Improving the Correlation between OATS, RF Anechoic Room and GTEM Radiated Emissions Measurements for Directional Radiators at Frequencies between approximately 150 MHz and 10 GHz

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ABSTRACT

This paper presents the results of investigations into how well the results of different measurement methods correlate at higher frequencies where near field effects can be ignored but the directivity of the radiation is important. A simplified derivation of the GTEM equations is presented to allow a clearer comparison with other methods. The effect of different Open Area Test Sites (OATS) is considered, and a universal specification suggested to define a correct result when there are differences. Existing Fully Anechoic Room and GTEM methods are then investigated, and where necessary modifications are proposed to ensure similar results. Experimental results for a mobile phone are then presented.

INTRODUCTION

A mobile phone is just one example of the rapid change in technology which is seeing higher microprocessor speeds and data transmission rates, and an increase in time division multiplex and frequency hopping techniques etc. which will require existing EMC measurement methods to be re-evaluated. For Radiated Emissions, as the frequency increases, the tendency for any radiating source to become directional increases, and suitable unambiguous methods need to be used. Lower frequencies where near field and other effects dominate, and higher frequencies where the radiation is in narrow beams have been excluded. The end frequencies covered by this paper are of necessity arbitrary; 150 MHz is the lowest frequency where free space waves are possible from an Equipment Under Test (EUT) 1 m ($\lambda/4$) above the ground, and 10 GHz is a round number.

DIRECTIVITY OF RADIATING SOURCES

The most common form of intentional radiator is the resonant half wave dipole; a vertically polarized dipole has a simple omnidirectional radiation pattern in the horizontal plane, and a directional pattern consisting of 1 lobe in the vertical plane. At frequencies lower than resonance, where half a wavelength is less than the radiating length, there will be reduced antenna efficiency, but the radiation pattern will be similar. This situation is usually assumed for most methods of radiated emission measurements. Most commercial random noise or comb generators used for site comparisons have relatively small radiating elements to ensure this.

At frequencies at or above resonance, various additional causes of directionality can occur:
An asymmetric or bent dipole becomes directional.
If double the resonant frequency is fed to a vertical mounted dipole, 2 lobes are produced in the vertical plane symmetrically at an angle from the horizontal plane. (3 lobes will be produced at 3 times the resonant frequency etc.)

The addition of parasitic radiating elements, earth plates, slots in the equipment casing, connecting leads etc. could also assist in ensuring that any radiation has directional characteristics.

Although every possible cause of directivity in the EUT radiation has not been described, it must be considered if accurate measurements are to be made, particularly if consistency is required between different OATS, anechoic rooms, GTEMs etc.

SIMPLIFIED ANALYSIS OF GTEM USING ANTENNA FACTORS

To aid the understanding of the behaviour of a GTEM, an alternative analysis using antenna factors (which are defined as being in the direction of maximum gain) is described.

The fundamental GTEM equation for the relationship between the vertical electric field (midway between the septum and the base) and the signal (across the apex terminals) is

$$E[\mathrm{V/m}] = e_0\sqrt{P[\mathrm{W}]} = e_0 V_{out} / \sqrt{50[\Omega]} \tag{1}$$

where e_0 is $\sqrt{Zc}/h$; h[m] is the septum height, and Zc[Ω] is the GTEM characteristic impedance (usually assumed 50 Ω). Taking logarithms of (1) gives

$$V_{out}[\mathrm{dBV}] = E[\mathrm{dBV/m}] + 20\log\left(\sqrt{50}\right) - 20\log(e_0)\ . \tag{2}$$

So a GTEM can be considered as having an Antenna Factor:

$$AF_{GTEM} = 17 - 20\log(e_0)\ . \tag{3}$$

Simulation of a Dipole Source (Substitution Method)

Consider that the field produced by the EUT can be simulated by a vertical resonant half wave dipole (again mounted midway) as defined in CISPR 16-1 G5 [1] as having a far field Antenna Factor:

$$AF_{dipole} = -31.9 + 20\log(f) \tag{4}$$

where f is the frequency [MHz]. Because there is no site loss, (3) and (4) give

$$V_{out}(\mathrm{GTEM}) = V_{in}(\mathrm{dipole}) - AF_{GTEM} - AF_{dipole}$$

and substituting in gives

$$V_{in}[\mathrm{dB}] = V_{out}[\mathrm{dB}] + 17 - 20\log(e_0) - 31.9 + 20\log(f) \tag{5}$$

This method is defined in some specifications and is also useful for calibration or software verification.

