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# Measurement of Transmission through Printed Circuit Boards: Application to Enclosure Shielding

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***Abstract*—It is important when considering the shielding effectiveness (SE) of an enclosure to take into account any contents the enclosure may have. Contents such as printed circuit boards (PCBs) will absorb electromagnetic energy and so affect the SE of the enclosure. Previously, it has been shown that the absorption cross section (ACS) of PCBs and the transmission cross section of apertures can be used in the power balance method to predict the SE of simple enclosures. However, in a more realistic enclosure, multiple cavities may be formed by PCBs that cover a large proportion of the enclosure cross section. In this case, the transmission through the PCBs, as well as through the apertures, needs to be considered. In this paper, we describe measuring the transmission through a PCB using a method normally used to measure the SE of planar samples. This measurement is quick and efficient to carry out, as no special preparation of the PCB is required. The results are shown from a selection of PCBs and limitations of the measurement discussed. The data collected can be used in power balance or computational modelling to allow engineers to determine a more accurate estimate of enclosure SE when designing electronic systems.**

***Keywords—shielding effectiveness, printed circuit boards, shielded enclosures, transmission, power balance***

## I. Introduction

The shielding effectiveness (SE) of an enclosure is affected by its contents, such as printed circuit boards (PCBs) [1]. For electrically large enclosures, the power balance (PWB) method can be used to predict SE [2],[3]. In the simple case where the contents are all within the same volume, the enclosure can be simply considered as a single cavity. In this case, knowledge of the absorption cross section (ACS) of the contents and the transmission cross-section of any apertures in the enclosure is sufficient to determine its SE [2]-[4]. If multiple PCBs are placed so that they obscure a large proportion of the cross section of an enclosure then it may be necessary to consider the enclosure as a number of separate cavities coupled by means of any apertures between them or by transmission directly through the PCBs separating them. As far as the authors are aware, there is no published information on the transmission of energy through PCBs.

In this paper, we consider the measurement of the transmission through printed circuit boards. The problem is similar to that of measuring the shielding effectiveness of a planar sheet. Various techniques are available for the measurement of the SE of a planar sheet [5] but many of them require the edges of the sample to be quite flat and conductive. This is not possible with real PCBs as components are often mounted quite close to the edge, and even when no components are mounted, the surface may not be conducting. We developed a method of measuring the shielding effectiveness of planar samples that minimises the requirement for edge conductivity, known colloquially as the absorber box method [6]. Here we have used the absorber box method to measure transmission through several PCBs from ICT equipment.

Section II of this paper considers the power balance method and the problem of PCBs creating cavities inside enclosures. Section III details the samples that have been tested and Section IV describes the measurement technique. Sections V and VI contain the measurement results. Section VII is the conclusion.

## II. Shielding Effectiveness and the Power Balance Model

The power balance model is mainly used in reverberant environments where the assumption that the power density is uniform and isotropic in each cavity [2]. It can be used to calculate the SE of an enclosure with contents such as PCBs. We assume a reverberant environment in the following explanation of PWB.

### *A. Single cavity enclosure PWB model*

Fig. 1 shows an enclosure with an aperture through which energy may pass and contents into which energy may be absorbed. For the sake of simplicity, energy absorbed into the walls of the enclosure is assumed negligible.

The PWB method uses the principal of conservation of energy which implies that, in the steady state, the power entering the cavity through the aperture, $P_{10}^t$, must equal the sum of the power leaving the cavity through the aperture, $P_{01}^t$, plus the power absorbed in the contents, $P_1^a$:

$$P_{10}^t = P_1^a + P_{01}^t \tag{1}$$

The power flow through the aperture in each direction depends only on the power density incident on the aperture,

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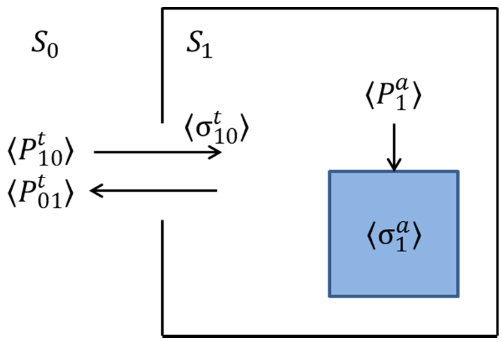


