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Examination of the E-field distribution in the MEB 1750 GTEM cell

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By

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ABSTRACT

The purpose of this report is to investigate the **E**-field distribution in a GTEM cell over the range 30 MHz to 1 GHz using a set of calculable dipole antennas and an isotropic field probe, the FP-2000. The vertical **E**-field along the longitudinal axis of the cell is examined and also the cross-polar components using the 300 MHz and 1 GHz dipole elements. The previously observed longitudinal peak at around 130 MHz is examined in detail. A NEC model was used to calculate the free space antenna factors of the dipoles and to examine the theoretical broadband response. The AF's calculated by the NEC model agree with the manufacturer's model (which is an implicit NEC-based model) at the resonant frequency of each dipole pair and so the models were assumed to agree over the appropriate frequency range.

From measurements taken towards the tip of the GTEM it appears that for small Equipment Under Test (EUTs) without cables there may be an advantage in measuring at two different positions at which the longitudinal component appears at different frequencies. The effect of cabling on both vertical and longitudinal **E**-fields is examined, and the dipole measurements compared with the FP-2000, which uses a fibre-optic link.

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1. Introduction

The GTEM cell is used by many research institutions and EMC test laboratories as a tool to evaluate the response of small EUTs (equipment under test) to electromagnetic radiation in conditions approximating to free space. GTEMs are a cheaper alternative to the large Open Area Test Sites (OATS) such as the one at NPL. Despite GTEM cells having been in existence for over ten years, little progress has been made on improving the uncertainty of these devices. It is hoped that by improving our knowledge of the properties of the GTEM, causes of uncertainty can be identified and quantified. If such causes can be identified, it is hoped that either the effects can be reduced, or a correction term applied to convert the measurement to an equivalent free space value.

Two types of probe are used in this report. The calculable dipoles are used as the antenna factors can be predicted very accurately from modelling. The disadvantage of the dipoles is that they must be fed by co-axial cables, which can produce coupling effects, particularly if used in the small volume close to the GTEM tip. This effect becomes even more significant when using the dipoles to measure the cross-polar component of the **E**-field. As a result the second probe, the isotropic FP-2000 probe was also used, as it has a non-perturbing optical link, and these results were compared to those measured with the calculable dipoles.

The report concludes that while it may be advantageous to measure small EUTs at two positions in the cell to avoid a longitudinal standing wave, this may be counter productive if the EUT has RF cables, as the effect of cabling close to the cell tip is significant. NPL is currently in the process of examining a dipole sensor with a fibre-optic link, which should provide better results from field-mapping within the cell. In addition, NPL are participating in a national survey of GTEM cells, co-ordinated by the GTEM User Group, which will involve all users evaluating the same probe under identical conditions to determine the agreement between different GTEM cells. Further, NPL is investigating the effects of lining the walls of the GTEM cell with absorber to see if this limits higher order mode propagation, which could be adversely affecting measurements. This may also make it productive to carry out field-mapping exercises at higher frequencies.

2. Experimental set-up

2.1 Defining the geometry of the GTEM

For the purposes of this report the centre of the GTEM and the co-ordinate system is defined as in Figures 1 and 2 below. The GTEM used by NPL is the MEB 1750. In the transverse (*x*) direction, the centre is half way between the GTEM walls on the central axis. In the vertical (*y*) direction, the centre is half way between the floor and the septum. In the longitudinal (*z*) direction, the centre is defined as the midpoint of the door.

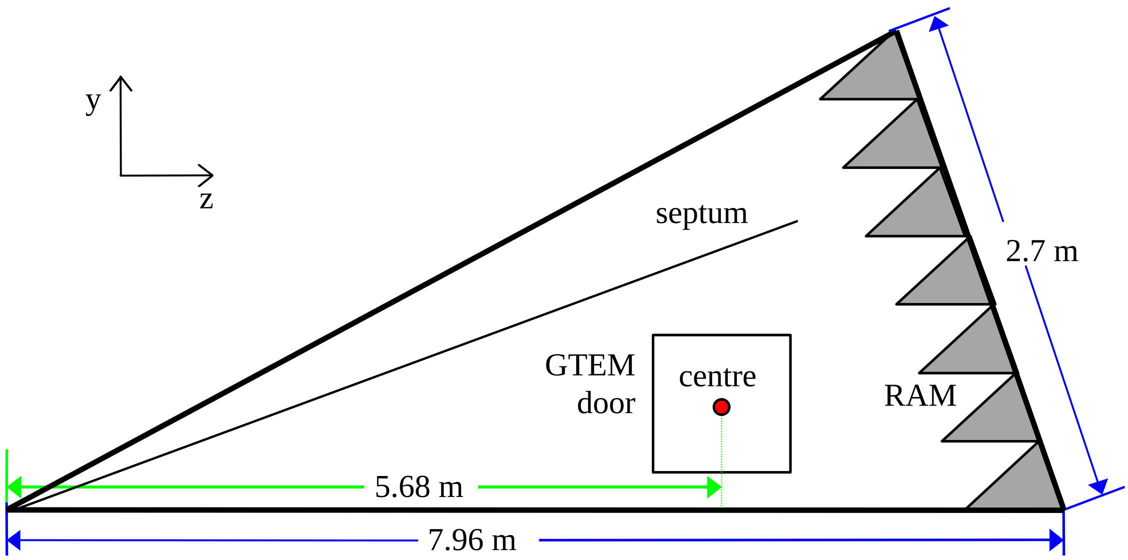

Figure 1 : Dimensions of GTEM, side cutaway through centre

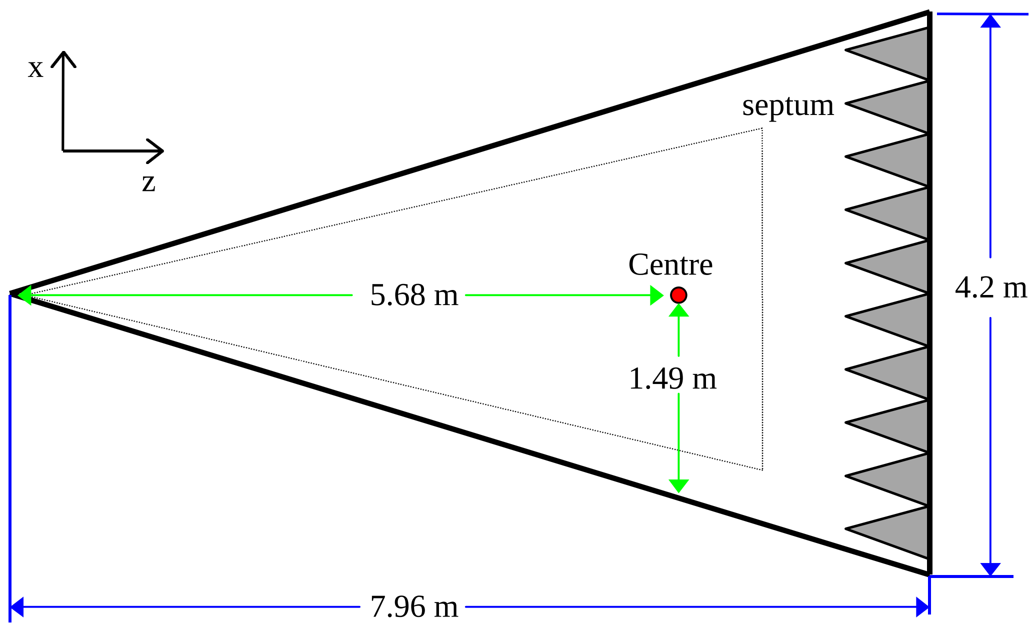

Figure 2 : Dimensions of GTEM, plan view

At each measurement position the probe is half way between the floor and septum at that point in the cell.

