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You had me at "Reverb"!

A cruise over the fascinating world of ***Reverberation Chambers***

Shielding metrics, Absorption Cross-Section, & Measurement challenges for board level shields

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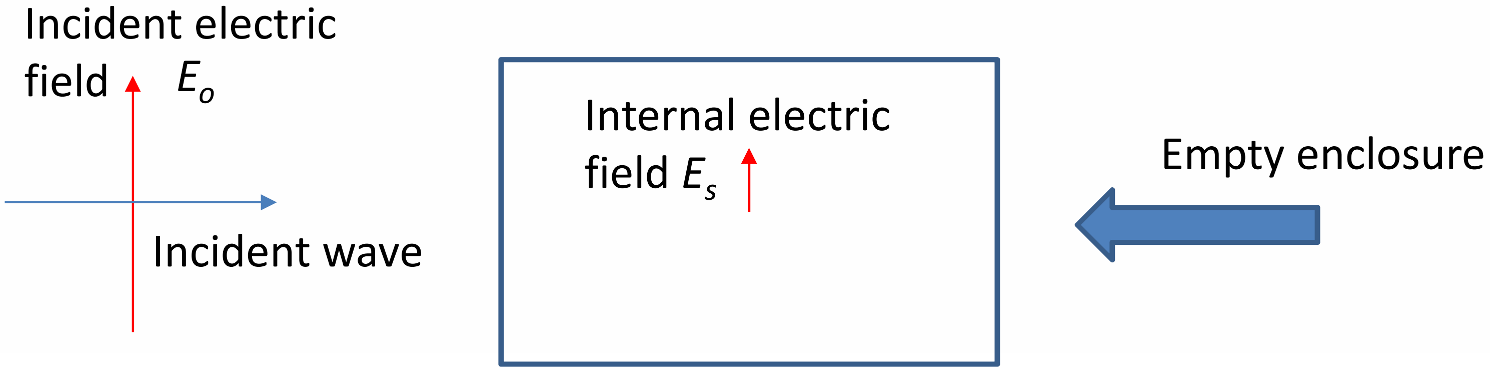
IEEE
EMC EUROPE 2022
GOTHENBURG, SWEDEN
EMC SOCIETY

CONVENTIONAL ENCLOSURE SHIELDING EFFECTIVENESS (SE)



Incident electric field E_o

Incident wave

Internal electric field E_s

Empty enclosure

The internal field amplitude varies with position inside the enclosure. Its orientation (polarisation) changes with position. How does it vary with the arrival direction and polarisation of the incident wave?

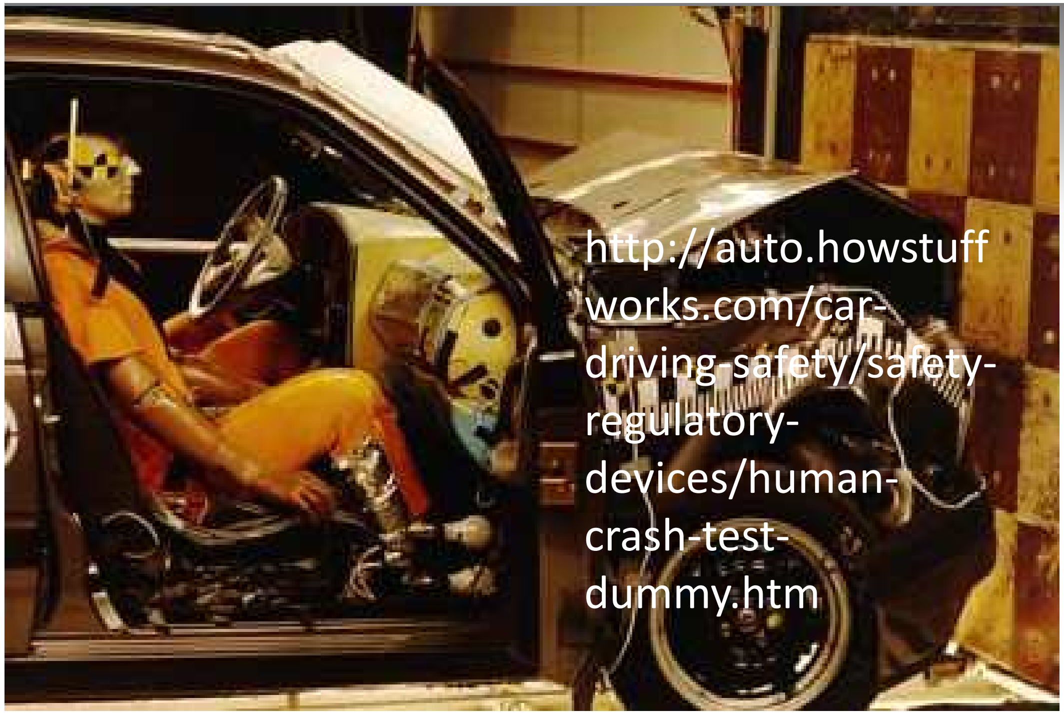
$$\mathrm{SE} = {}^{E_o}\!/_{E_s}$$

$$SE_{dB} = 20log_{10}(SE)$$

Typical Screened Room. It’s a big empty enclosure.
SE okay? Probably.

Typical PC enclosure. It’s smaller and has a significant amount of ‘stuff’ inside.
SE okay? Questionable.

IT rack enclosure. Small and packed with ‘stuff’.
SE okay? Suggest not.



http://auto.howstuffworks.com/car-driving-safety/safety-regulatory-devices/human-crash-test-dummy.htm

A road vehicle is a kind of shielded enclosure.
Its crash worthiness is not tested with the vehicle empty.
An instrumented crash test dummy is used to give a standard repeatable and reproducible evaluation of the protection offered to the occupant(s).