Fig. 1. Simplified power balance model of a single cavity.

and its average transmission cross-section, $\langle \sigma_{10}^t \rangle$, defined so that the power flow into the cavity is:

$$P_{10}^t = S_0 \langle \sigma_{10}^t \rangle \tag{2}$$

and the power flow out of the cavity is:

$$P_{01}^t = S_1 \langle \sigma_{10}^t \rangle \tag{3}$$

where $S_0$ is the power density external to the cavity and $S_1$ is the internal power density.

Similarly the power absorbed by the contents depends only on its ACS, $\langle \sigma_1^a \rangle$, and the power density in the cavity:

$$P_1^a = S_1 \langle \sigma_1^a \rangle \tag{4}$$

Using (1-4) the power balance relationship can be written as:

$$S_1 \langle \sigma_{10}^t \rangle = S_2 (\langle \sigma_1^a \rangle + \langle \sigma_{10}^t \rangle) \tag{5a}$$

and the SE of the cavity under external illumination can be written as:

$$SE = \frac{S_1}{S_0} = \frac{\langle \sigma_1^a \rangle + \langle \sigma_{10}^t \rangle}{\langle \sigma_{10}^t \rangle} \tag{5b}$$

### B. Multi cavity enclosure model

If an enclosure were divided into two cavities (Fig. 2) then the PWB model must be extended to determine the separate levels of shielding experienced by each cavity.

In this case, the power balance equation in the cavity with power density $S_1$ is

$$\langle P_{10}^t \rangle + \langle P_{12}^t \rangle = \langle P_{01}^t \rangle + \langle P_{21}^t \rangle + \langle P_1^a \rangle \tag{6}$$

and in the cavity with power density $S_2$ is:

$$\langle P_{21}^t \rangle = \langle P_{12}^t \rangle + \langle P_2^a \rangle \tag{7}$$

When substituting the net power flow into these equations the PWB relationship can be written in matrix form:

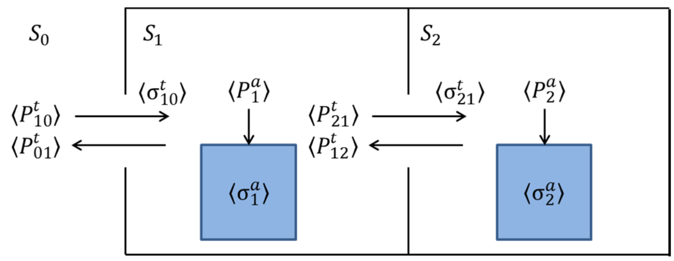


Fig. 2. Simplified power balance model of an enclosure divided into two cavities.

$$\begin{bmatrix} S_0 \langle \sigma_{10}^t \rangle \\ 0 \end{bmatrix} = \begin{bmatrix} \langle \sigma_1^a \rangle + \langle \sigma_{21}^t \rangle + \langle \sigma_{10}^t \rangle & -\langle \sigma_{21}^t \rangle \\ -\langle \sigma_{21}^t \rangle & \langle \sigma_2^a \rangle + \langle \sigma_{21}^t \rangle \end{bmatrix} \begin{bmatrix} S_1 \\ S_2 \end{bmatrix} \tag{8a}$$

so the SE of the two cavities with respect to the external field can be written as:

$$\begin{bmatrix} S_1/S_0 \\ S_2/S_0 \end{bmatrix} = \begin{bmatrix} \langle \sigma_1^a \rangle + \langle \sigma_{21}^t \rangle + \langle \sigma_{10}^t \rangle & -\langle \sigma_{21}^t \rangle \\ -\langle \sigma_{21}^t \rangle & \langle \sigma_2^a \rangle + \langle \sigma_{21}^t \rangle \end{bmatrix}^{-1} \begin{bmatrix} \langle \sigma_{10}^t \rangle \\ 0 \end{bmatrix} \tag{8b}$$

### C. PCBs forming multiple cavities

In electronic systems today, PCBs may take up a significant part of an enclosure. Fig. 3 shows a simplified diagram where a single PCB, shown as a dotted line, divides an enclosure into two separate cavities. Here, transmission from one cavity to the other can happen in the apertures produced by the gap between the enclosure walls and the edges of the PCB. We must also consider the transmission through the PCB itself.