2.2 Experimental set-up of the calculable dipoles

The calculable dipoles used here are from ARCS (Austrian Research Centre, Seibersdorf) and are comprised of eight dipole elements pairs, from 300 MHz to 1 GHz.

2.2.1 Measurement of vertical field component

Figure 3 shows the experimental set-up using the dipoles. The dipoles are supported with polystyrene blocks which have electrical properties very similar to air, to minimise perturbation of the **E**-field by the support. For vertical **E**-field measurements the cable from the dipole is routed towards the back of the cell and then drops vertically down to the floor. It is also loaded with ferrites to minimise coupling effects. The dipole elements are positioned exactly half way between the floor and the septum and are aligned vertically. Below the cut-off frequency of the empty GTEM, the **E**-field propagates as a spherical wave, perpendicular to the septum and the floor. Therefore at the half height of the cell the **E**-field is expected to be slightly offset from the vertical. It is hoped that this effect will be negligible compared with the vertical field component. This is evaluated later in the report (Section 4.1).

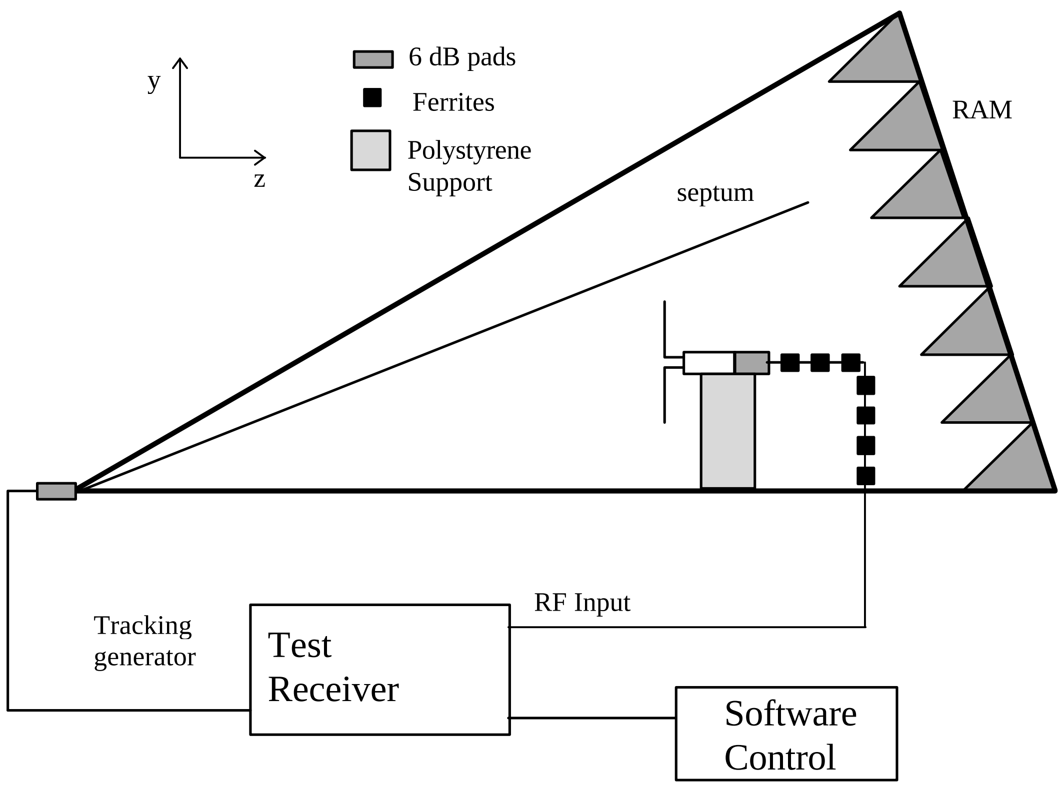

Figure 3 : Schematic diagram of experimental set-up

The test receiver is controlled by software which allows the frequency step and input power to the GTEM to be automated so that the power entering the cell remains constant. The system was evaluated between 30 MHz and 180 MHz in 1 MHz steps, and between 182 MHz and 1000 MHz in 2 MHz steps. Before connecting the dipole a through measurement is carried out over this frequency range to determine the cable loss, which is then subtracted from the measured "site" attenuation. In this case the measurement "site" is the GTEM cell. In Figure 3 the cables are shown routed towards the RAM and out of the cell. It was found that cable positioning has a significant effect on the measurements.

2.2.2 Longitudinal measurements

For the longitudinal (i.e. *z*-directed) component the dipole is placed in the GTEM as shown in Figure 4. For these measurements, the cable is routed out of the cell in the transverse direction. Again this is to minimise effects from cable coupling. The instrumentation external to the GTEM is the same as in Figure 3. The centre of the dipole is in the same position as before.

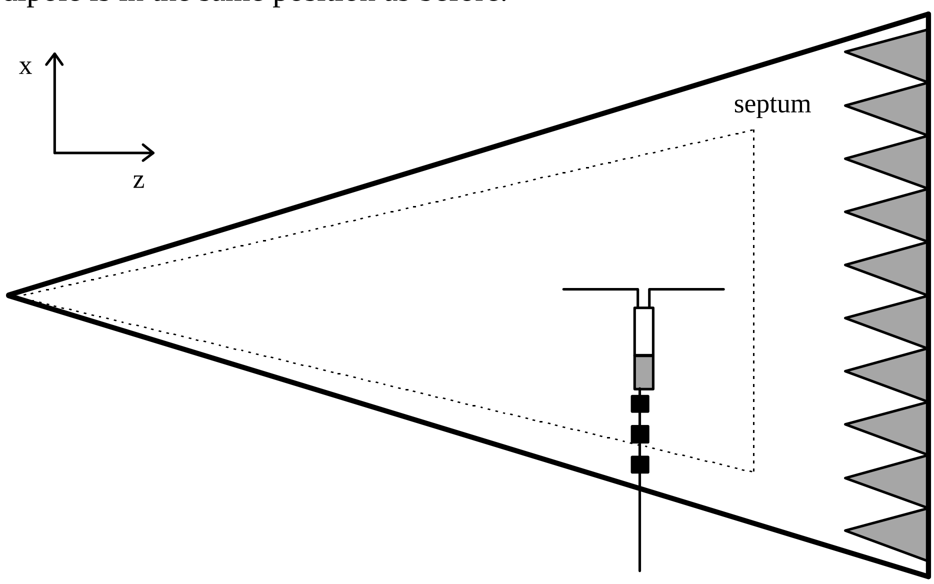

Figure 4 : Schematic diagram showing position of dipole and cables for cross-polar measurements

2.3 Experimental set-up of the isotropic probe

The isotropic probe was placed at the same positions as the calculable dipoles, but has its own plastic support stand. Because the probe has a fibre-optic link there is no cable reflection. Therefore comparison with the dipole measurements can be used to quantify the effect of cable positioning on measurements taken with the dipoles. The probe consists of three mutually orthogonal monopoles, and records the three orthogonal components individually as well as the total isotropic value. As a result it does not need to be moved to measure the cross-polar component. The experimental set-up is more complex than that using the dipoles, and is shown in Figure 5 below.

The system is controlled using the Visual Basic program control.vbp, developed at NPL and contains a feedback loop. A power meter is connected to the tip of the cell and a calibration run is carried out to quantify the output of the signal generator required to keep the **E**-field at the centre of the cell constant. This then enables the user to set up a constant **E**-field at the centre of the cell across the whole frequency range, which, for the purposes of this project, was set to 8 Vm^{-1}. By continuing to monitor the power entering the cell it is possible to check that the output amplifier hasn't drifted over the time taken to carry out the measurement run.