"Not cars. Here we're testing oblivious texters walking into walls."

Elderly female, obese male and adult male crash-test-dummies. Adult female, pregnant female, child and infant dummies and others are also used.


© University of Michigan

Is SE the right metric?

- Shielded rooms have SE values of around 100dB.
- Equipment enclosures have other functions. Structural constraints limit their SE values to around 40dB. Lower values are typical.
- Shielded enclosure contents absorb electromagnetic energy.
- Immunity; Energy absorption into contents is the immunity problem.
- Emissions; Contents are the source and a sink of radiated energy.

Shielding of Reverberant Enclosures

- In the microwave frequency region the enclosure itself is likely to be electrically large – its dimensions are much greater than the wavelength.
- For example a 480mm dimension 19inch rack unit is 1.6 wavelengths across at 1GHz and 16 wavelengths across at 10GHz.
- Two issues arise from this;
    - The empty enclosure is now a resonant cavity. The number of resonant modes may be very large.
    - The enclosure radiating as an unintentional antenna has the potential to exhibit significant directional properties.

Shielding and Power Balance

In 1994 David Hill and Mark Ma from NIST published their seminal paper;

"Aperture Excitation of Electrically Large Lossy Cavities"

(TEMC, vol 36, no 3, August 1994, pp 169-177).

The paper accounts for the power conservation in the system by considering the power entering the cavity and leaving the cavity (apertures or antennas), the power absorbed into the cavity walls and the power absorbed into the cavity contents.

The cavity is electrically large and thus reverberant with multiple modes excited at any frequency.

This power balance formulation is ideal for studying the Shielding of enclosures in this class.

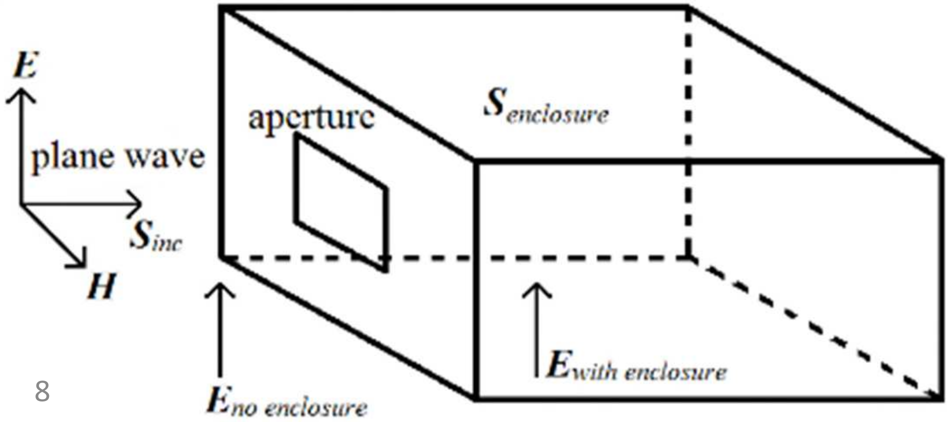
Shielding Effectiveness (Power)

- Shielding effectiveness (SE)
- Definition:

$$SE = \frac{S_{inc}}{S_{enclosure}} = \frac{E^2_{no\cdot enclosure} / \eta_0}{E^2_{with\cdot enclosure} / \eta_0} = \left(\frac{E_{no\cdot enclosure}}{E_{with\cdot enclosure}} \right)^2$$

S−power density

η_0−free space impedance



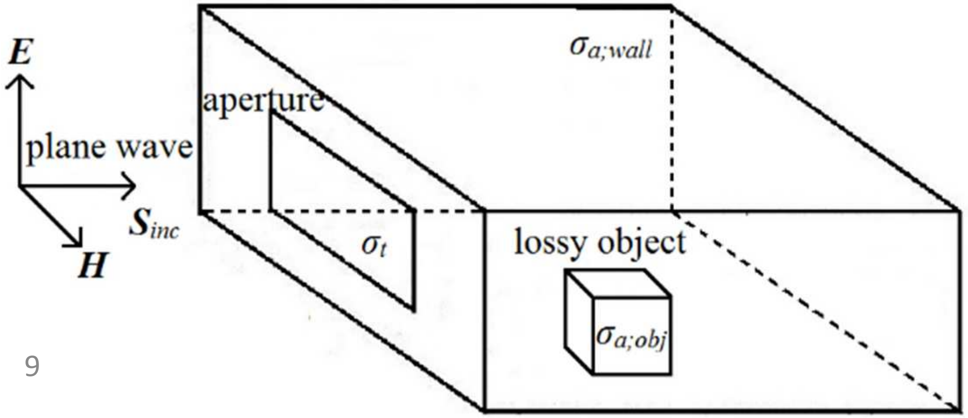
Shielding Effectiveness (Power)

Power balance method (PWB). At steady state, input power=dissipated power

$$P_{input} = P_{dissipated} = P_{object} + P_{aperture} + P_{wall}$$

$$P_{input} = S_{inc}\sigma_t = S_{enclosure}\left(\sigma_{a;wall} + \sigma_{a;obj} + \sigma_t\right) = P_{dissipated}$$

Strictly speaking the power dissipated in any internal probe antennas should also be accounted for.



