Comparisons of Planar versus Spherical Emission Measurements for Unintentional Emitters

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Abstract
The emission patterns from electrically-large objects are complex and require time-consuming spherical scans to determine the emission maximums. A planar cut through the spherical pattern is a relatively easy measurement to make and resembles the techniques used in present EMC emissions and immunity standards. However, a planar cut is likely to miss the maximum emission from a test object. This paper explores how planar cut data can be used to estimate the spherical emissions maximum. Simulated data including both the full spherical radiation pattern and planar cut estimates for a random emitter are presented. The key result is that, if planar cut data can be used to accurately approximate the mean radiation power, then directivity estimates for electrically large emitters can be used to accurately predict the maximum emissions. The results presented here have application to emissions and immunity measurements at frequencies above 1 GHz where most objects will be electrically large and have complex emissions and receiving patterns.

1. INTRODUCTION
Present emission measurement procedures probe a limited conical volume about the equipment under test (EUT) to determine the maximum emitted field strength (e.g., a 3 m separation and a 1 to 4 m receiving antenna height sweep over an open area test site (OATS)). As the EUT emission pattern becomes more complex, the probability that this limited cone contains the direction of maximum emissions will decrease. At frequencies above 1 GHz most EUTs will be large compared to the wavelength and can be expected to have complex emission patterns. Thus, simply applying current test geometry configurations to higher frequencies will not reliably determine maximum EUT emissions. Three-dimensional scans of the emission pattern will be required to accurately determine maximum emissions. Immunity tests face similar difficulties.

One approach to a three dimensional scan is to use a fully anechoic room (FAR) and progressively rotate the EUT through a sequence of planar cuts. This will yield the desired answer but requires an expensive facility and a time-consuming measurement. The sampling density must also increase with frequency. A second approach is to use a near-field scan (planar, cylindrical, or spherical). The application of near-field scanning techniques to electromagnetic interference measurements was the topic of a special session at the 2001 IEEE EMC Symposium [1]. Again, the basic drawback is time and expense. In both cases, the full emission pattern, including both peaks and nulls, is precisely determined. This is more information than needed for EMC purposes, where only the emission maximum is typically of interest. Details of pattern nulls are not needed.

An alternative approach is to determine the total radiated power and bound the maximum emissions using theory-based estimates for directivity [2-3]. The total power emitted by a EUT can be efficiently measured in a reverberation chamber at frequencies where the reverberation chamber is operating well [4]. Reverberation chambers suitable for EMC measurements will typically be a few meters on a side and should operate well above a few hundred MHz. Thus, frequencies above 1 GHz are well covered by this technique. Reverberation chambers are presently not widely available as EMC measurement tools. Therefore an approach based on limited OATS or FAR sector data remains desirable.

This paper applies the analytical directivity estimates developed in [2-3] to relate planar-cut measured emission pattern data to full three dimensional pattern data. The goal is to estimate the emissions maximum based on a single measured planar cut, as could be conveniently done at a FAR or OATS facility.

The paper is organized as follows. Section 2 reviews expected values for the directivity of electrically large emitters for either the full pattern or a planar cut. These are used to relate the spherical and planar cut data in Section 3. Section 4 uses numerical simulations to investigate how well the spherical-to-planar relations estimate the simulated maximum emitted power for a complex, electrically large emitter. Section 5 presents measured data that compare mean received power measured over planar cuts to the mean received power determined via measurements of the total radiated power in a reverberation chamber. Section 6 presents some conclusions.
2. DIRECTIVITY BOUNDS: PLANAR VERSUS SPHERICAL ESTIMATES