In Fig. 3, $\langle P_{xx,ap}^t \rangle$ is the power moving between cavities via the aperture(s) around the edge of the PCB, $\langle P_{xx,pcb}^t \rangle$ is the power that moves from one cavity to the other through the PCB itself and $P_x^a$ is the power absorbed by any contents in each cavity. In this case, this will include the power absorbed by the PCB forming the cavity wall. So $\langle \sigma_{21}^t \rangle$ in (8b) is becomes the sum of the transmission cross sections:

$$\langle \sigma_{21}^t \rangle = \langle \sigma_{21,\mathrm{ap}}^t \rangle + \langle \sigma_{21,\mathrm{pcb}}^t \rangle \tag{9}$$

and the ACS of the contents must include that of the side of the PCB which separates the sub-cavities.

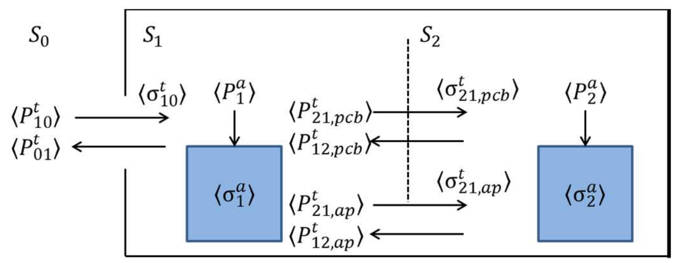


Fig. 3. Simplified power balance model of two cavities formed by a PCB inside a shielded enclosure.

## III. Materials under test

Three types of sample have been measured as part of these experiments. A plain sheet of aluminum with dimensions of 395 mm × 240 mm; a sheet of PCB substrate with copper on one side only and dimensions of 300 mm × 227 mm; and a number of real PCBs. The photographs in Fig. 4 show the aluminum and substrate sheets and Fig. 5 shows the real PCBs.

The three real PCBs were taken from a selection from an ICT cabinet. Each PCB had dimensions of 365 mm × 210 mm and has a variety of different components on it including heat sinks, connectors, integrated circuits and passive components. The PCBs were given the identification codes PCB1, PCB2 and PCB5. PCB1 has the largest amount of metallic components, such as heat sinks, on its surface. PCB2 has the smallest amount. It also has a larger amount of passive components such as capacitors and inductors on it. PCB5 still has a number of metallic components on it. All three PCBs have previously had their ACS measured [8]. The underside of each PCB also has some low profile components on which cause the board to be lifted slightly from the surface the PCB is lying on. This distance was measured using a pair of calipers as being 3 mm ± 0.05 mm.

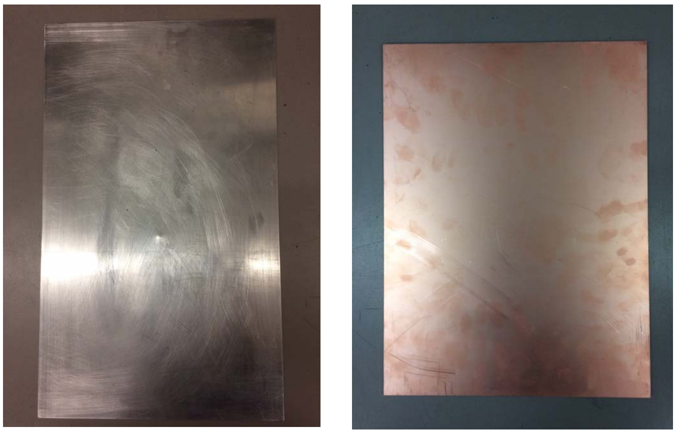

Fig. 4. Photograph of the aluminum sheet on the left and the PCB substrate with the copper facing up on the right.