Shielding Effectiveness (Power)

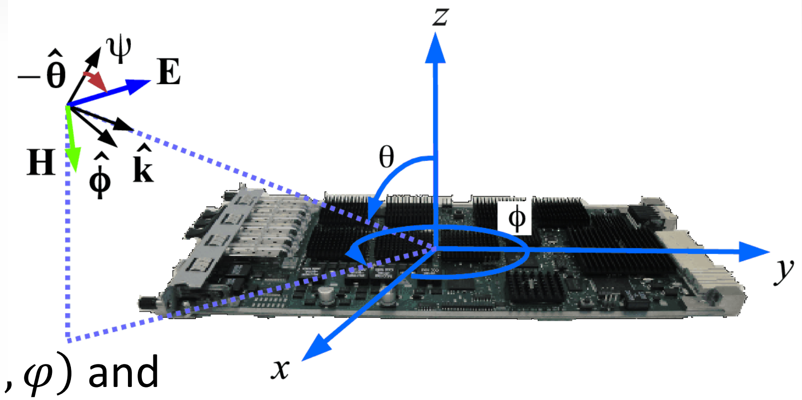
- Absorption cross section (ACS): $\sigma_a = P_{absorbed} / S$
- Transmission cross section (TCS): $\sigma_t = P_{transmitted} / S$
- Calculate SE from ACS and TCS:

$$SE_{loaded} = \frac{S_{inc}}{S_{enclosure}} = \frac{\sigma_t + \sigma_{a;wall} + \sigma_{a;obj}}{\sigma_t} = 1 + \frac{\sigma_{a;wall}}{\sigma_t} + \frac{\sigma_{a;obj}}{\sigma_t}$$

$$= SE_{empty} + \frac{\sigma_{a;obj}}{\sigma_t}$$

Absorption Cross-section (ACS) Techniques

- The absorption cross-section of an object is the total power it absorbs from an incident plane-wave per unit power density
- Far-field quantity



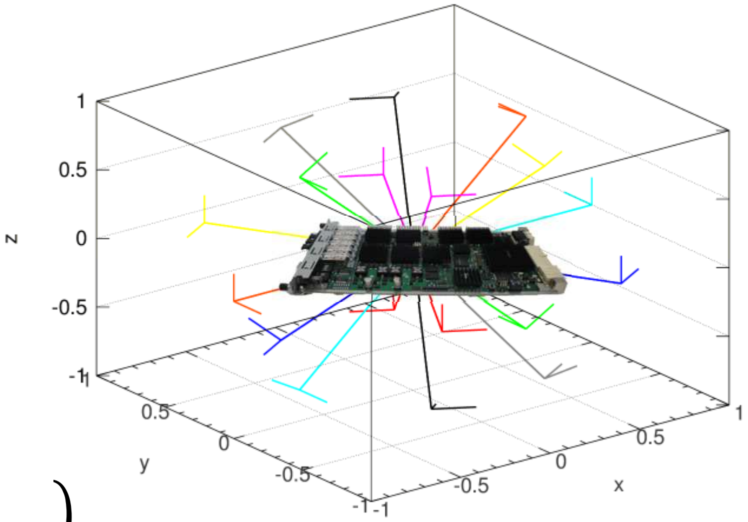
- Depends on angle or arrival of the plane-wave (θ, φ) and its polarisation angle ψ
- Many absorption process in PCBs: trace loads (including devices), substrate, packaging,…

$$\sigma^{\mathrm{a}}(\theta,\varphi,\psi) = \frac{P^{\mathrm{a}}(\theta,\varphi,\psi)}{S_{\mathrm{inc}}}$$

$$S_{\mathrm{inc}} = \frac{|E_{\mathrm{inc}}|^2}{2\eta_0}$$

ACS Measurement in a Reverberation Chamber (RC)

- RC is most efficient environment for high frequency SE measurement
- Good RC – uniform and isotropic plane-wave spectrum (Hill)
- Measure average ACS of enclosure contents in the RC
- Use to predict SE in loaded enclosures



$$\langle \sigma^{\mathrm{a}} \rangle = \frac{1}{2}\frac{1}{4\pi}\left\{ \iint_{4\pi} \sigma^{\mathrm{a}}(\theta,\varphi,0^{o})\,d\Omega + \iint_{4\pi} \sigma^{\mathrm{a}}(\theta,\varphi,90^{o})\,d\Omega \right\}$$

PCB Characteristics

A typical PCB is a complex structure. It has many different types of component.

One thing that the components have in common is that their absorption characteristics microwave frequencies are not specified!

The typical PCB is a three dimensional structure. As well as the absorption of the circuit elements, the substrate absorbs energy with increasing efficiency as the frequency is increased in the microwave range. In many applications PCBs are stacked to form a complex periodic array within the enclosure.

RC Measurement of ACS

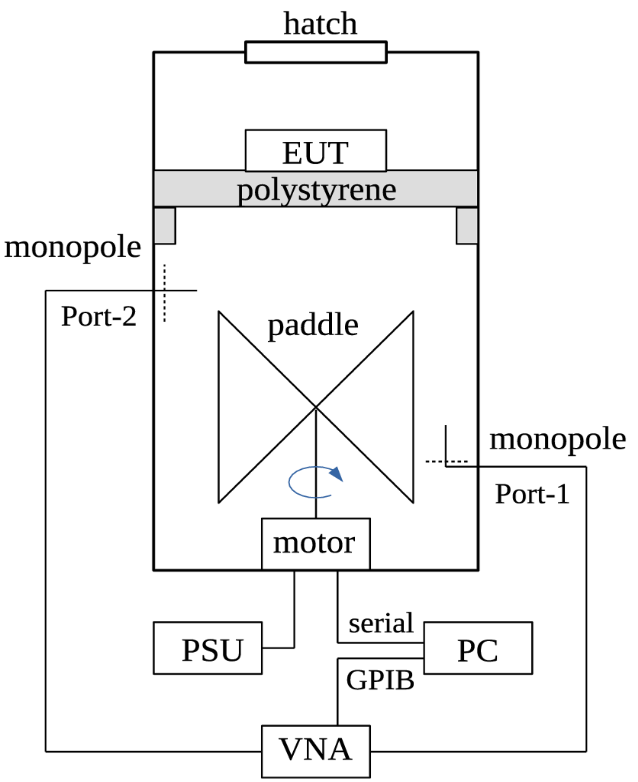
Average ACS determined by difference in insertion loss between loaded and unloaded chamber

$$\langle \sigma^{\mathrm{a}}_{\mathrm{EUT}} \rangle = \frac{\lambda^2}{8\pi} \eta_1^{\mathrm{T}} \eta_2^{\mathrm{T}} (IL_{\mathrm{loaded}} - IL_{\mathrm{unloaded}})$$