This section considers the difference between maximum emissions estimates based on spherical scan data and planar cut data. The starting points are the ratio of the expected value for the maximum received power over a sphere \(G'_{\text{sph,m}}\) to the mean received power \(\langle P_D\rangle\) over a sphere; i.e., directivity, and the ratio of the expected value for the maximum received power over a planar cut \(G'_{\text{cut,max}}\) to the mean received power \(\langle P_{\text{cut}}\rangle\). These quantities are all defined for a single polarization and an unintentional emitter [2-3]:

\[
\frac{\langle P_{\text{sph,max}} \rangle}{\langle P_{\text{sph}} \rangle} = 0.577 + \ln(N_{\text{sph}}) + \frac{1}{2N_{\text{sph}}} \quad ka > 1 , \text{and}
\frac{\langle P_{\text{cut,max}} \rangle}{\langle P_{\text{cut}} \rangle} \approx 0.577 + \ln(N_{\text{cut}}) + \frac{1}{2N_{\text{cut}}} \quad ka > 1 ,
\]

where \(N_{\text{sph}} = 4(ka)^2 + 8ka\), \(N_{\text{cut}} = 4(ka) + 2\), and \(ka\) is the electrical size of the smallest sphere enclosing the EUT. (\(k\) = the wavenumber, \(a\) is the minimal sphere radius). For \(ka\) large, the ratio of the two cases may be approximated as:

\[
\frac{\langle P_{\text{sph,max}} \rangle}{\langle P_{\text{cut,max}} \rangle} \approx \ln(N_{\text{sph}}) + \ln(N_{\text{cut}}) \approx 2\ln(2ka).
\]

This simple result suggests that, if the whole sphere and planar-cut mean received powers are equal, then the expected value for the whole sphere emissions maximum from an electrically large emitter is somewhat less than twice that of the planar cut value. A plot of \(\langle P_{\text{cut}} \rangle / \langle P_{\text{sph}} \rangle\) versus \(ka\) is shown in figure 1, where it is assumed that \(\langle P_{\text{cut}} \rangle / \langle P_{\text{sph}} \rangle = 1\). Figure 1 shows a slowly varying function between 1.3 and 1.7 over the range of \(ka\) from 1 to 100. This figure suggests that a ratio of 1.5 is a reasonable approximation for most test objects.

The planar-cut data are relatively simple to obtain compared to the whole sphere data (e.g., rotation of the EUT about the vertical axis in a FAR or over an OATS. OATS measurements have the added effect of the ground reflection and the usual vertical antenna sweep. However, at higher frequencies, such as above 1 GHz, the maximum coupling occurs near minimal separation (i.e., the receive antenna at the same height as the test object). A simple approximation for the ground plane effect is to double the received maximum field. Thus, reducing the measured field level by two would approximate the FAR planar cut. The question then is how well does the planar-cut mean for received power approximate the spherical mean received power.

3. MEAN RECEIVED POWER: PLANAR VERSUS SPHERICAL ESTIMATES

The above directivity estimates for an unintentional emitter are based on the assumption that the spherical mode expansion for the fields from the emitter will have wave coefficients whose real and imaginary parts are independent and Gaussian distributed with zero mean [3]. This results in far-field power densities that are chi-square distributed with two degrees of freedom. If we take independent samples from the far-field power density distribution, then the reproductive property of the chi-square distribution [5] means that the sum of the samples is chi-square distributed with \(n\) degrees of freedom, where \(n\) equals the sum of the degrees of freedom of the individual sample distributions (in this case, 2 for each sample). We can form the mean of these samples by summing and dividing by the sample number. In the spherical case using \(N_{\text{sph}}\) samples, this yields an expected mean and variance given by

\[
\left\langle \frac{1}{N_{\text{sph}}} \sum_{i=1}^{N_{\text{sph}}} P_{\text{rec},i} \right\rangle = \frac{1}{N_{\text{sph}}} N_{\text{sph}} \langle P_{\text{sph}} \rangle = \langle P_{\text{sph}} \rangle
\]

variance \(\frac{1}{N_{\text{sph}}} \sum_{i=1}^{N_{\text{sph}}} P_{\text{rec},i}^2\) = \(\frac{1}{N_{\text{sph}}} 2\langle P_{\text{sph}} \rangle = \frac{4}{N_{\text{sph}}} \)