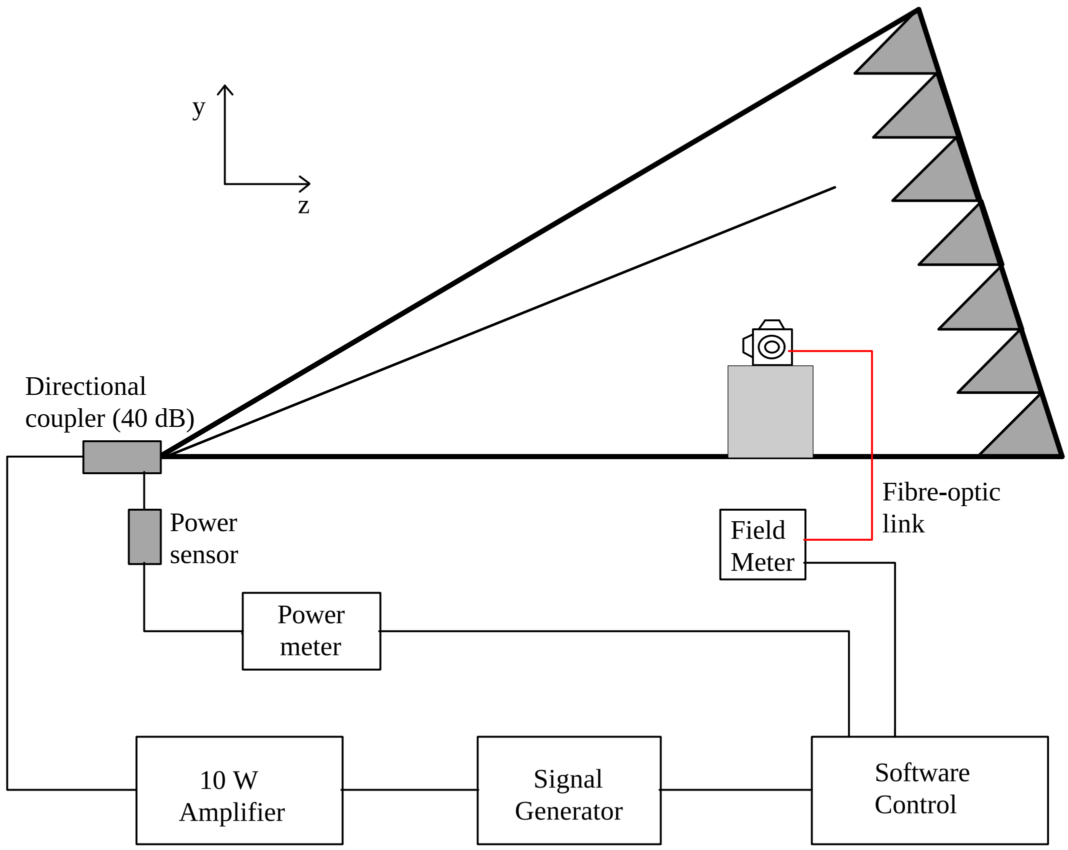

Figure 5 : Experimental set-up of the isotropic probe in the GTEM

2.4 Calculation of the dipole AF's from measured data

The test receiver records the measured site attenuation, SA_{Meas}, of the system, which incorporates the dipole, the cabling and the GTEM. To isolate the dipole antenna factor it is necessary to allow for the cable loss and the antenna factor of the cell. The cable losses are accounted for by connecting the cables and measuring the attenuation and then subtracting this from the measured site attenuation with the cables in place. Providing that the TEM mode is the dominant mode of propagation, the **E**-field in the cell can be approximated by

$$E = V/d \qquad [1]$$

where d is the septum height and V is the voltage between the septum plate and cell walls. The antenna factor of the GTEM in dB is given by the equation

$$AF_{GTEM} = 20\times\log_{10}\left(E/V\right) \;=\; -20\times\log_{10}(d) \quad \text{dB} \qquad [2]$$

assuming the **E**-field obeys Equation [1].

$$AF_{Meas.} = SA - Through(dB) - \left(20\times\log_{10}(d)\right) \quad \text{dB} \qquad [3]$$

This can now be compared to the free space AF predicted by the NEC model.

3. The NEC model and free space AFs

3.1 Construction of the NEC[1] model of the calculable dipoles

The NEC input file for modelling the dipole elements is included in Appendix A. Each pair of elements is modelled as a single wire with 31 segments of equal length and radius. The length is that specified by the manufacturer plus the width of the balun (15 mm), and the radius of the elements is 1.5 mm. The free space antenna factor is determined by modelling a 100 Ω load on the central segment and illuminating the dipole with a linearly polarised plane wave[2]. The current across the load is then used to determine the antenna factor. For each dipole pair the NEC model was run twice to cover the required frequency range, from 30 MHz to 180 MHz in 1 MHz steps, and from 182 MHz to 1 GHz in 2 MHz steps. This is the same range and stepping intervals as measured with the test receiver.

3.2 Calculation of theoretical free space AF

The free space antenna factor of the dipole, AF_{FS} is given by

$$AF_{FS} = AF_{NEC} + ATT_{Balun} \qquad [4]$$

where AF_{NEC} is the antenna factor of the elements as calculated by NEC (see Section 3.1), and ATT_{Balun} is the attenuation of the balun. The balun attenuation has been measured by the manufacturer, Austrian Research Centre Seibersdorf (ARCS) and is included in the specifications. The balun is of type PRD-B, s/n 063. As the change in attenuation across the entire frequency range is only 1.1 dB, at frequencies not explicitly stated in the specifications, the values are interpolated.

3.3 Comparison with manufacturer's data

The manufacturers specifications show only the antenna factor for each dipole pair at its resonant frequency. This is derived using the manufacturers own NEC-based program. Table 1 shows the resonant antenna factors given by the manufacturer and those derived using the NPL NEC model. These show very good agreement and therefore indicates that we are using a very similar, if not identical, NEC model as the manufacturer.

Frequency, MHz	Manufacturers specs., dB	NPL model, dB
300	14.74	14.74
400	17.24	17.24
500	19.18	19.17
600	20.76	20.76
700	22.10	22.10
800	23.26	23.25
900	24.28	24.28
1000	25.20	25.19

Table 1 : Antenna factors of dipoles at resonant frequencies, from the manufacturers specifications and derived from a NEC model.

The specifications recommend that each element pair may be used over a 15 % bandwidth, which allows the combination of dipoles to cover the entire range from 300 MHz to 1 GHz. For the purposes of this experiment, all dipole elements were evaluated over the entire frequency range. If the different length elements produce the same results at a particular frequency, then the broadband calculated AFs are correct. It is expected that for each element pair, agreement between measured and predicted AFs will be best near their resonant frequency. Making measurements over a wide frequency range will test the antenna in two ways; first the usefulness of using this set of calculable dipoles broadband, and second, a further test of the accuracy of the NEC model.

4. Results obtained with the calculable dipoles

4.1 Calculated and measured antenna factors

The difference between the free space AF's derived from the NEC model compared to the measured AF's (ΔAF) is given by combining Equations [3] and [4]

$$\Delta AF = AF_{FS} - AF_{Meas} = \left(AF_{NEC} + ATT_{Balun}\right) - \left(SA - Through(dB) - 20 \times \log_{10}(d)\right)$$ [5]

The differences between the theoretical and measured free space antenna factors were found for all element pairs at all longitudinal positions. The difference at the central position is shown in Figure 6.