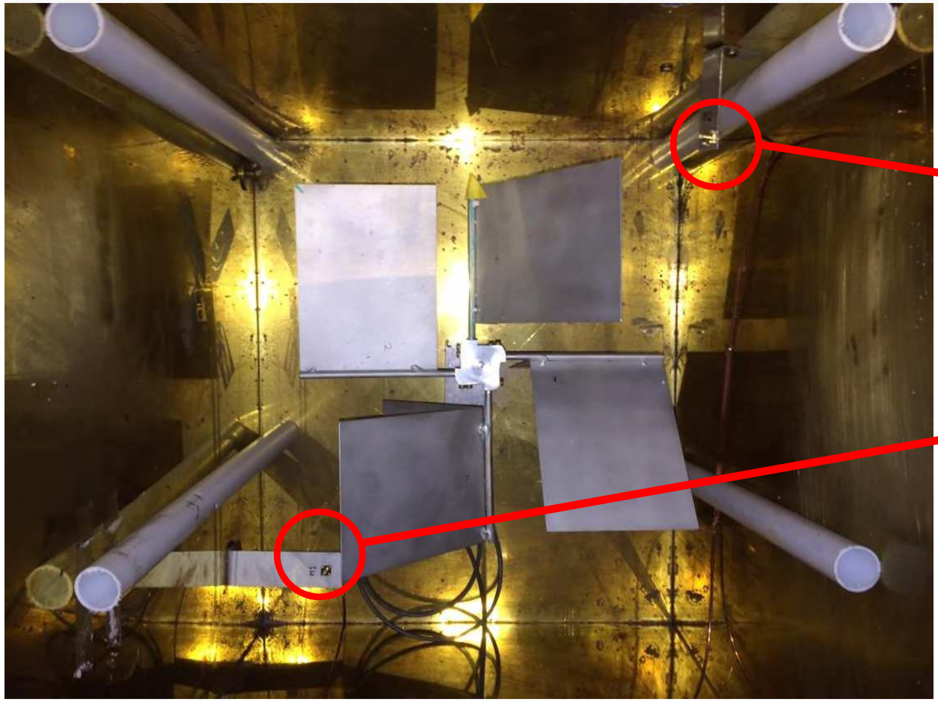
Insertion loss $IL = \frac{1}{\langle |S_{21}|^2 \rangle}$

Total efficiency of antennas

$$\eta_i^{\mathrm{T}} = \eta_i^{\mathrm{rad}} (1 - |\langle S_{ii} \rangle|^2)$$

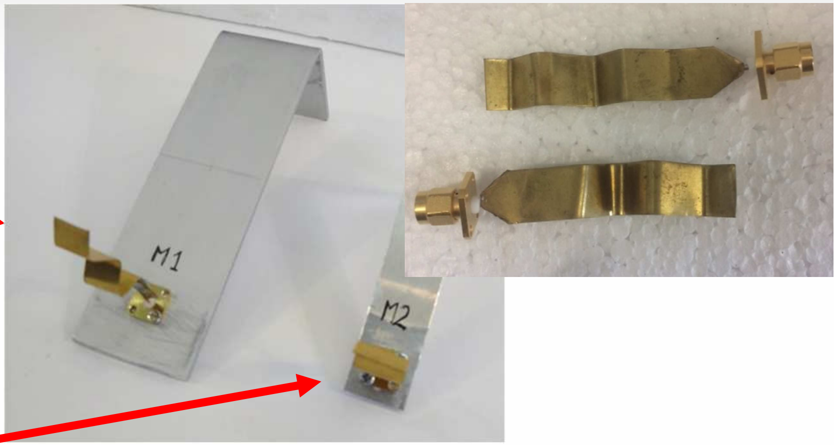


View of Small RC Interior (0.6m x 0.7m x 0.8m)



