Total Radiated Power Limits for Emission Measurements in a Reverberation Chamber

Christopher L. Holloway, Perry F. Wilson, Galen Koepke and Marco Candidi

National Institute of Standards and Technology (NIST), 325 Broadway, Boulder, CO 80305, USA
Phone: (303)-497-6184, email: holloway@boulder.nist.gov

Abstract
In this paper we present a limit on total radiated power for emission measurements in reverberation chambers. This total radiated power limit is intended to be equivalent to the FCC maximum E-field limit for emission testing over a ground plane.

INTRODUCTION
Electronic products that have devices with clock speeds of 9 kHz or higher are tested for conducted and radiated emissions [1]. Devices and/or products are tested for emissions to ensure that electromagnetic field strengths emitted by the device and/or product are below a maximum specified electric (E) field strength over the frequency range of 30 MHz to 1 GHz. These products are tested either on an open area test site (OATS) or in a semi-anechoic chamber. Products are tested for either Class A (commercial electronics) or Class B (consumer electronics) limits, Class A equipment having protection limits at 10 m, and Class B equipment having protection limits at 3 m. Figure 1 shows the maximum E-field limit for both the Class A and Class B limit.

These limits are based on a OATS-based model in which a product is placed above a conducting ground plane, a receiving antenna (at either 3 m or 10 m separation) is vertically scanned from 1 to 4 m, and the maximum E-field is noted (see Figure 2). One problem to this approach is that it is possible to miss energy propagating in directions not covered by the scan area (e.g., from the top of the product). Efficient alternative test methodologies or facilities that account for this other energy are needed. One such facility is a reverberation chamber. A reverberation chamber is well suited to determining the total radiated power from a product. A question that needs be answered is: "How does a total radiated power measurement in a reverberation chamber relate to the maximum E-field measured on an OATS or in a semi-anechoic chamber?" In this paper we present a total radiated power limit, which is intended to be equivalent to the maximum E-field limit. A particular equipment under test (EUT) that passes the current E-field limit should also pass this total radiated power limit, and a EUT that failed the E-field limit would also fail this total radiated power limit.

Figure 1: Maximum E-field limit.

TOTAL RADIATED POWER LIMIT
If we assume that the EUT radiates as a simple dipole over a ground plane (see Figure 2), the maximum received E-field is given by [2]

\[ E_{\text{max}} = \eta_0 \frac{D_{\text{max}} P_0}{4\pi r} \]

where \( P_0 \) is the total radiated power, \( \eta_0 \) is the free-space impedance and \( D_{\text{max}} \) is the maximum directivity of the
EUT. $D_{\text{max}} = 3/2$ for a simple electric or magnetic dipole and $D_{\text{max}} = 3$ for combined electric and magnetic dipoles. We assume the $D_{\text{max}}$ is that of a dipole (i.e., $3/2$). Below we discuss the choice of $D_{\text{max}}$ for electrically large EUTs. The geometry factor $g_{\text{max}}$ is polarization dependent and defined by

$$g_{\text{max}} = \begin{cases} \frac{e^{-j\beta r_1} - e^{-j\beta r_2}}{r_1 - r_2} & \text{horizontal} \\ \frac{\cos^2 \theta}{r_1} - \frac{\sin^2 \theta}{r_2} & \text{vertical} \end{cases}$$

where $k$ is the wave number, $r_1 = \sqrt{r^2 + (R_H - h_g)^2}$ is the distance from the EUT to the receiving antenna (see Fig.1), $r_2 = \sqrt{r^2 + (R_H + h_g)^2}$ is the distance from the image of EUT to the receiving antenna, $h_g$ is the EUT height over the ground plane, and $R_H$ is the height of receiving antenna above the ground plane. The maximum is found by varying $R_H$ over the range 1-4 m with $h_g = 1$ m. Figure 3 shows the values of $g_{\text{max}}$ for both a 3 m and 10 m antenna separation.

It is interesting to observe the value of $R_H$ where $g_{\text{max}}$ occurs. Figure 4 and 5 shows the values of $R_H$ where the maximum occurs (referred as $h_{\text{max}}$). Notice that $h_{\text{max}}$ tends towards $h_g$ (i.e., 1 m) as the frequency is increased and the phase interference from the reflected path becomes less pronounced.

Rearranging equation (1), we obtain the following expression for the allowable radiated power

$$P_{\text{max}} = \frac{4\pi}{\eta} \frac{|E_{\text{max}}|^2}{D_{\text{max}}^2}$$  

where

$$G = \max \left(g_{\text{max,v}}, g_{\text{max,h}}\right).$$

Figure 6 plots $G$ versus frequency for both a 3 m and 10 m separation distance. Figure 7 plots this total radiated limit for both the Class A and Class B limit. These limits should provide equivalence for electrically small sources measured in either a reverberation chamber or an OATS. For general sources, these limits provide a meaningful test level, which could be refined by product committees. Similar ideas have been proposed for equivalent radiated emission voltage measurements in TEM cells [3].

Figure 3: The geometry factor $g_{\text{max}}$.

Figure 4: $h_{\text{max}}$ for 3 m separation distance.

Figure 5: $h_{\text{max}}$ for 10 m separation distance.
We see that this total radiated power limit has a complicated functional form (resulting for the OATS model, i.e., ground plane with 1-4 m height scan). Similar to what is done in the E-field limit, we can set the radiated power limit to a constant value over the four frequency bands used in the E-field limits. The constant value chosen is the average power level (the average of the computed power levels in Figure 7) in each frequency band. This modified radiated power limit is shown in Figure 8. For comparison, this figure also shows the total radiated power limits presented in Figure 7.