Fig. 5. Photographs of each of the PCBs under test. From the top: PCB1, PCB2, PCB5. The photograph has been blurred to preserve design confidentiality.

## IV. PCB Transmission measurements

The absorber box method used for the transmission measurements was first proposed in [11]. It was described as a way of measuring the SE of planar materials that have non-conducting surfaces. The measurement set up using the absorber box is shown in the diagram in Fig. 6 and the photograph in Fig. 7.

The absorber box has dimensions of 600 mm × 600mm × 330 mm and the aperture in the absorber between the antennas is 140 mm × 150 mm. The sample is placed over the aperture between two blocks of layered LS22 carbon loaded absorber. Two ridged horn antennas are positioned above and below the sample under test. The absorber around the sample acts to terminate the sample so that the energy that would be diffracted around the sample is

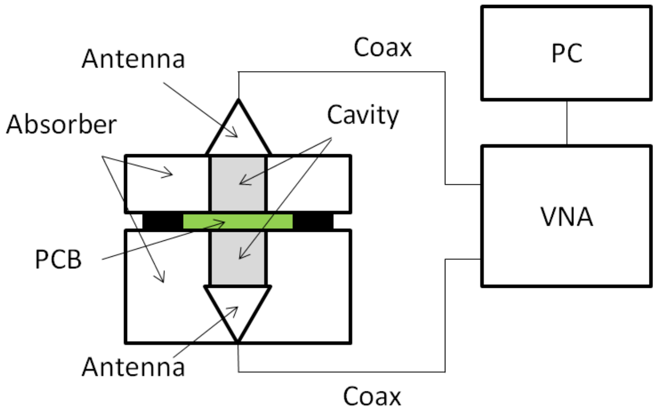


Fig. 6. Diagram of the absorber box measurement set up.

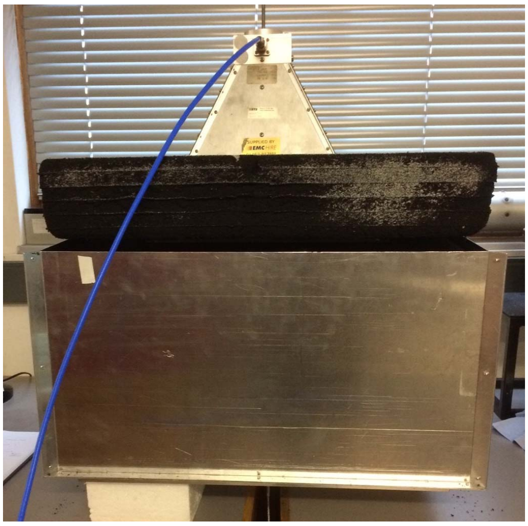

Fig. 7. Photograph showing the absorber box with the top horn antenna connected to the VNA using a coaxial cable.

absorbed. The two antennas are connected to a Vector Network Analyser (VNA) using coaxial cables and a full set of S-parameters are collected between 500 MHz and 8 GHz. 1601 points were taken over this frequency range with a sweep time of 5 seconds. The height of the components on one side of the PCBs causes the top block of absorber to be lifted away from the bottom block by approximately 3mm, so additional absorber material was packed around the sample being tested. This is to ensure that leakage around the sample is reduced as much as possible. A full description of the absorber box can be found in [11].

In additional to measuring the sample, a reference measurement is required to be able to calculate more accurately the transmission through the sample. This reference measurement is taken using the circular brass plate shown positioned in the absorber box in Fig. 8. The plate has an array of circular holes spaced 10 mm apart with a 3 mm diameter. The corrected transmission through the sample, $T_C^{sample}$, is then calculated as:

$$T_C^{sample} = S_{21}^{sample} \frac{T^{ref}}{S_{21}^{ref}} \qquad (10)$$

Where $T^{ref}$ is the known transmission through the reference sample, $S_{21}^{ref}$ is the measured transmission through the reference sample and $S_{21}^{sample}$ is the measured transmission through the sample under test.