Figure 1. The ratio of the expected value for the maximum received power for a full spherical pattern compared to the planar cut expected value as a function of the electrical size \(ka\) of the emitter.
This result states that the expected value of a mean based on \(N_{\text{sph}}\) samples of the power density is simply the actual mean of the power density and that the variance decreases as the sample size increases. There is an analogous result for the planar cut case. Returning to equation (2), it may be reasonable to assume that \(\left(\langle P_{\text{cut}}\rangle / \langle P_{\text{sph}}\rangle\right) = 1\) for complex, electrically large EUTs (this question will be examined in the next section using simulations); however, the variance of the planar cut data will be larger by the ratio \(N_{\text{sph}} / N_{\text{cut}}\). Thus, the simplest estimate for the maximum received power based on planar cut data, is given by

\[
\frac{\langle P_{\text{sph, max}}\rangle}{\langle P_{\text{cut}}\rangle} = 0.577 + \ln(N_{\text{sph}}) + \frac{1}{2N_{\text{sph}}} \quad \text{for } ka > 1. \tag{4}
\]

The validity of this expression will be examined in the next section using some simple numerical simulations.

4. SIMULATED DATA

A program was written to simulate the emissions from a set of randomly excited point sources randomly distributed on the surface of a sphere. The program can be used to simulate emissions from electrically large unintentional emitters. More details on the program model may be found in [3]. The far-field pattern due to the simulated source can be used to calculate the total radiated power, mean radiated power, directivity, and planar-cut patterns. Thus, the program can be used to test how well mean radiated power based on planar cut data approximates the actual mean radiated power.

Figure 2 shows an example of a planar cut pattern near 1 GHz (\(ka = 5\)) for the case of 25 point sources distributed over a sphere of radius 0.25 m. Figure 3 shows data for the same emitter near 5 GHz. The patterns show an increasing complexity as frequency is increased. Determining the direction of maximum emissions becomes progressively more difficult as the electrical size of the test object increases. However, for EMC purposes these types of patterns are both a "good news, bad news" situation. The bad news is that testing a small number of directions, such as the four normal directions to the sides of a rectangular box (e.g., as prescribed in IEC 61000-4-3 immunity standard) can lead to a very poor estimate of the maximum radiation. This is demonstrated by the pattern shown in figure 3 where the angles 0, 90°, 180°, 270° are near nulls. If the box sides were to align with these normal directions, then the pattern maximum would be significantly underestimated. The good news is that despite the complexity of the pattern in figure 3, the magnitudes of the pencil beams tend to be similar since the sources are not phased for a preferred direction. This suggests that the many local maxima are of the same magnitude. This may mean that measurements based on a small sample from the full sphere may inadvertently give a good approximation to the overall pattern maximum if a representative local maximum is found.

Figure 2. A simulated planar cut pattern at 955 MHz (\(ka = 5\)) for 25 random point sources distributed over a 50 cm sphere.

Figure 3. A simulated planar cut pattern at 4.8 GHz (\(ka = 25\)) for 25 random point sources distributed over a 50 cm sphere.

Figure 4 shows an example of directivity estimates as a function of electrical size \(ka\) up to a frequency of about 5 GHz for the same 25 sources and 0.25 m radius sphere used in the previous two figures. The various estimates shown in figure 4 represent the following estimates: a) the theoretical expected value based on equation (1), b) three planar cut estimates based on equation (4) using the mean received power in each plane (the three planes are defined by the an arbitrary coordinate system and are the x-y, y-z, z-x planes), and c) an estimate based on using the average of the three planar-cut mean received power values in equation (4). The same estimated directivity data normalized to the simulated (actual) directivity and converted to dB are shown in figure 5. For this simulation run, figure 5 shows that the directivity estimates based on
planar-cut mean received power are within +/- 2 dB of the actual simulated directivity. This improves to +/- 1 dB if the three-cut mean is used. Repeated simulations suggest that these ranges are typical for an EUT of this complexity.

Figure 4. Simulated and estimated directivities for 25 random point sources distributed over a 50 cm sphere.

Figure 5. The ratio of various estimated directivities to the simulated directivity for 25 random point sources distributed over a 50 cm sphere.

For comparison, figure 6 shows the maximum received power over a planar cut normalized to the maximum received power over the whole sphere as a function of the electrical size for each of the three planar cuts. This simulates a straightforward planar cut measurement approach to determining the maximum emitted field. Figure 6 shows that, for any given cut, there are large bands where the planar cut maximum will be at least 3 dB less than the actual maximum. Here we assumed that the planar cut has been densely sampled so that the true planar cut maximum is found. A sparse sampling over the planar cut will worsen results. Taken together, the figures suggest that using planar cuts to estimate the mean emitted power and then using theoretical directivity approximations to estimate the maximum emitted power gives a better estimate of the overall maximum emitter power than does simply using the maximum measured emitted power over the planar cut.