Simulation of Electric Field at a distance D

For free space under far field conditions (from the Friis Transmission Equation) the free space Normalized Site Transmission Loss is

$$NSTL[\mathrm{dB}] = 32 + 20\log(D) - 20\log(f) \qquad (6)$$

where D[m] is the measuring distance from the EUT. As the EUT is actually at the same position as the GTEM and not at a distance D away, the vertical electric field can be computed from (3) and (6) to give

$$E = V_{out} + AF_{GTEM} - NSTL \ ,$$

or

$$E[\mathrm{dBV/m}] = V_{out}[\mathrm{dBV}] + 17 - 20\log(e_0) - 32 - 20\log(D) + 20\log(f) \qquad (7)$$

Derivation of full IEC 1000-4-20 Correlation Algorithm

Instead of only the vertically polarized signal, 3 orthogonal measurements of the EUT are made in the GTEM, and the resultant V_{res} is used for V_{out} in equation (5) or (7):

$$V_{res} = \sqrt{\left(V_x^2 + V_y^2 + V_z^2\right)} \ [\mathrm{V}] \ ,$$

or

$$V_{res} = 10\log\left(10^{Vx/10} + 10^{Vy/10} + 10^{Vz/10}\right) \ [\mathrm{dBV}] \ . \qquad (8)$$

The same IEC 1000-4-20 [3] OATS ground reflection simulation is also required which adds the worst case vertical or horizontal polarization ground reflection effect (approximately +5 dB).

The validity of these two procedures will be discussed below.

DESCRIPTION OF DIFFERENT METHODS OF MEASUREMENT

(a) Open Area Test Site (OATS)

Traditionally, OATS have been used for radiated emissions measurements and most regulatory authorities will only accept this method. An OATS geometry is shown in Fig. 1.

The EUT is placed on a turntable at say 1 m height, and a measuring antenna placed on a mast a specified distance away. The ground plane must be perfectly conducting with no obstructions around the site, and the measuring antenna is raised and lowered (whilst the turntable is rotated by 360° at each frequency) so as to maximize the signal. The measurement is repeated for both vertical and horizontal polarization. If an omnidirectional radiation pattern in the vertical plane for both EUT and measuring antennas is assumed, the maximum signal will be when the direct signal from the EUT and that reflected off the ground plane arrive in phase at the measuring antenna, so that the result is up to about 5 dB greater than any free space value. This can be very confusing as the ground plane and height search effectively give some gain and therefore a result which is higher than the free space value. (The height search cannot be omitted as it ensures that the direct and reflected signals arrive together in phase rather than with arbitrary phase or indeed out of phase giving no signal at all.)

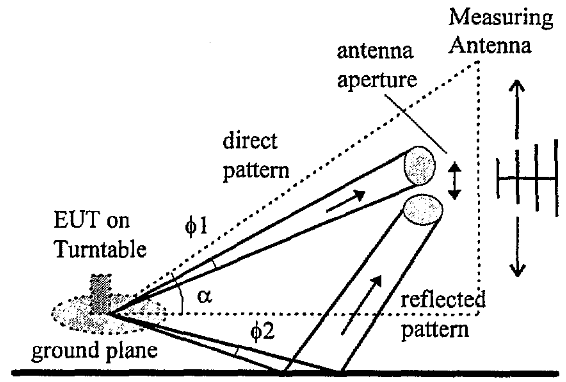

Figure 1. EUT measured on an OATS

CISPR 16-1 16.6.1 [1] allows 3 sites: 30 m distance with 2-6 m height search, 10 m distance with 1-4 m height search, and 3 m distance with 1-4 m height search.