**VALIDATION OF TOTAL RADIATED POWER LIMITS**

The correlation between reverberation chamber and OATS measurements can be seen by comparing measurements of a well characterized radiator. One such radiator is a spherical dipole. Figure 9 compares the E-field of a spherical dipole at a 3 m distance. The results in this figure are for measurements of total radiated power in the NIST reverberation chamber and electric field measurements on the NIST OATS. The total radiated power is measured in the reverberation chamber, and the results are then used in the above expressions to calculate the E-field at a 3 m distance. The data indicate a good agreement between the facilities.

If no ground plane were present then the E-field for the dipole in free space could be obtained. A free-space measurement can be realized with a fully anechoic chamber. Figure 10 shows the E-field of the spherical dipole at a 3 m distance in free space. The results in this figure are for measurements of total radiated power in the NIST reverberation chamber and electric field measurements in NIST's full anechoic chamber. The total radiated power is measured in the reverberation chamber, and the results are then used in the above expressions to calculate the E-field at a 3 m distance. For free space, $g_{\text{max}}$ reduces to the following for both polarization:

$$g_{\text{max}} = \frac{e^{-\lambda r_1}}{r_1}$$

(5)
Figures 9 and 10 indicate that the measured E-field in either an OATS or an anechoic chamber can be correlated to the E-field obtained from a measurement of the total radiated power in a reverberation chamber (with the use of equation (1)). The more general question is: if an EUT exceeds the E-field limit by some margin, will the measured total radiated power exceed the total radiated power limit in a similar manner?

To test the validity of this total radiated power limit, various devices were tested both on NIST's OATS and in NIST's reverberation chamber. Figure 11 shows the maximum E-field of a loop driven by a comb generator (details of the EUT are given in [4]) measured on NIST's OATS at a 3-m separation distance. Also shown on this figure is the maximum E-field limit, which is only specified to 1 GHz. Notice that this intentional emitter exceeds the limit. Figure 12 shows the total radiated power of the loop EUT measured in NIST's reverberation chamber. Also shown on this figure is the total radiated limit from Figure 8. Notice that the device exceeds the limit as well. The question is: is the amount by which the limits are exceeded (defined as $\Delta$) similar for both sets of data? Figure 13 shows this $\Delta$ (the amount the EUT surpasses the limits, both E-field and power). Notice that the values of $\Delta$ from both types of test are very similar. This indicates that the total radiated power limit is equivalent in stringency to the E-field limit.
The above examples show that the simple EUT (a loop) exceeds the two limits in a similar manner. We now look at an EUT that does not behave as a simple dipole. A box with an aperture has a more complicated radiated pattern. Figure 14 shows the maximum E-field of a box with an aperture (details of the EUT are given in [4]) measured on NIST’s OATS at a 3 m separation distance. Also shown on this figure is the maximum E-field limit. Notice that the device again exceeds the limit. Figure 15 shows the total radiated power of the box measured in NIST’s reverberation chamber. Also shown on this figure is the total radiated limit presented above. Notice that the device exceeds the radiated power limit as well.

Figure 13: The amount the loop emissions exceeds the limits.

Figure 14: Maximum E-field measured on NIST’s OATS for a box with an aperture.

The values of delta from these two sets of measurements are shown in Figure 16. We see that the values of delta for the two measurements are similar; however, we also see that the reverberation chamber measurements are generally lower than those from the OATS measurements. This discrepancy is due to the fact that the EUT does not behave like a simple dipole; that is to say that for this type of EUT, $D_{max}$ is greater than $3/2$. References [4] and [5] shows that $D_{max}$ for electrically large unintentional emitters can be estimated by

$$D_{max} = \max\left\{ 1.55, \frac{1}{2} \left[ \frac{0.577 + \ln(4ka^3) + 8ka + 1}{8(ka^2 + 16ka)} \right] \right\}$$

where $a$ is the radius of the minimum sphere enclosing the EUT. The regime $ka > 1$ defines an electrically large object, while $ka \leq 1$ defines an electrically small object.

For this EUT, $D_{max}$ is approximately 3 for the center of the frequency band. Using this in Eq. (3) gives a different power limit and the delta for such a limit is also shown in Figure 16. The new comparison shows differences on the order of 2 dB. Obviously we do not want a radiated power limit that is a function of the EUT size. However, this example illustrates that complicated EUTs behave differently from simple dipoles and standards based on a simple dipole models may need to be generalized.

CONCLUSION AND DISCUSSION
In this paper we have presented a total radiated power limit for emission measurements inside reverberation chambers. This radiated power limit is intended to be equivalent to the FCC maximum E-field limit for emission testing in OATS.
An emission limit for total radiated power of a product could prove to be a very valuable tool in future years as the need for product testing includes frequencies above 1 GHz. We should add that the total radiated power limit presented here is an arbitrary limit because it is based upon the current radiated emission E-field limit, which itself is a somewhat arbitrary limit. With this said, the examples shown here indicate that the total radiated power limit is equivalent in stringency to the E-field limit.

The reader is referred to [6] and [7] for discussions of measurements uncertainties in the various test facilities present here. The total radiated power limit presented here should provide equivalence for electrically small EUTs measured in either a reverberation chamber or an OATS. For general sources, these limits provide a meaningful test level, which could be refined by product committees.

![Graph showing the box emissions excess the limits](image)

Figure 16: The amount the box emissions exceed the limits

REFERENCES