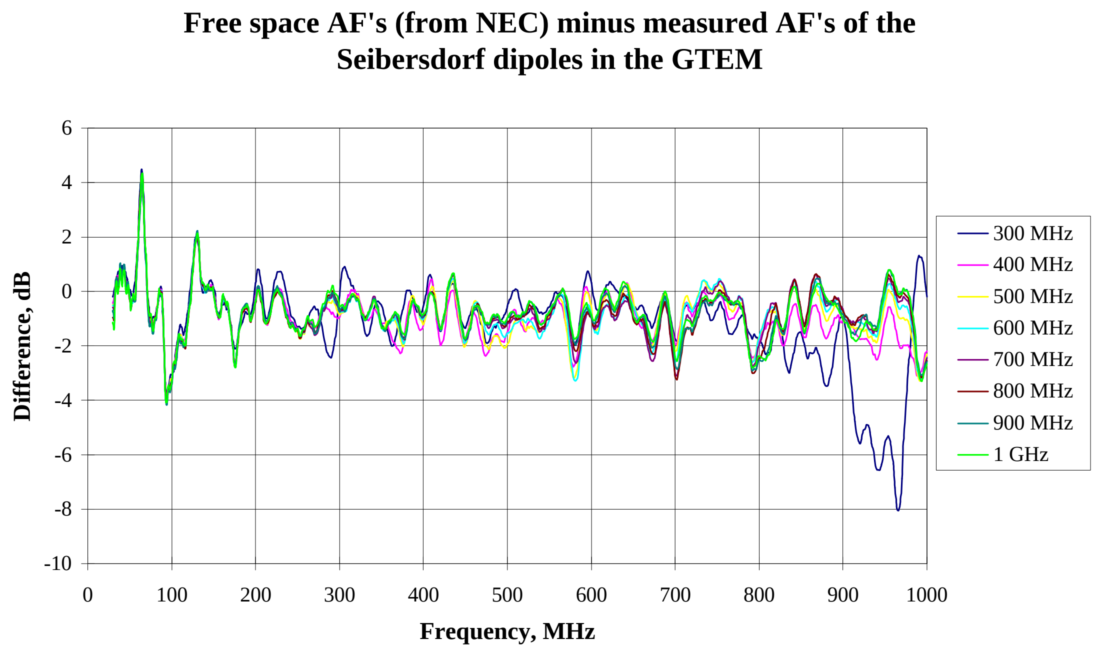

Figure 6.

The graph demonstrates that the measured and modelled values show relatively good agreement, even broadband. with the only significant variation occurring at the top end of the frequency range using the 300 MHz dipoles. Allowing for a systematic offset of -1 dB, the agreement is generally within ± 1 dB. This could be due to the **E**-field not quite obeying the equation *E* = *V/d*, or by a loss in the system not already accounted for. Another possibility that was considered was the fact that the dipole element is placed vertically in the cell, but the direction of the **E**-field at each point should be tangential to the wavefront at that point. The angle between the septum and the cell floor is approximately 13.5° and therefore halfway between the septum and the floor the **E**-field will be at an angle of 6.7° with the vertical. The vertical **E**-field in dB therefore will be reduced by

$$\left(20\log_{10}\cos(6.7°)\right) = \text{-0.06 dB}$$ [6]

This is not enough to explain the discrepancy. However, this does show that the uncertainty produced as a result of positioning the antenna vertically is negligible compared to other sources of uncertainty.

At the higher end of the frequency range the two largest element pairs (i.e. 300 MHz and 400 MHz) show less agreement and deviate by up to - 8 dB at ~ 970 MHz, but this is to be expected as these elements are now operating at at least twice their resonant frequencies, which is the limit of their usable bandwidth of 200%. In addition, as the dipole elements are longer, they will be in closer proximity with the GTEM walls, and therefore there will be more coupling effects though this effect is probably negligible.

4.2 Vertical component moving along longitudinal axis

The measurements discussed in Section 4.1 were repeated at 10 positions 0.5 m apart moving along the longitudinal axis of the cell, with the probe halfway between the septum plate and the cell floor. The purpose of this was twofold, first to evaluate the effect of the finite length of the dipoles, and second to examine whether it may be preferable to measure small EUTs closer to the tip of the GTEM over part or all of the frequency range.

The 300 MHz elements are the longest with a tip to tip length of 0.471 m including the balun. Moving towards the tip of the GTEM the floor to septum height diminishes and so mutual coupling between the antenna and the cell will increase. Figure 7 shows the vertical **E**-field measured by the 300 MHz dipoles at several positions along the longitudinal axis of the GTEM.

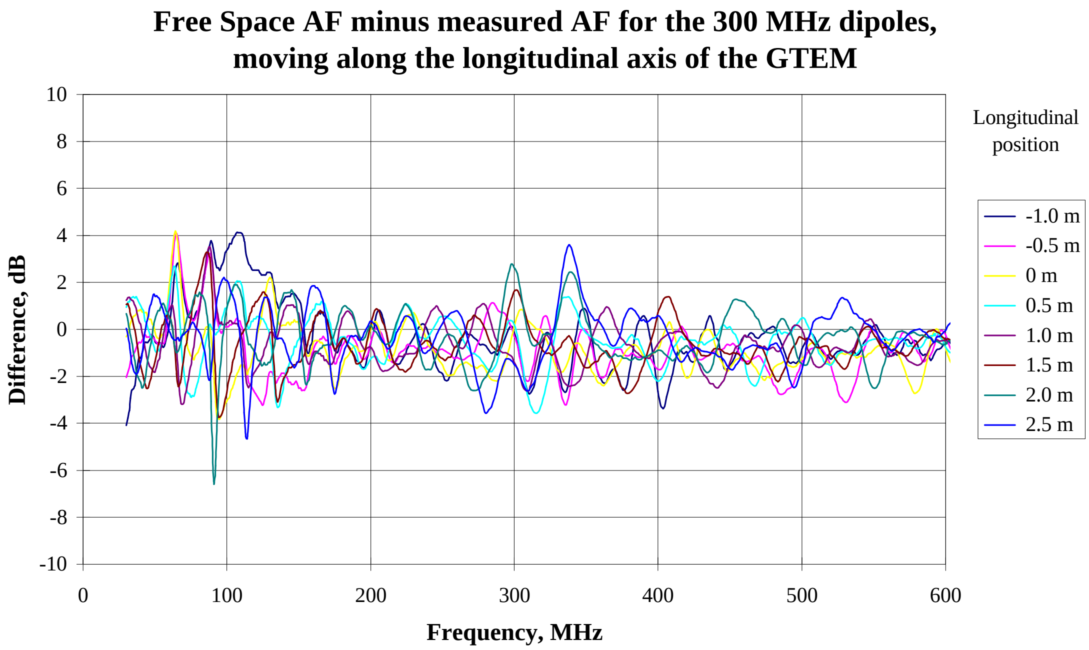

Figure 7.

Figure 7 shows that for most of the frequency range the differences between measured and predicted antenna factors are within ± 4 dB. The graph only shows data up to 600 MHz, the upper limit of the usable frequency of this dipole pair. It is not clear from this graph whether moving the dipole along the *z*-axis of the cell will improve the correlation between measurement and theory. Figure 8 shows the difference between measured and predicted results using the 300 MHz elements. This does not show any significant benefit in carrying out measurements closer to the apex of the GTEM. Indeed it appears that amplitude variations are worse as the dipoles approach the apex. However, this makes no allowance for any cross-polar component of the **E**-field, and also these are the longest element pairs and so will have the most mutual coupling. This is discussed further in Section 4.4.