This method was originally defined for low frequency use where the long wavelengths meant that it was impractical to do free space measurements. Here, the ground plane has a large effect, and the measuring distance means that near field and mutual coupling effects need to be considered.

Problems with directional radiation from EUTs Unfortunately for EUTs with significant directivity, the measurement is ambiguous because not only are the direct and reflected signals measured, but also the direct radiation pattern of the EUT over the angle α is measured. For an EUT positioned at a height equal to the bottom of the height search, the radiation from the EUT over the surface of a sphere up to α = 8° (30 m site), 17° (10 m site), 45° (3 m site) is also measured. Any ambiguity will be much worse for a 3 m site.

More precisely, at any single antenna height, for each frequency, turntable position, and polarization, the signal received at the antenna consists of the sum of the lobes directly radiated from the EUT over its aperture, together with the sum of the lobes radiated downwards towards the ground plane and reflected to the antenna. The angles of the radiation ($\phi1$ & $\phi2$) from the EUT received over the antenna aperture will also increase for decreased measuring distance.

For example, an EUT with one main lobe inclined upwards at 45°, will give a much larger result on a 3 m site than on a 10 or 30 m and any ground reflection may be negligible within the height search range. Or, an EUT with one main lobe inclined downwards could result in only a reflected signal being picked up within the height search range.

Additional effects of the directivity of the Measuring Antenna Real measuring antennas have increased directivity with increasing frequency. For low frequencies with antennas such as a biconical antenna, there is limited directivity in the vertical plane. The directivity is greater for a log periodic used between say 200 MHz and 1 GHz, and even greater for a double-ridged waveguide horn for use at greater than 1 GHz. Because of this, tilting of a directional antenna to ensure equal pickup of direct and reflected paths is recommended in CISPR 16-1 15.5.2 [1], but the actual result is difficult to compute as for each path it really depends on the sum of the EUT and antenna radiation patterns.

Proposal for a Universal Specification From CISPR 16-2 2.6.2.4 [2] it is stated that the whole purpose of the height search is to ensure that the direct and reflected rays are in phase and by implication not to measure the directional characteristics of the EUT in the vertical plane.

A proposal for a universal specification for comparing test methods can be stated as "the maximum field strength allowed at a specified distance from the EUT at a specified frequency, at all angles in an azimuthal plane for both vertical and horizontal polarization."

It is NOT intended to measure the radiation over the surface of the sphere from the EUT or to maximize any slant, or circularly polarized radiation horizontally radiated from the EUT. Such a universal free space definition would allow any test method to be used for any EUT with each method corrected or allowance made for any errors. In circumstances where the EUT had no directionality, OATS could still be used with appropriate correction to give the free space field. It should also be noted that the uncertainty principle applies in that if more spatial directions are specified to cover radiation upwards etc., the test time either tends to infinity or not every combination of parameters can be measured, particularly with the increasing use of time varying and frequency hopping modulation techniques.

RF Semi Anechoic Room This will not be considered in any detail as it is basically the OATS method indoors to eliminate external interference - an RF screened room is lined with radio absorbent material (RAM) except on the floor. The main problem is that it has to be very big, particularly at the low frequency end to avoid wall reflections and resonances within the room.

(b) RF Fully Anechoic Room

This consists of an RF screened room fully lined with RAM including the floor, to simulate a free space environment. It is shown in Fig. 2.

The arrangement is similar to the OATS except that the height search is omitted with the antenna fixed at the same height as the EUT. At each frequency and for both polarizations, the signal received at the antenna consists only of the sum of the lobes directly radiated from the EUT over the measuring antenna's aperture for a full 360 ° rotation. If log periodics are used at >200 MHz, say, and horns at >1 GHz, the aperture will be smaller with increased frequency. Both antennas are usually positioned symmetrically within the room and although 3, 10, or 30 m will normally be used, any distance can be used with the appropriate mathematical correction, although the angle ϕ will increase slightly for reduced distance. Also, small distances which could cause mutual coupling errors should be avoided.