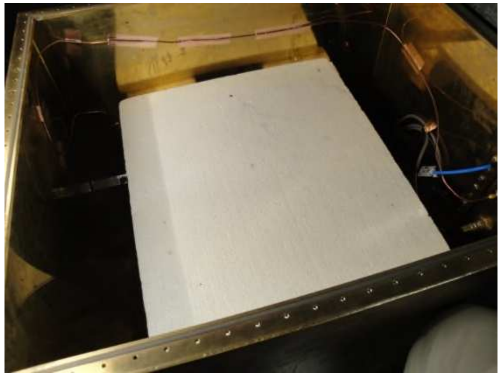
Lower part of chamber with paddle

100 paddle positions
100 MHz frequency stirring bandwidth



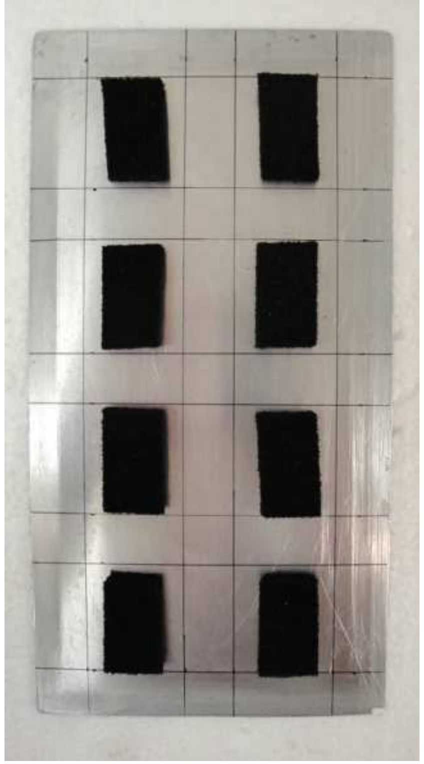
Broadband monopole antennas

Expanded polystyrene support

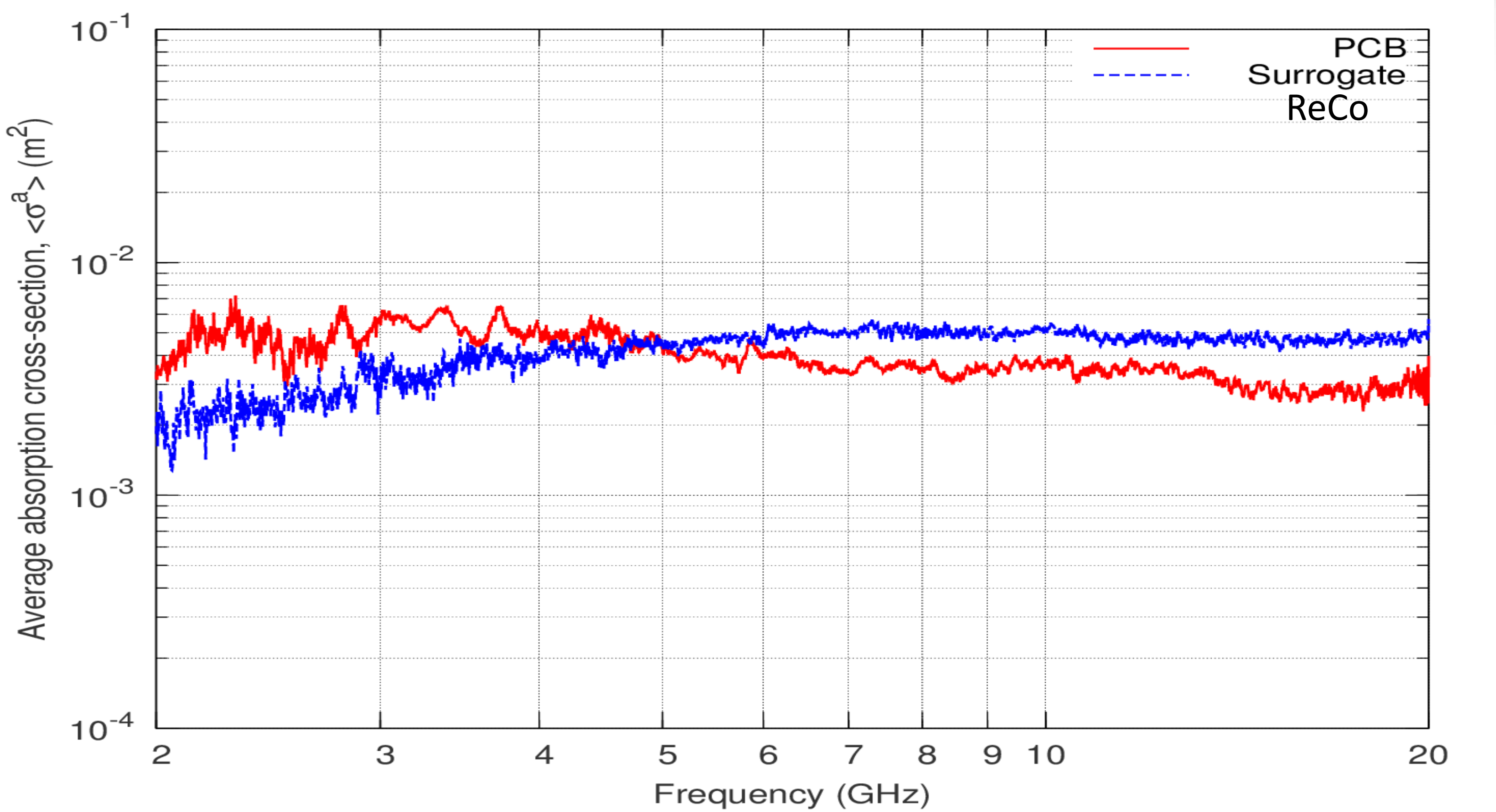


Representative Contents