Figure 6. The ratio of the maximum received power for three arbitrary planar cuts to the simulated maximum received power over the full radiation pattern for 25 random point sources distributed over a 50 cm sphere.

5. MEASURED DATA
A self-contained emitter was measured in various EMC facilities (OATS, anechoic chamber, reverberation chamber, broadband TEM cell) at NIST as part of a comparison study. The emitter consisted of a battery operated comb generator housed in a small metal box to which various antennas (e.g., dipole, loop) could be attached. Or the comb generator itself could be located inside a larger metal box with variable antenna configurations external to the box (e.g., plate antenna, slot, monopole). More details about the emitter, the measurement set-up, and the facilities comparison may be found in [6-7]. The electric field $E_{cut}$ over planar cuts was measured in a fully anechoic chamber (3 m separation) for various emitter configurations. The total radiated power $P_{tot}$ was measured in a reverberation chamber for the same emitter configurations. This allows us to compare the mean of the emitted power over the planar cut measurement points, as measured in the anechoic chamber, to the mean of the emitted power over the full sphere, as measured in the reverberation chamber. These are given by

$$\langle P_{cut} \rangle = \frac{\langle E_{cut}^2 \rangle}{\eta_0}$$ and

$$\langle P_{sph} \rangle = \frac{\langle D \rangle}{4\pi r^2} P_{tot},$$

where the mean directivity $\langle D \rangle = 1/2$ for a single polarization [3], as measured here, and $r$ denotes the sphere radius. Thus, these data allow us to examine whether the
assumption $\langle P_{cut} \rangle / \langle P_{sph} \rangle = 1$ is well met for the test objects measured. Two configurations of the self-contained emitter are presented here: a loop antenna connected directly to the comb generator and a plate antenna attached to one side of a box and driven by the comb generator (located inside the box).

Figure 7 shows the mean power density for the loop antenna as estimated using six planar cut measurements (eq. 5, three planes and two polarizations were used) and as estimated from total radiated power measurements in a reverberation chamber (eq. 6, $r = 3$ m). The reverberation chamber data were taken in 0.3 MHz frequency steps. The planar cut data were taken at selected frequencies. The planar cut means are near or below the total radiated power means suggesting that the emission pattern is not similarly distributed in all planes and polarizations. A loop alone will have broad nulls in planes perpendicular to the loop plane. Thus, the lower planar cut data values in some cases are not surprising. Unlike the simulations presented in the previous section, the loop is not behaving like an electrically large emitter with randomly excited moments but rather as a simple dipole.

Figure 8 shows the same comparison of power density means for the plate antenna and box configuration. The results are much the same as for the loop antenna case again suggesting a rather simple radiation pattern. These emitters may be too simple to satisfy the $\langle P_{cut} \rangle / \langle P_{sph} \rangle = 1$ in any arbitrary plane. Emitters with more complex patterns are needed.

6. CONCLUSION
This paper investigated the use of planar cut data to estimate the maximum emissions from an electrically large source. The basic result is that if the mean of the planar cut data well approximates the actual mean radiated power, then theoretical directivity expressions can be used to well estimate the maximum emissions form the device. This approach should yield better results than simply measuring the maximum emissions over a planar cut and using that value as the estimate for the maximum emissions from the device. The goal is to simplify the measurement effort required by EMC emission and immunity standards as test frequencies move above 1 GHz where most objects will be electrically large, assuming that EMC devices are unintentional emitters not designed to strongly radiated power in a preferred direction. The paper used numerical simulations to investigate the validity of the derived relations. Simulations show that planar cut based estimates are within $\pm 2$ dB of the actual simulated maximum emitted power for electrically large, complex emitters. Measured data for simpler emitters show much larger spreads. More work remains to investigate the validity of these expressions through measurements on actual devices. The difficulty is that full spherical scans of EMC test objects are sufficiently expensive that they are rarely performed.

REFERENCES