The room must be sufficiently large and the RAM suitably designed so as to minimize the wall reflections and resonances, particularly at low frequencies. The RAM effectively reduces the 'Q' of these resonances. The floor RAM allows the use of a smaller although still large RF Screened Room compared with the Semi Anechoic Room. Positioning of the measuring antenna becomes more critical at higher frequencies due to smaller apertures, and with complex radiation patterns.

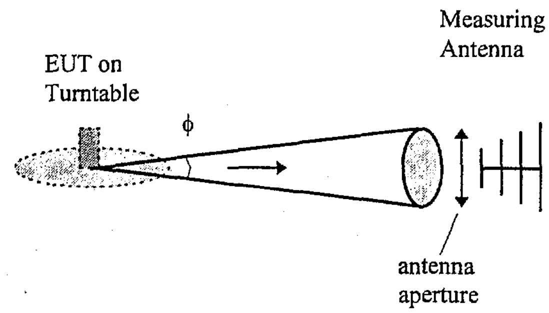

Figure 2. EUT measured in a Fully Anechoic Room

Ground Reflection Simulation To allow the results to be compared with the OATS results, the effect of ground reflections can be simulated mathematically [6]. Separate frequency correction curves for vertical and horizontal polarizations can be derived to increase the results by up to about 5 dB. These simulations assume a perfect OATS with no directionality in the EUT or measuring antenna. Where the EUT radiation pattern is not omnidirectional or unknown, such mathematical manipulation will not be accurate or desirable.

Fully Anechoic Room with height search This should not be done as there will be no ground reflection to maximize, and it will only measure the radiation pattern up to +45 °.

(c) GTEM Cell with IEC 1000-4-20 Correlation Algorithm

When looking at the use of a GTEM, it is necessary to consider independently the GTEM cell itself and the validity of the assumptions made in the so called 'correlation algorithm'.

GTEM Cell itself From the mathematical theory using Antenna Factors above, it can be seen that an EUT measured in a GTEM can simply be visualized as the limiting case of the EUT placed D metres opposite a measuring antenna in free space where the distance D is zero. The GTEM measures vertically polarized signals radiated in the direction of the apex. (To be precise, for maximum sensitivity the radiation should be tilted down towards the apex along the centre line.) The basic operation of the GTEM is shown in Fig. 3.

In terms of the antenna analogy used in this paper, for an EUT on the centre line, the equivalent GTEM 'aperture' can be considered to be physically coincident with the EUT, which gives some positional tolerance and can be advantageous with large EUTs. Because the GTEM is a waveguide, the same radiation pattern will be measured at any position on the centre line. As at any position, the signal measured at the apex will be due to the vector sum of the radiation components from the EUT in the direction of the apex, for higher frequencies and more complex radiation patterns, the angular mounting of the EUT relative to the direction of maximum sensitivity becomes critical. This can be a problem with any sources of radiation not on the centre line where the maximum sensitivity vector of the GTEM can deviate from pointing at the apex. The use of a GTEM also avoids the need to change antennas.

The disadvantage of the GTEM is that sensitivity drops by 6 dB/ octave frequency; it also drops by 6 dB/ doubling of septum height which could give measuring equipment sensitivity problems with very