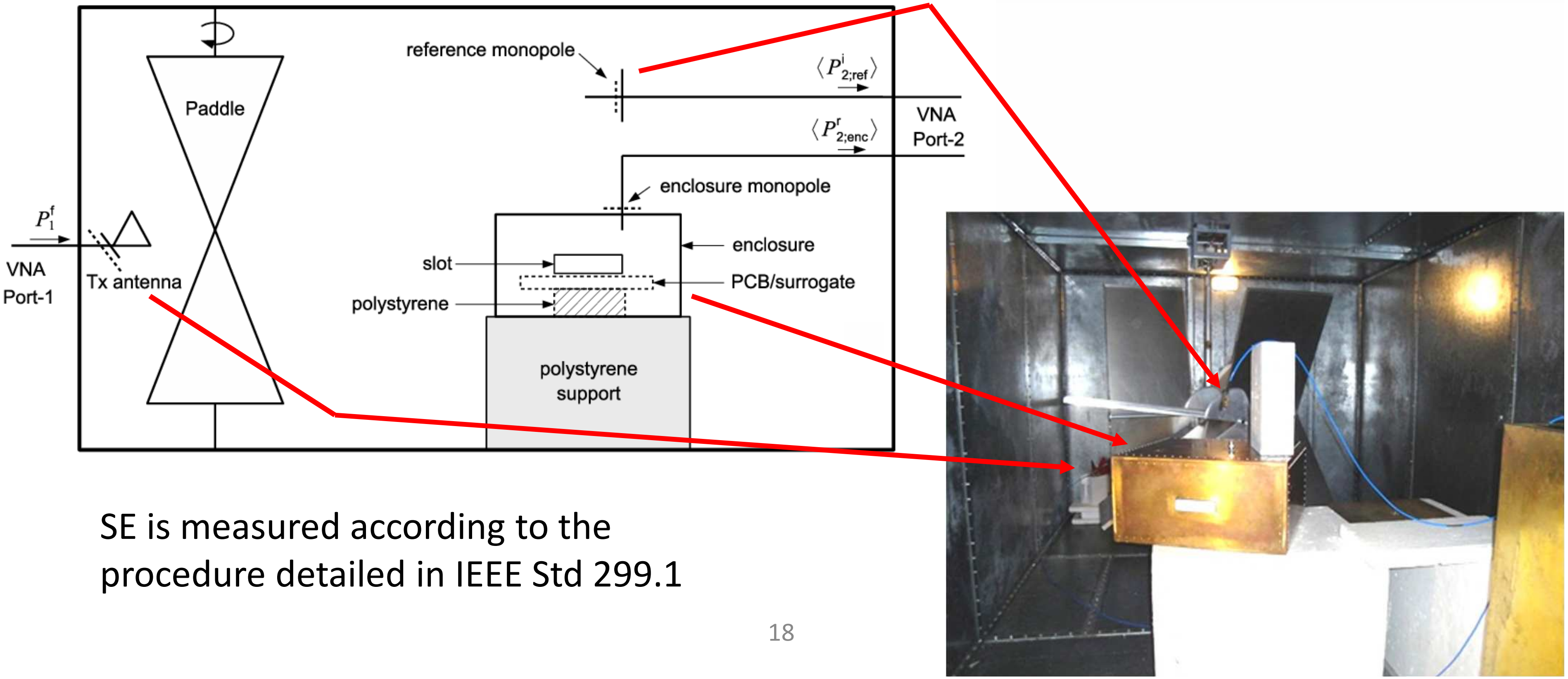
The surrogate PCB is fabricated from a conducting sheet with tailored blocks of carbon loaded polyurethane foam to replicate the absorption of the PCB components. The conducting sheet replicates the PCB ground plane structure. This prototype is single sided.