## V. Simple Sheet Measurement

The aluminum sheet and PCB substrate were measured in four different configurations. The sheets were measured on the block of absorber (labelled as 0 mm) and then lifted 1 mm, 2 mm and 3 mm above the block using 1 mm height plastic spacers. Measuring the aluminum sheet flat on the absorber shows the minimum transmission that can be measured using this set up as a sheet of aluminum should have negligible transmission. The aluminum sheet is also measured at different distances from the absorber block to estimate the effect of 3mm gap under the PCB on the transmission measurement.

Fig. 9 shows the corrected transmission measurements for the aluminum sheet and PCB substrate. Fig. 9 shows that the minimum measurable transmission is approximately -70 dB from 2 GHz to 8 GHz. As the aluminium sheet is lifted further from the absorber the transmission increases to a maximum of around -55 dB above 2 GHz but still has approximately the same structure as when there is no gap between the absorber and the sample under test. As the sheets are lifted above the absorber the size of the gap increases which causes more leakage around the sample thus increasing the measured transmission.

Fig. 10 shows a similar result for the PCB substrate. In this case the transmission is higher at the lower end of the frequency range but decreases to roughly the same transmission as the aluminium sheet between 6 GHz and 8 GHz for the 0 mm case. The reason for this is most likely to be due to the slightly smaller sample size. This causes more leakage around the sample at the lower frequencies.

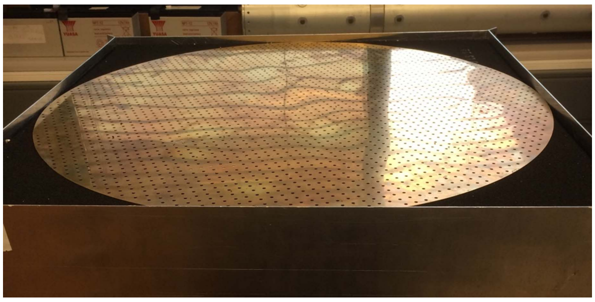

Fig. 8. Photograph of the brass reference sample in the absorber box.

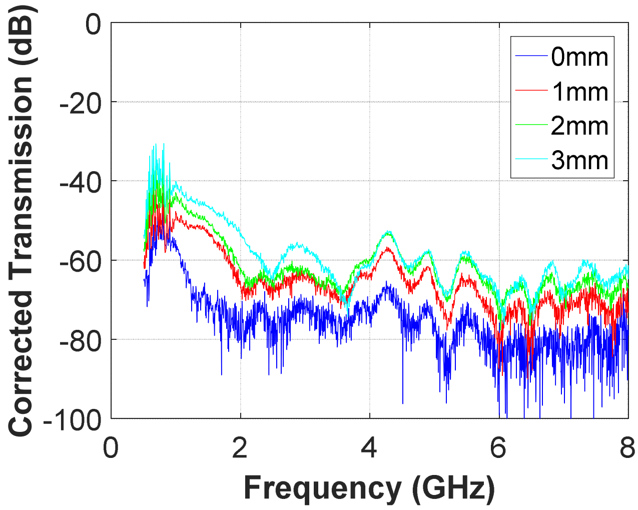


Fig. 9. Measured corrected transmission of the aluminum sheet flat on the bottom absorber block (0mm) and lifted 1mm, 2mm and 3mm up from the absorber block.

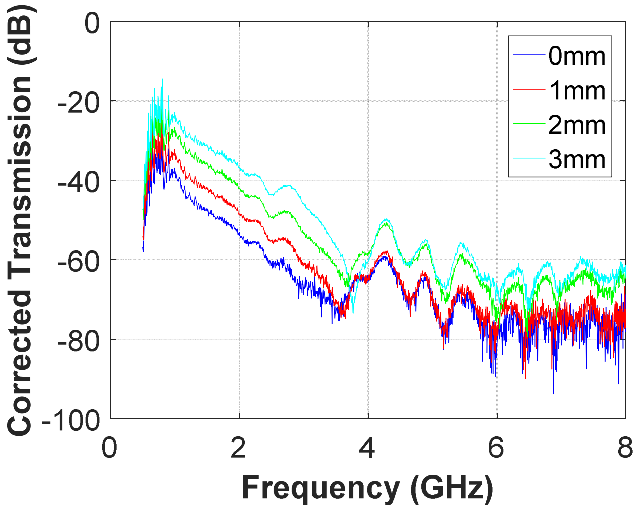


Fig. 10. Measured corrected transmission of the PCB substrate sheet flat on the bottom absorber block and lifted 1mm, 2mm and 3mm up from the absorber block.