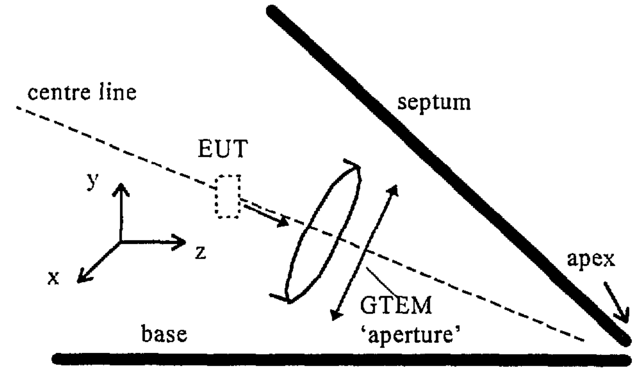

Figure 3. EUT measured in a GTEM

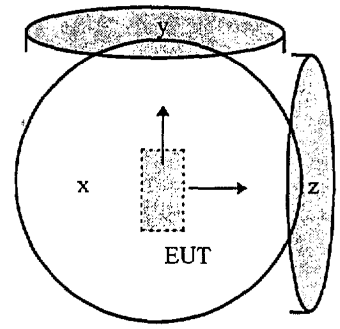

Figure 4. EUT measured with IEC 1000-4-20 Algorithm

high frequencies. It should be noted that the GTEM antenna factor varies from the ideal by typically ±2 dB above about 100 MHz depending upon the size of cell (as measured with a signal generator and an isotropic field probe) due to standing waves in the cell.

Correlation Algorithm The correlation algorithm requires that the EUT is placed in the GTEM on a device called a manipulator and 3 orthogonal frequency sweeps are made for x, y, z orientations; these frequency sweeps can be stored in a computer, and equations (7) and (8) above are used to give the resultant radiation from which the equivalent electric field at the specified distance can be computed. The advantage of such a procedure is that a print-out is obtained of the radiation at all frequencies; on the previous methods the full turntable rotation is usually only carried out on signals that have previously been identified. Therefore test time is reduced. Fig. 4 shows the measured directions of the EUT.

This procedure can produce differences between the methods at any measurement frequency because:
(i) the EUT is only placed in one position in each plane and not rotated: The result will be too low if the main lobe of the radiation is not pointing at the apex of the GTEM.
(ii) the EUT is measured in x, y, z directions: It might measure radiation from the EUT in a direction which an OATS or anechoic room does not, e.g. radiation directly upwards from the EUT will also be measured with the GTEM algorithm. This could give a result which is too high.

The fact that this correlation algorithm has limitations is well known; indeed in IEC 1000-4-20, rotation of the EUT to determine the position of maximum coupling is required. More complex GTEM correlation algorithms [7], and a method of modifying the algorithm accurately to give the maximum gain of a single lobe [8] are examples but these are largely concerned only with reducing problem (i) above. The measurement of the radiation pattern of a simple antenna [9] can also be made. Other algorithms improve low frequency performance where near field effects become significant.

Ground Reflection Simulation The same problems of simulating an OATS apply as for the Fully Anechoic Room case. The only difference is that a single worst case horizontally and vertically polarized correction is applied. Again, this can give results which are up to 5 dB too high.

(d) GTEM Cell with 4 Face Correlation Algorithm

A new method was devised as a way of avoiding the problems of method (c) (i) and (ii) which simulates free space as does the Fully Anechoic Room. Unlike the other algorithms, this implies a restriction on the faces to be measured to simulate the single plane measurement of the universal specification (which can sometimes miss lobes entirely).

The EUT is placed on a turntable and rotated about a vertical axis so that each of its 4 faces is towards the apex in turn. A full sweep is done for each face, and the maximum value at each frequency for the 4 sweeps is printed out. This is possible for an EUT such as a mobile phone which does not have a very directional radiation pattern in the azimuthal plane. (Ultimately, a full turntable rotation would be required for a very directional EUT.) The turntable is then rotated by 90 ° in the plane perpendicular to the centre line to give horizontal polarization, and 4 further sweeps are made. For maximum accuracy in both polarizations, the turntable axis should be tilted to be perpendicular to the GTEM centre line. That is, the direction z should be in the direction of the centre line.

The obvious disadvantage is that 8 sweeps are required compared with 3 for method (c). However, the procedure has the maximum compatibility with the radiated immunity specification IEC 1000-4-3 [4], and also the >1 GHz procedure in ANSI C63.4-1992 para.8.2.4 [5]. Fig. 5 shows the measured directions of the EUT.