ReCo and target PCB ACS comparison

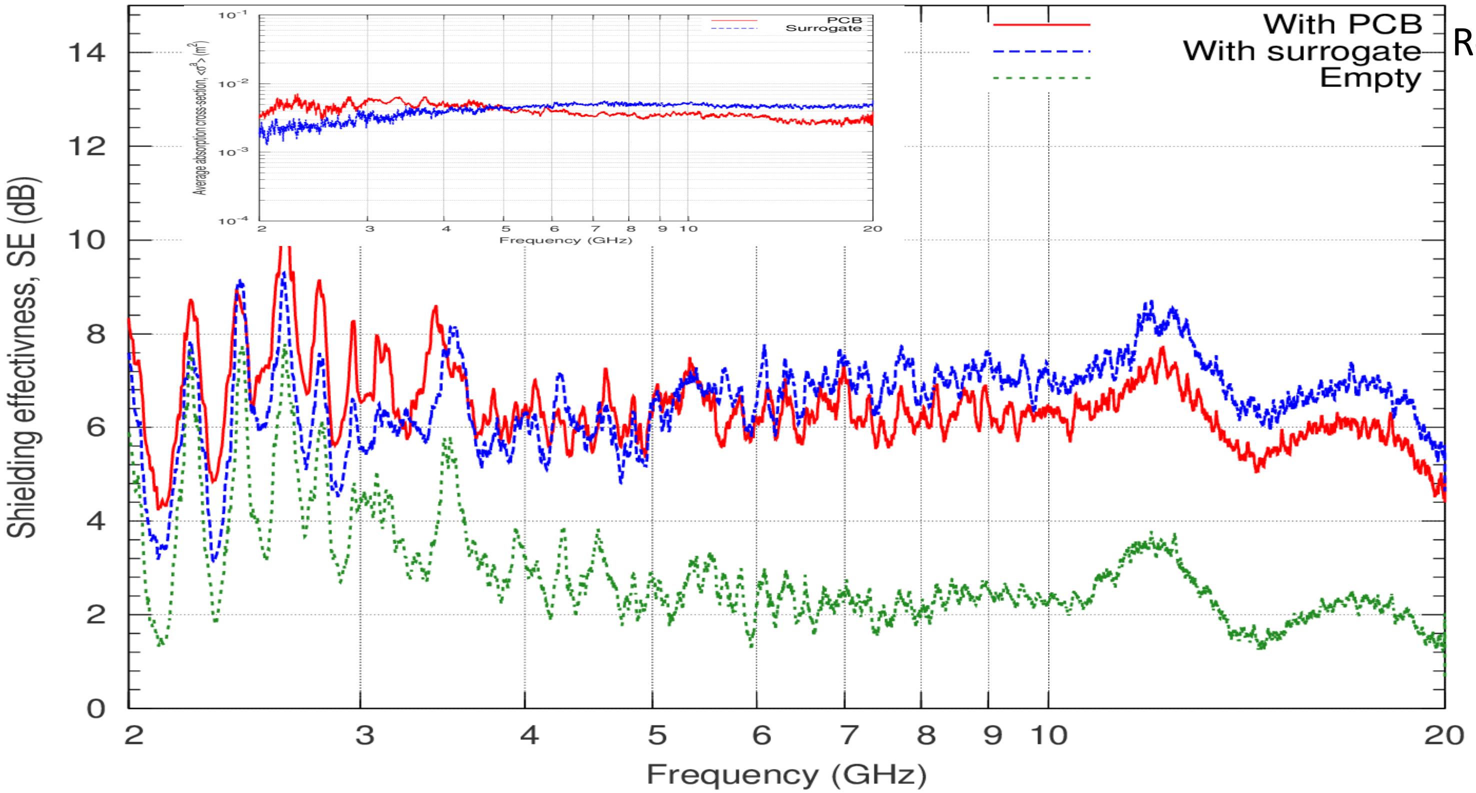


SE Measurement



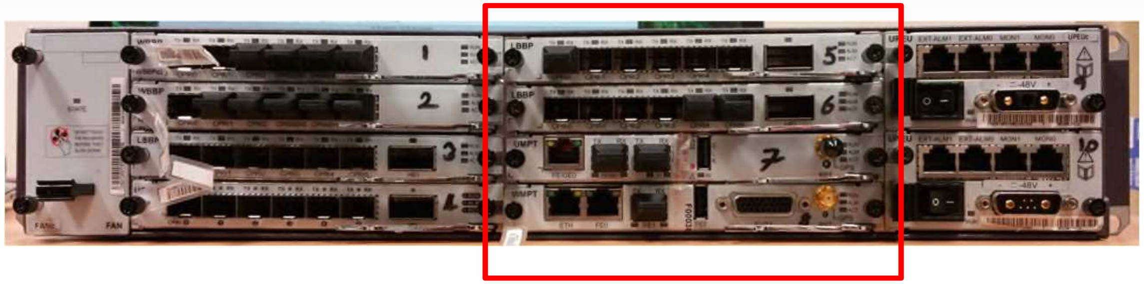
SE is measured according to the procedure detailed in IEEE Std 299.1

SE Measurement Results



ReCo

Multiple PCB Issues



Stack of four PCBs for ACS measurements

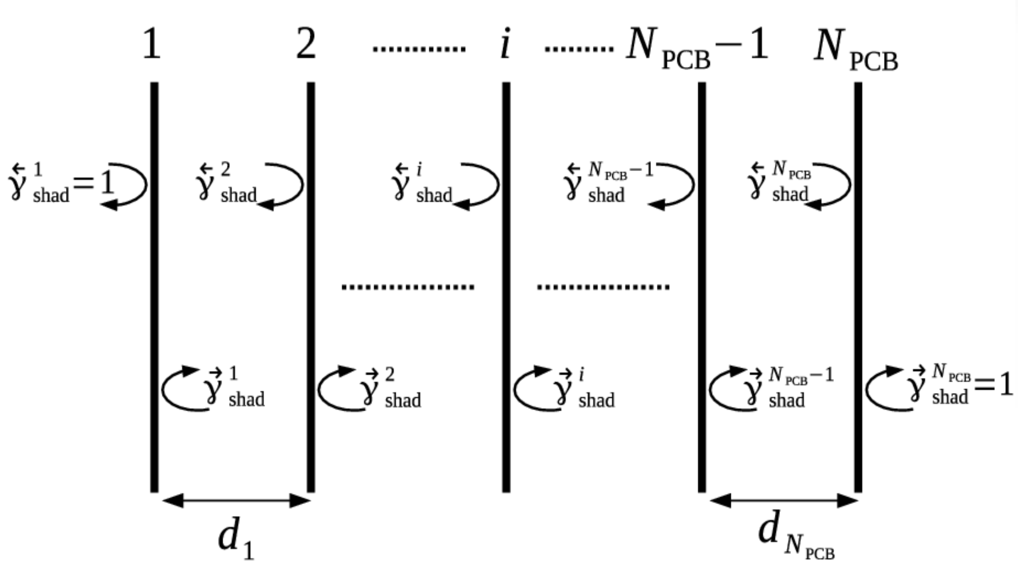
PCBs can be closely stacked in an IT enclosure. How does this effect the overall ACS?

Shadowing of Closely Stacked PCBs

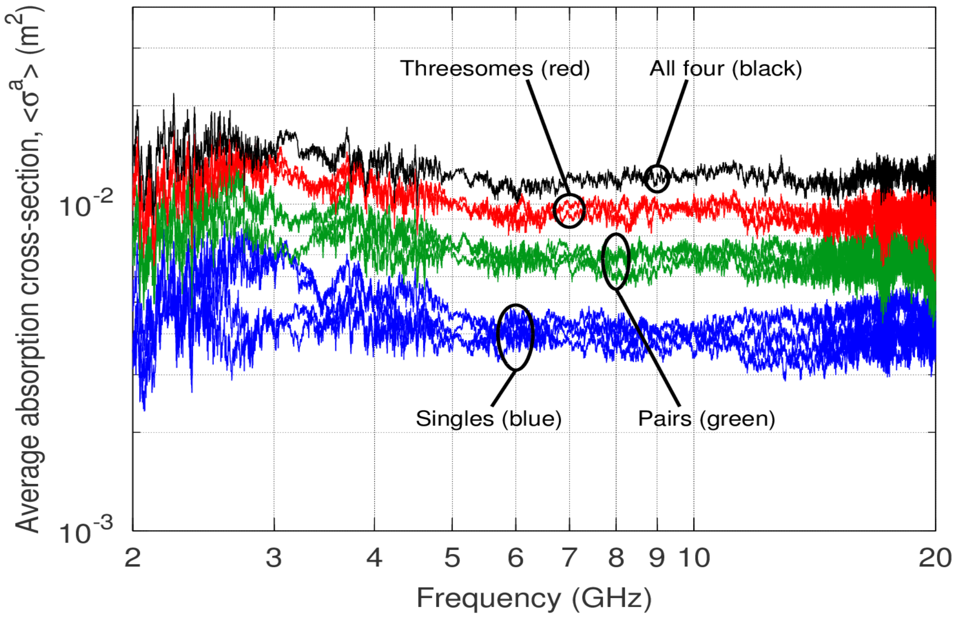
Closely spaced PCBs will shadow each other, reducing overall absorption compared to widely spaced PCBs.

