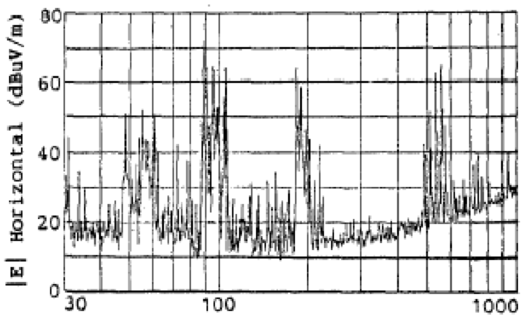

Fig. 12 PC-radiation covered by background noise at the ABB Baden rooftop ground screen. The horizontal electric field is being measured 3 m above the ground screen.

5. RELATION TO OTHER METHODS

Typical Calibration/Error Bounds for EMC Test Facilities

Open Area Test Site	Shielded Rooms	Small Strip Lines	Reverb. Chamber	Anechoic Chambers	ABB GTEM 1500
30-1000MHz		< 40 MHz	> 200MHz	30-1000 MHz typically > +/- 5 dB	0-1.8GHz
VDE +/- 3 dB	up to +/- 30 dB	+/- 2 dB	+/- 10 dB	FCC compliant chambers > +/- 2 dB (2.4 m absorber)	+/- 3 dB
FCC +/- 2 dB	above cavity resonances of the room	(MIL Std 462 A)	> 2 GHz +/- 2.5 dB		

The above table gives a brief comparison of the applicable frequency range and expected field uniformity for typical test environments presently in use. As may be seen, the GTEM cell compares favorably. In addition, GTEM results are highly repeatable; thus, it would serve well as a standard test environment.The GTEM cell is presently included in VG 95903 (Part 50) and is actively under consideration for inclusion in further standards.

6. CONCLUSION

The use of a tapered TEM cell - anechoic chamber hybrid for both **susceptibility** and **emission** measurements has been considered. For susceptibility testing the cell provides;

- a precisely known, uniform field over the recommended test volume (+/- 1 dB),
- broadband frequency coverage exceeding 1 GHz without separate antennas,
- frequency dependent field variations of < +/- 3 dB,
- pulse testing capability (including high voltage / power), and
- a cost effective, versatile test environment.

The cell may also be used for emission testing resulting in;

- short measurement times,
- a high sensitivity with minimal background noise, and
- good correlation to standard type ground screen measurements.

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