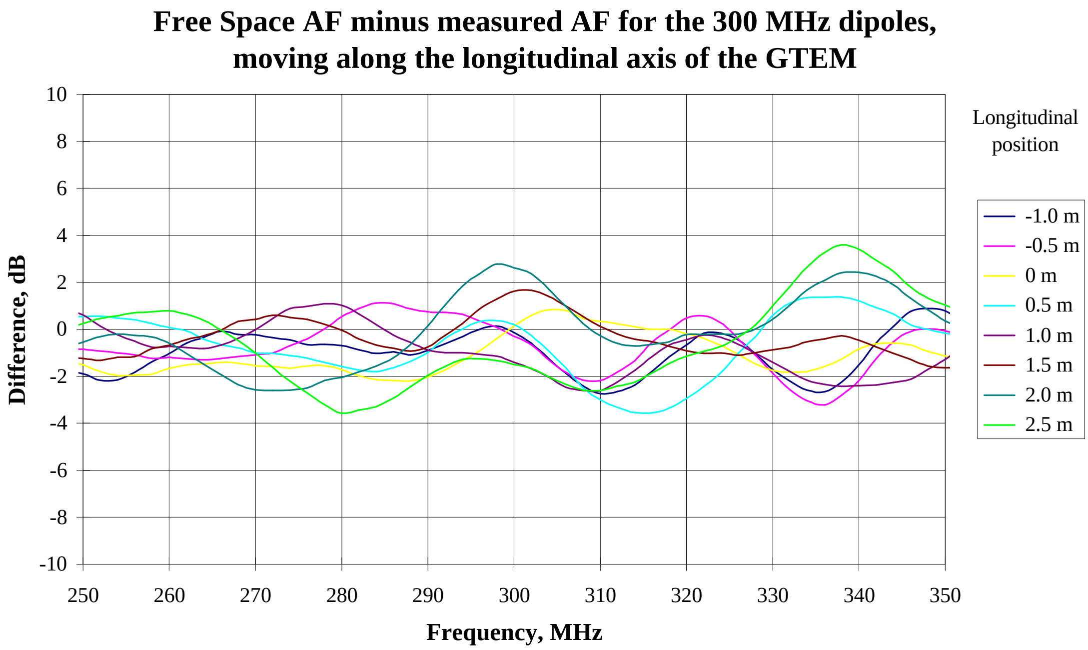

Figure 8.

4.3 Vertical component along transverse axis

The vertical **E**-field was also measured with the dipoles in different positions along the transverse (*x*) direction towards the cell door. An example of the differences between free space AFs and measured AFs, using the 600 MHz dipoles, in shown in Figure 9.

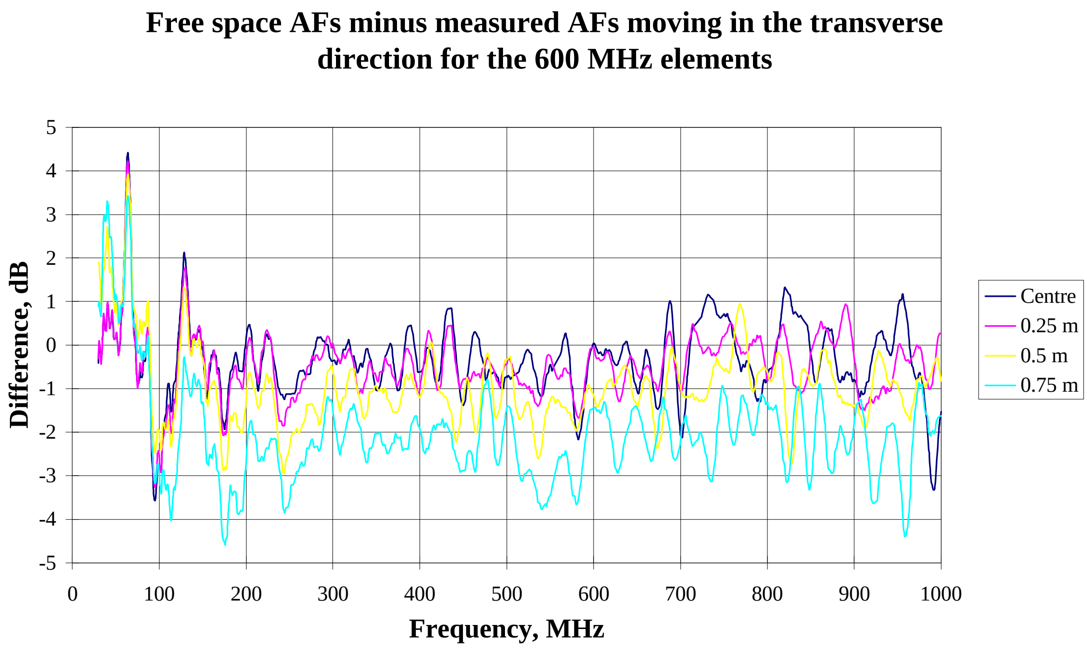

Figure 9.

At 0.25 m from the centre there is no obvious discrepancy between the theoretical free space AFs and the measured values, but at 0.5 m and 0.75 m the two data sets differ by around 1 dB and 2 dB respectively. This is most likely to be a result of fringing effects at the edges of the septum. The usable test volume of a GTEM is defined to be ± (septum height/6) = ± 0.253 m for the NPL GTEM. At 0.25 m from the centre there appears to be no change from the field measured at the centre of the cell for the 600 MHz dipoles, which supports this definition of the usable test volume. In practise a test volume of *d*/3 is commonly used in TEM/GTEM cells.

4.4 Longitudinal component of E-field

It has been demonstrated in previous reports that some GTEM 1750 cells display a longitudinal resonance at around 130 MHz. Previous investigations in the NPL GTEM using an isotropic probe, the FP-2000, showed that at the central position this occurred at around 125 MHz. The cross-polar component of the **E**-field was then measured using the 300 MHz element pairs. By examining this peak at the centre of the GTEM and repeating measurements along the length of the cell it was hoped to determine whether it was possible to find a position where this effect did not occur, or whether it would just be shifted in frequency. For the purposes of this report, cross-polar refers only to the longitudinal (*z*-directed) **E**-field component. The transverse (*x*-directed) field was measured but found to be in the noise floor.

Figure 10 shows the cross-polar component in dB moving along the longitudinal axis of the GTEM measured using the 300 MHz dipole pair. The measurement was carried out across the whole frequency range, but this graph concentrates on the region where the longitudinal peak occurs. It does appear from this graph that at 3 m from the central point of the GTEM towards the tip, the longitudinal peak at approximately 125 MHz does not appear. However, the graph shows a ripple up to about 130 MHz. Higher order mode propagation and cable pick-up and re-radiation (see section 4.5) may be responsible for this effect.

The measurement was repeated using the isotropic FP-2000 E-field probe to evaluate the effect of an interaction between the cell and the dipole. This probe has a smaller sensor element than the calculable dipole, and also has fibre-optic cables, which will not perturb the field though the sensor volume is greater. This is shown in Figure 11.