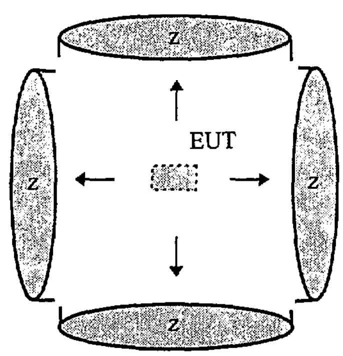

Figure 5. EUT measured with 4 Face Algorithm (Top View for Vertical Polarization)

	(a) OATS	(b) FAR		(c) GTEM 5305		(d) GTEM 5305		(d) GTEM 5311	
AMPS Ch799 S/N 059	V&H max	Vert	Horiz	max	min	Vert	Horiz	Vert	Horiz
TX fund 849MHz	24	25 ±0.5	12 ±1	25	17	25	16	26	12
TX 2nd harm 1.7GHz	-35	-36 ±3	-39 ±1	-33	-40	-37	-44	-35	-40
TX 3rd harm 2.55GHz	-34	-30 ±5	-31 ±5	-22	-31	-26	-29	-31	-33
TX 4th harm 3.4GHz	-42	-42 ±2	-42 ±3	-41	<-48	-46	-44	<-45	-43
TX 5th harm 4.25GHz	-33	-30 ±4	-33 ±3	-30	-38	-28	-32	-29	-41
TX 6th harm 5.1GHz	-25	-29 ±4	-23 ±0	-27	-35	-30	-26	-30	-25
TX 7th harm 5.95GHz	-20	-20 ±5	-22 ±5	-26	-33	-30	-20	-28	-30
RX Band 878MHz		-73	-83	-74	-85	-76	-94	-77	-87
RX Band 887MHz		-75	-84	-77	-85	-81	-95	-77	-88

Table 1. Results for an AMPS Mobile Phone (dBm)

EXPERIMENTAL RESULTS USING A MOBILE PHONE

The different methods were compared using an AMPS analogue mobile phone which has the advantages of having no connecting leads, a known transmitter output power, and small size so as to avoid differences due to radiation coming from different positions within the EUT making comparisons too complex. This was set up to transmit continuously to avoid problems of spectrum analyzer sweep times and detector type.

Partly because the antenna was in one corner of the phone, the vertically polarized radiation pattern of the fundamental transmitter frequency was found to deviate from the expected circular pattern in having about 6 dB more radiated signal in the direction away from this corner than in the opposite direction; it was also slightly tilted. For the unintentional transmitter harmonics, it was found that radiation could also come from the printed circuit board tracks, explaining a shift to predominantly horizontal polarization for the higher harmonics. The lobes for the highest harmonics were also more directional. The amplitude stability of the harmonics was also worse due to thermal drift etc. Some spurious signals (frequencies not related to the antenna resonant length) in the receive band were also measured. All these signals violate the omnidirectional assumption for the OATS and GTEM IEC 1000-4-20 procedures.

A calibration dipole was used to verify the software/ lead loss correction etc. at various frequencies below 1 GHz, within the limitations of the presence of the feeder cable.

Description of Test Methods

(a) OATS 3m site, EUT on turntable, Height search with no measuring antenna tilt for increased height. Log periodic (<1 GHz), and horn (>1 GHz) measuring antennas. Note: The calculated equivalent resonant dipole signal (dBm) was assumed to be 97.4 dB less than the measured field (dBuV/m at 3 m).

(b) Fully Anechoic Room 5 x 2.4 x 2.4m with 2.2m site, EUT on turntable. Both EUT and antenna centrally placed within the room with no height search. Antenna types and equivalent resonant dipole calculation as OATS. No ground reflection simulation.

(c) GTEM with IEC 1000-4-20 Algorithm EMCO 5305 using equations (5) & (8) above, plotting the vector sum of the 3 sweeps (dBm). No ground reflection simulation.

(d) GTEM with 4 Face Algorithm EMCO 5305 & 5311 using equation (5) above, and plotting the maximum of the 4 sweeps (dBm). No ground reflection simulation.

A summary of the results is given in Table 1.