## VI. PCB Measurement Results

Fig. 11 shows the measured corrected transmission for the three PCBs. PCB1 and PCB5 have a transmission of approximately between -70 dB and -45 dB over the frequency range 2 GHz to 8 GHz. This corresponds to a transmission

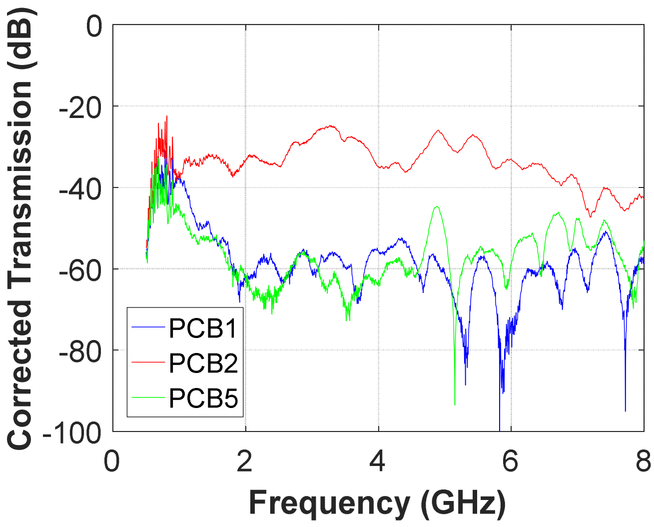


Fig. 11. Measured corrected transmission of PCB1, PCB2 and PCB5 using the absorber box set up.

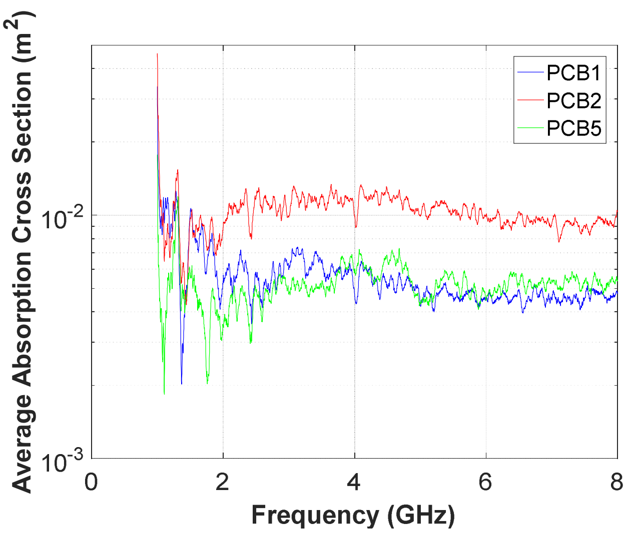


Fig. 12. Measured ACS of PCB1, PCB2 and PCB5.

cross-section, $\langle \sigma^t_{21,\mathrm{pcb}} \rangle$, of between $3 \times 10^{-5}$ m$^2$ and $5.3 \times 10^{-4}$ m$^2$ which can be used in the PWB to calculate the SE of an enclosure. There are a number of minima that are below $-80$ dB, which reach the minimum measurable transmission for this set up. PCB2 has a significantly higher transmission than the other two PCBs and is between -25 dB and -55 dB between 2 GHz to 8 GHz. This corresponds to a transmission cross section of between $5.3 \times 10^{-3}$ m$^2$ and $1.6 \times 10^{-4}$ m$^2$. As discussed in Section III PCB2 has a smaller number of metallic components on compared to PCB1 and PCB5. This additional shielding on PCB1 and PCB5 may be causing their decreased transmission compared to PCB2.