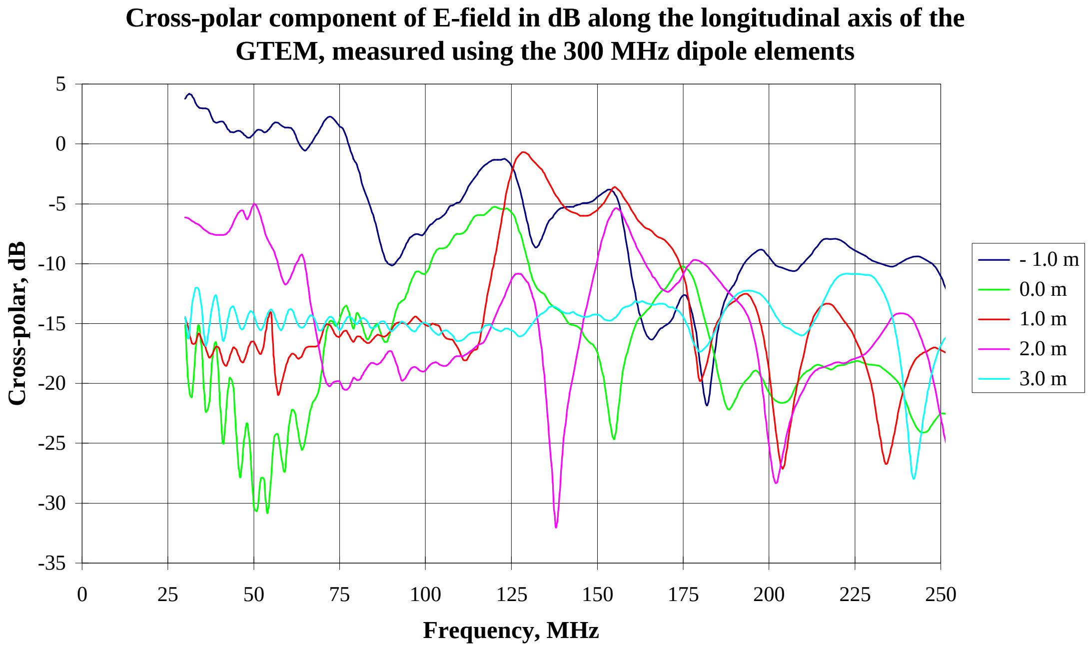

Figure 10.

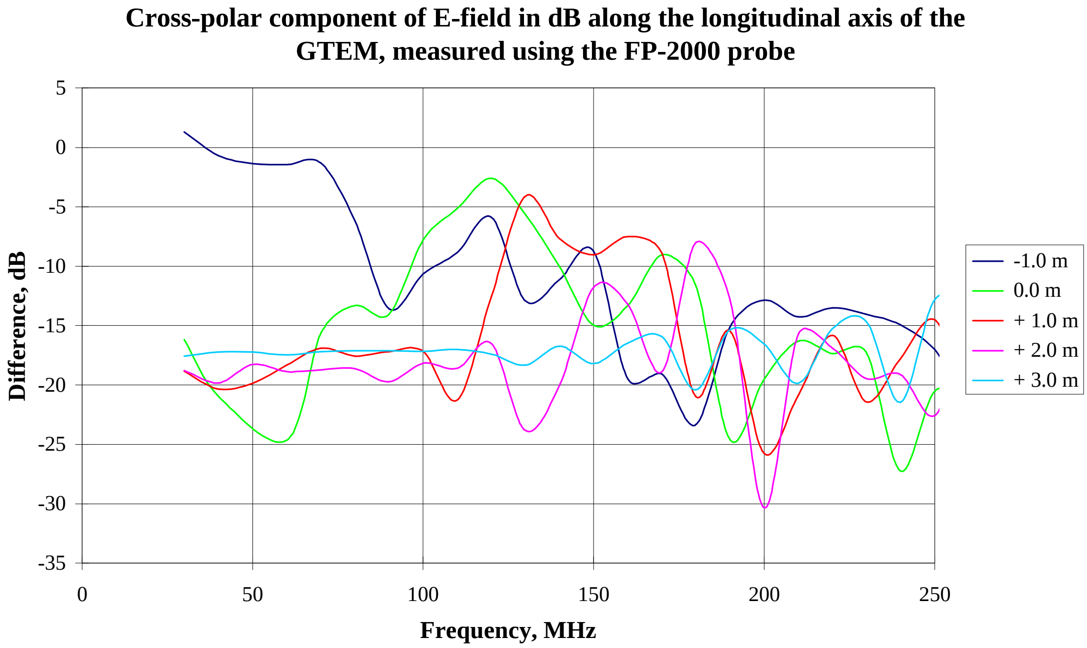

Figure 11.

The results from the FP-2000 probe also demonstrates that at 3 m the longitudinal peak does not appear. The ripple effect observed from the dipole measurements does not appear, implying that this particular effect is possibly explained by interaction of the fields with the co-axial feed of the dipole.

Figure 11 also shows that as the probe is moved closer to the GTEM tip, the peak moves up in frequency and decreases in amplitude. It is noticeable that at the position closest to the RAM there is a very high longitudinal component measured by both probes under about 90 MHz. At this position the probes are very close to the RAM and could be susceptible to interference resulting from reflections in the RAM. In addition, this frequency is around the point where the pyramidal RAM takes over from the resistor board as the dominant absorber and this could also be contributing to the field perturbation.

Figure 12 shows the cross-polar component of the **E**-field over the whole frequency range, 30 MHz to 1 GHz, at the centre position and 3 m towards the apex measured by the FP-2000.

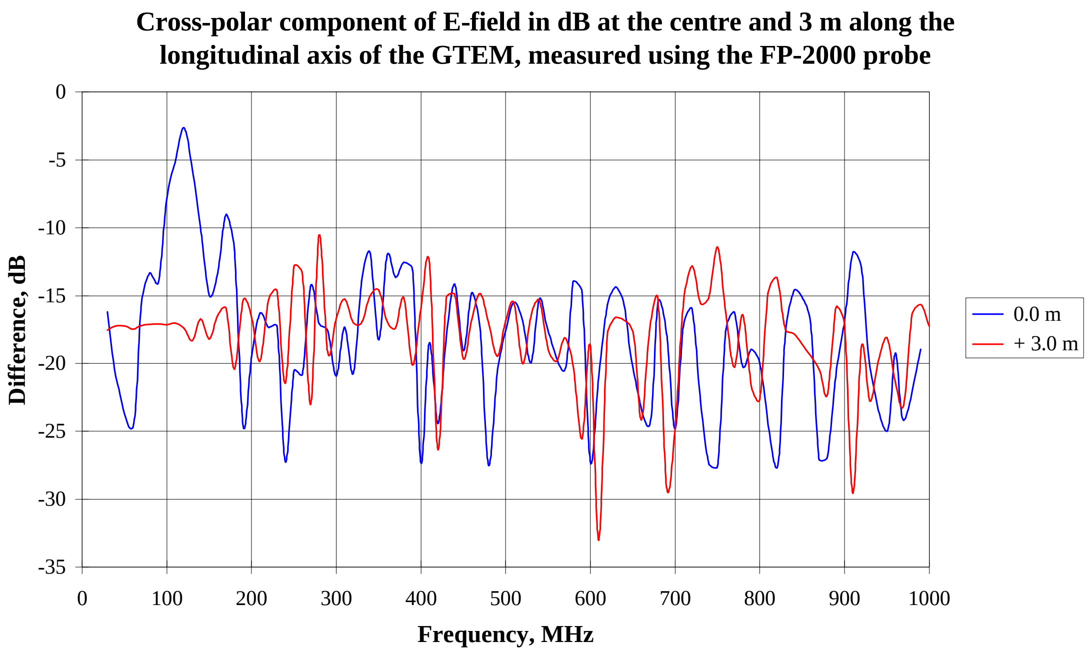

Figure 12.

Figure 12 clearly shows that the longitudinal peak is not present in the 3 m measurement. However, as the frequency increases there is more fluctuation at the 3 m position than at the centre point. As a result it may be beneficial to measure small cable-less objects (see next section) at two positions, close to the apex for low frequencies (e.g. up to 250 MHz) and at the normal measurement point for the rest of the frequency range.