Discussion of Results

(a) OATS The OATS gives similar results to the other methods. However, there seemed to be no significant increase in signal by the 5 dB (approx.) expected due to the maximizing of the direct and reflected rays by the height search. In particular, the transmitter power of 24 dBm is about what would be expected from the known conducted power, and is similar to the other methods For the harmonics, the ground reflection effect would also appear to be negligible, and any increase or decrease of signal when measuring angled lobes cannot be identified. The absence of measuring antenna tilt may partially explain this.

(b) Fully Anechoic Room A spread of results is shown in the table as several runs were made over a period of time. The results are similar to the other methods. There was significant variability of the harmonics (particularly the odd harmonics). This is partially due to small room size, poor absorber, and the positioning being critical, but also due to the thermal/ mechanical drift of the phone. Further work and a larger room are really required to reduce this variability.

(c) GTEM with IEC 1000-4-20 Algorithm For all the signals there is a large spread in the results (about 8 dB). Minimum and maximum results are shown in the table for each frequency, and these represent not the limits of a variable spread, but the limits of a discrete set of results due to the arbitrary choosing of the phone position in each of the x, y, z axes. Clearly to get a transmitter power of 17 dBm by following this basic test method cannot be acceptable, and either the direction of maximum radiation has to be determined before measuring, or additional measurements are required afterwards. However, it can be seen that for some frequencies simply selecting the maximum may give a result which is high compared with the other methods. Although not shown here, it should be noted that for a chosen arbitrary orientation, the positioning in the GTEM along the centre line is not very critical.

(d) GTEM with 4 Face Algorithm The results are comparable to methods (a) and (b), and the 2 GTEMs allow a good assessment of the stability of the GTEM method. Subsequent to these measurements being taken, the 3rd harmonic vertically polarized signal was investigated as it was notably higher in the GTEM. This showed that because of the 3 lobes, the angle of the phone to the centre line was extremely critical. In one GTEM, the phone was found to be mounted above the centre line, and in this position the maximum sensitivity direction of the GTEM was found to be at a small though significant angle to the centre line. This angle also seemed to vary with frequency. As the turntable/ manipulator was only moved by hand, and aligned by eye, the priority for further work must be to improve the turntable. It was hoped that the GTEM frequency response measured for radiated immunity testing using an isotropic field probe could be used as a frequency response correction. However, this response did not seem to match the variation in the results, possibly due to the small size of the probe compared with the phone. Also, it was found that rotating the phone occasionally gave nulls in the radiation pattern at some frequencies. This was not investigated as improvements in turntable accuracy are required first. Also, as this method gives results which are the highest of the 4 faces, in the unlikely event of a null being present on one face, it will not have a large effect on the results, although a full 360° turntable rotation can always be made. (This problem is potentially more serious with method (c).)

CONCLUSIONS

Four different radiated emissions test methods have been compared using a universal specification which takes potential directivity of the EUT into account and is defined as "the maximum field strength allowed at specified distance from the EUT at a specified frequency, at all angles in an azimuthal plane for both vertical and horizontal polarization."

It has been shown that good correlation can be achieved over a wide frequency range between different methods provided that these methods are configured so as to measure the radiation from the EUT in the same directions. The optimizing of direct and reflected rays with the OATS can give highly variable results at the frequencies considered in this paper, and extreme care is needed; the simple way to resolve this would be to use a fixed antenna with no height search, and check that there is no ground reflection (or preferably remove this entirely). Also, the basic GTEM IEC 1000-4-20 correlation algorithm gives ambiguous results, but could be replaced by an alternative method with a turntable, often with a simplified procedure of only measuring 4 faces which only requires a simple software change.

Removing the link between the specification and the method would allow the most appropriate method to be chosen for the device and frequency being tested . The main unresolved problem is that most specifications and regulatory authorities require the use of an OATS up to 1 GHz, where alternative methods (if available at all) begin to be recommended. As measurement problems described in this paper can occur well below this frequency, there is an urgent need (particularly with the increasing use of new technologies mentioned in the introduction) to review the specifications which have been dominated by the problems of a relatively narrow low frequency band. There is also a severe lack of standardization between emissions and immunity procedures, which international standards bodies are now beginning to consider.

ACKNOWLEDGMENT

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