Fig. 12 shows the ACS of the PCBs which have previously been measured and presented in [8]. The figure shows that PCB1 and PCB5 have similar ACSs as well as similar transmission through the PCBs. As these two PCBs have the most metallic components on, it could be reasoned that the metal is causing most of the energy to be reflected from the surface of the PCB rather than be transmitted or absorbed. PCB2 has a higher transmission through it and also it has a higher absorption. As there are significantly fewer metallic parts, this could mean that as less energy is being reflected away more is available to be absorbed or transmitted through the PCB.

Fig. 13 summarises the main results in this paper by showing the corrected transmission results of a selection of the samples under test. The aluminium sheet lying flat on the absorber block demonstrates the limit of measurement. The aluminium sheet lifted 3 mm, PCB substrate lifted 3 mm, PCB1 and PCB5 all have a similar transmission of around -60 dB above 3.5 GHz. This might indicate that the measurement of the PCBs is limited by the 3 mm distance that the samples are lifted from the absorber block. The amount of energy being transmitted through these two PCBs is similar to that of the aluminium sheet and is at the limit of the measurement method. The low transmission through these PCBs is likely to be insignificant compared to the transmission through any apertures between cavities in the enclosure. In this

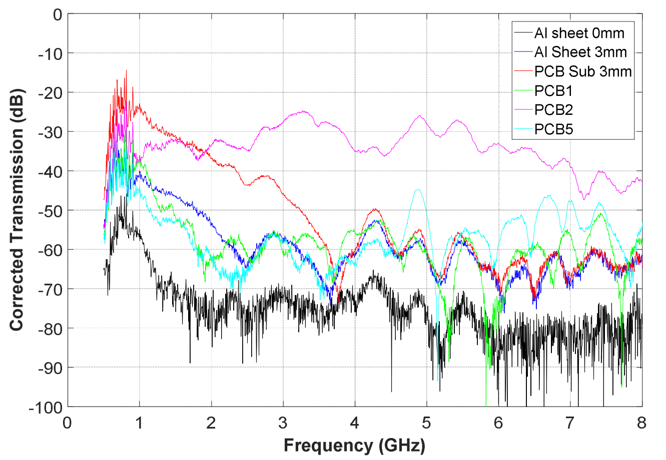


Fig. 13. Comparison of the measured corrected transmission of the aluminum sheet flat on the absorber block (0mm), lifted 3mm from the absorber block, the PCB substrate lifted 3mm from the absorber block, PCB1, PCB2 and PCB5.

case, this transmission mechanism may not need to be included in the power balance model. However, PCB2 has a higher transmission cross section which is comparable with the ACS of a typical PCB and so this would need to be included in the power balance model. The size of PCB2 is the same as PCB1 and PCB5 and they all have the 3 mm gap between the board and absorber block. The main difference between them is the smaller amount of metal and a greater amount of ceramic components on PCB2. As previously discussed this accounts for the difference in transmission.

## VII. Conclusions and Further Work

A measurement has been described which allows the transmission through PCBs to be calculated using the absorber box method. By measuring an aluminum and PCB substrate sheet it can be seen that the measurement range is limited by the gap underneath the PCBs and a minimum transmission of -60 dB for these PCBs can be measured at frequencies over 2 GHz. Of the three PCBs measured, two of the PCBs had a transmission low enough to be limited by this factor. This may mean the transmission through these PCBs does not need to be considered in the power balance method. The third PCB had a higher measured transmission of between -20 dB to -50 dB which is high enough that its effect should be considered in any power balance model. A possible reason for this is that PCB2 has significantly less metal on it.

Using the absorber box method is a quick and efficient way to measure the transmission through PCBs. The data collected using this method can be used in methods such as computational modelling as well as the power balance method described in this paper. This will allow a more accurate predication of the shielding effectiveness of an enclosure with contents such as PCBs in.

We are currently working to use the absorber box to measure also the reflection coefficient of the PCB so that its ACS might also be measured by this method. This is particularly useful, as it would allow us to measure separately the absorption due to each side of the PCB in a single measurement, as well as the transmission.

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