4.5 Cabling effects

It is known that the exact position of the cables can have a significant effect on the measured **E**-field. To quantify this effect within the GTEM, the 1 GHz dipoles were used to measure the vertical **E**-field with two different cable configurations. These were chosen as they are the smallest element pair and so will cause minimal field perturbation. No other parameters were changed. The configuration used for the purposes of this report had the cable leading back along the longitudinal *z*-axis before dropping vertically to the floor and routed out of the cell (see Figure 3). The probe was then rotated so that the cable was led out in the transverse (x) direction to the GTEM wall, then dropped vertically to the floor and routed out of the cell as before. These measurements were carried out at the centre of the GTEM and also 3 m towards the GTEM tip. The measured site attenuation for both configurations at both positions are shown below. These graphs concentrate on the frequency range where the longitudinal peak is observed.

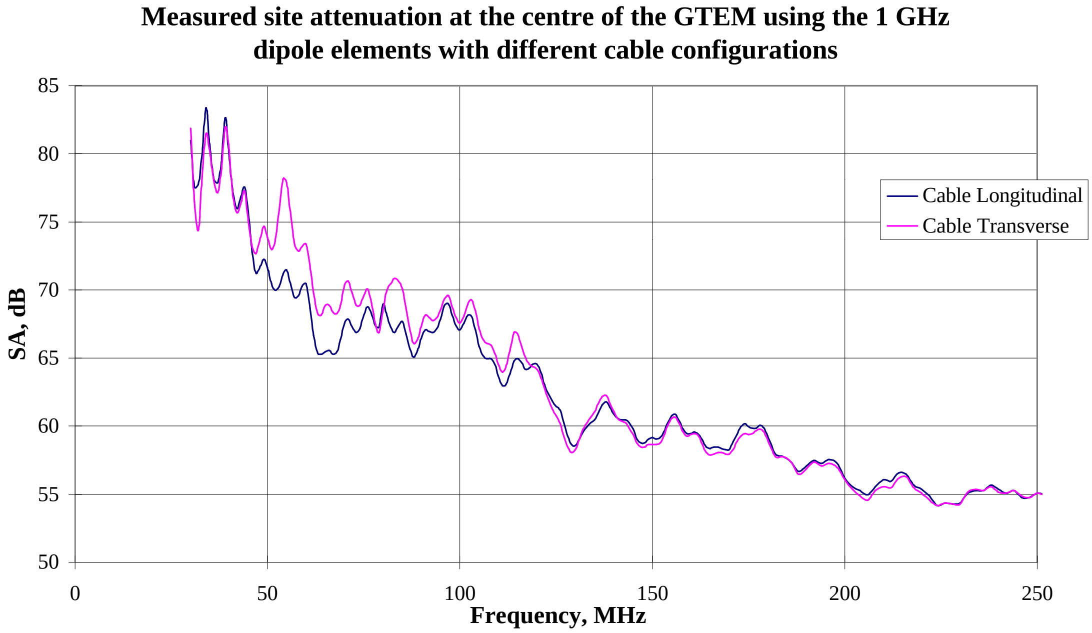

Figure 13 : Effect of cable configuration at the central GTEM position

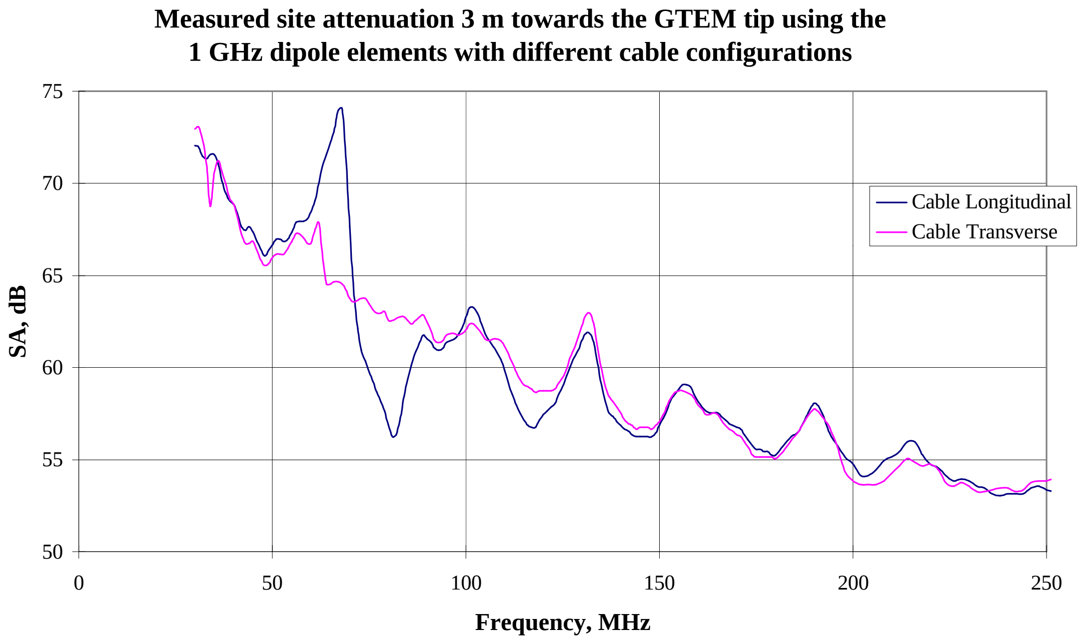

Figure 14 : Effect of cable configuration 3 m towards GTEM apex

It is clear from Figures 13 and 14 that the cabling does have a significant effect on the measured site attenuation, particularly below 150 MHz and that the effect is considerably greater at the 3 m position. Figure 15 shows this more clearly. The difference between the measurements obtained using the two different cable configurations vary between approximately + 4/- 7 dB at the centre position and + 10 /-6.5 dB 3 m towards the tip.

Longitudinal cable configuration minus transverse cable configuration measured in the GTEM using the 1 GHz dipole elements

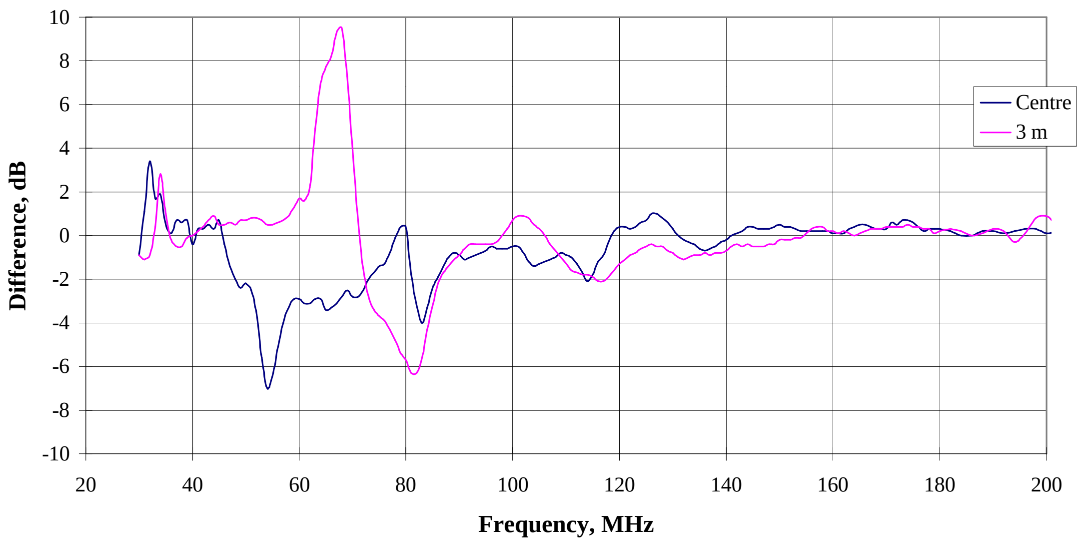

Figure 15.

These measurements were carried out from 30 MHz to 1 GHz, in 1 MHz steps from 30 MHz to 180 MHz, and in 2 MHz steps from 180 MHz to 1 GHz. Figure 15 shows the effect at the higher frequency end of the range.

Longitudinal cable configuration minus transverse cable configuration measured in the GTEM using the 1 GHz dipole elements

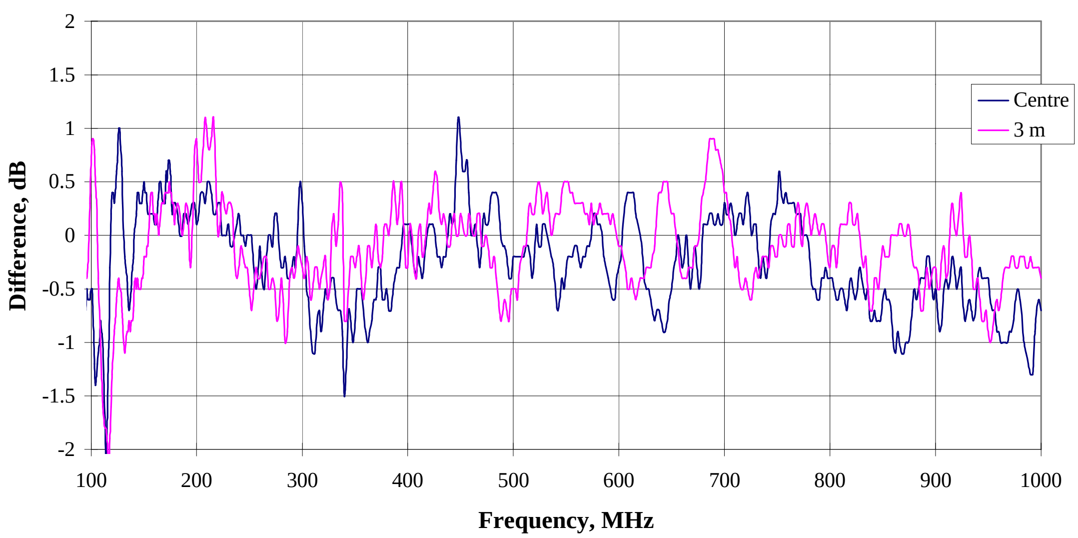

Figure 16.

Figure 16 shows that while the effect on the higher frequency measurements is lower, above 200 MHz changing the cable configuration causes a variation in site attenuation of +1/-1.5 dB. Again, this effect occurs at both positions and there is no obvious trend. This is certainly an area of GTEM measurement which requires more research.

5. Conclusions

5.1 Validity of the NEC model of the ARCS dipoles

Comparison of the results produced by the NPL dipole model with the results produced by the ARCS's model show very good agreement. Agreement between the modelled antenna factors and those measured in the GTEM show agreement within ± 1 dB with a systematic offset of 1 dB across 70 % of the frequency range, with larger discrepancies occurring at the maximum and minimum frequencies. This demonstrates surprisingly good agreement.

5.2 Uniformity of E-field in the test volume

From examination of the difference between the field measured at the cell centre and moving around the test volume, these measurements support the definition of the usable volume of the cell of ± $d/6$ as the **E**-field uniformity remains reasonably constant throughout the test volume.

5.3 Longitudinal component at 125 MHz

Examining the measurements made with the FP-2000 probe, it appears that there is an advantage of measuring small EUTs closer to the GTEM apex in order to avoid the longitudinal component at 125 MHz. The peak is not observable 3 m from the centre position, and therefore there would be an advantage in measuring up to around 250 MHz at this position instead. The results show generally good agreement up to 1 GHz at the 3 m position, but because of a couple of sharp troughs at around 600 and 900 MHz it is recommended that measurements above 250 MHz should be carried out at the cell centre.

5.4 Cabling effects

The results of changing the cable configuration of the calculable dipoles in the GTEM show that cable pick-up and re-radiation can have a very significant effect on measurements carried out in a GTEM. The EMC product simulated here was very simple, a dipole antenna with one ferrited cable, and for a more complex structure with more than one cable this effect would be even more significant. For this simple structure, the choice of cable layout produced an effect of + 1 / -1.5 dB, which is greater than the difference in measured and modelled free space antenna factors. While this substantiates the model, further research is needed to investigate whether this effect can be reduced by, for example, shielding the cable, or whether it is possible to derive a correction factor to allow for cabling.

5.5 Suggestions for further research

The extent of cabling effects observed in this investigation show a need for more research in this area. A possible option would be to use a well-known EUT, such as the calculable dipoles, in a variety of cable configurations in the GTEM to examine this effect further. In addition it may be worth investigating the effect of measuring close to the apex with non-isotropic cable-less EUTs, for example a mobile phone. Further, the option of measuring close to the apex of the GTEM cell is quite restrictive, since the EUT must be small and have no radiating cables, so further research into other options of reducing the cross-polar component is needed. This could involve adding some kind of absorber to the cell, optimising the resistive termination, or measuring the EUT in more than one orientation and developing a correlation function to compare to free field measurements. Finally, it would be useful to investigate the possibility of extending the usable test volume beyond $\pm d/6$ to accommodate larger EUTs in the GTEM.

6. References

[1] Burke, G.J. Numerical Electromagnetics Code - NEC4 Method of Moments Part 1: Users Manual (NEC-4.1), Lawrence Livermore National Laboratory, 1992

[2] Loader, B.G., Alexander, M.J. and Salter, M.J., Reduced measurement uncertainties in the frequency range 500 MHz to 1 GHz using a calculable standard dipole antenna, IEE Tenth International Conference on Electromagnetic Compatibility, Warwick, September 1997, pp175-180.

Appendix A - NEC model of calculable dipoles

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CM NEC model of the Seibersdorf dipoles in free space to
CM determine the antenna factors. Uses the receive
CM configuration as it is the quickest and simplest.
CM SHF 18/1/99.  Geometry from manufacturers data.
CM NOTE : this does not allow for the width of the balun.
CE 300 MHz elements
CE1 11 00.000 -00.228 00.000  00.000 00.228 00.000 0.0015
CE 400 MHz elements
GW1 11 00.000 -00.1683 00.000 00.000 00.1683 00.000 0.0015
CE 500 MHz elements
CE1 11 00.000 -00.1325 00.000 00.000 00.1325 00.000 0.0015
CE 600 MHz elements
CE1 11 00.000 -00.1087 00.000 00.000 00.1087 00.000 0.0015
CE 700 MHz elements
CE1 11 00.000 -00.0918 00.000 00.000 00.0918 00.000 0.0015
CE 800 MHz elements
CE1 11 00.000 -00.0791 00.000 00.000 00.0791 00.000 0.0015
CE 900 MHz elements
CE1 11 00.000 -00.0693 00.000 00.000 00.0693 00.000 0.0015
CE 1000 MHz elements
CE1 11 00.000 -00.0614 00.000 00.000 00.0614 00.000 0.0015
GE 0
CE Frequency cards - can only use one per run
FR 0 151 0 0 30.0 1.0
CE 0 411 0 0 182.0 2.0
CE Receive configuration
LD 4 1 6 6 50.0 0.0
EX 1 1 1 0 90.0 0.0 90.0
PT 0 1 6 6
XQ
EN
```