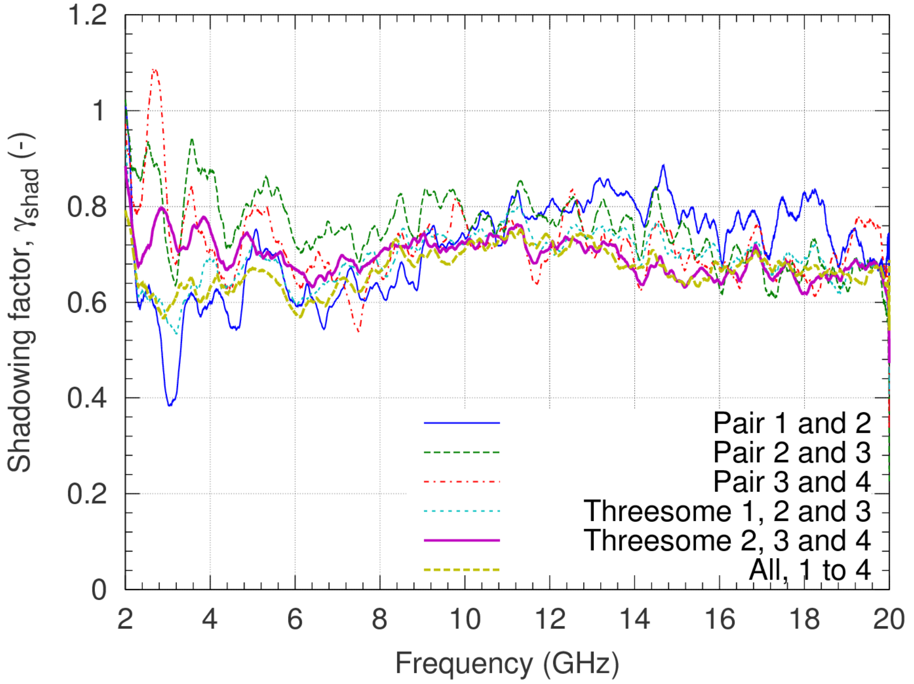
Quantify effect using quasi-optical shadowing factors $\overleftarrow{\gamma}^{i}_{\text{shad}}$ (left side) and $\vec{\gamma}^{i}_{\text{shad}}$ (right-side).

For simple analysis here assume all factors are the same.

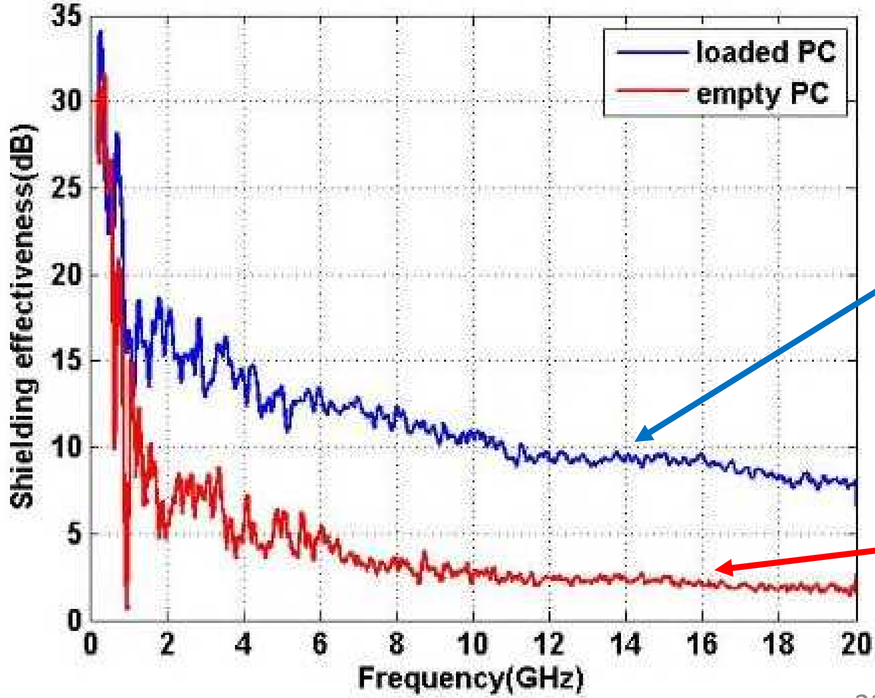


ACS Shadowing Measurements

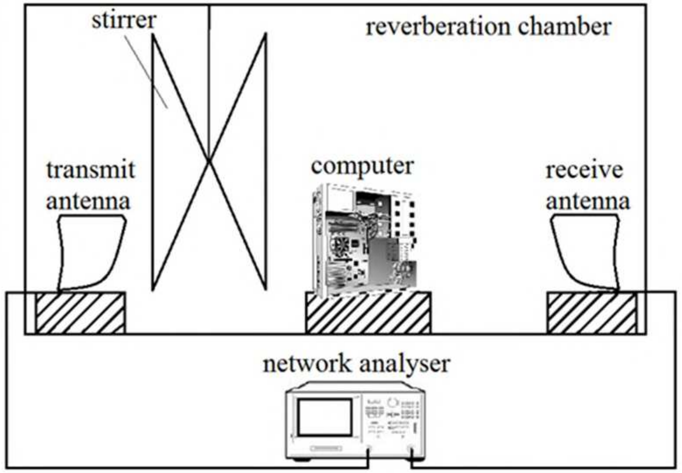




SE Measurements of a PC Enclosure



PC Circuit Card ACS Measurement

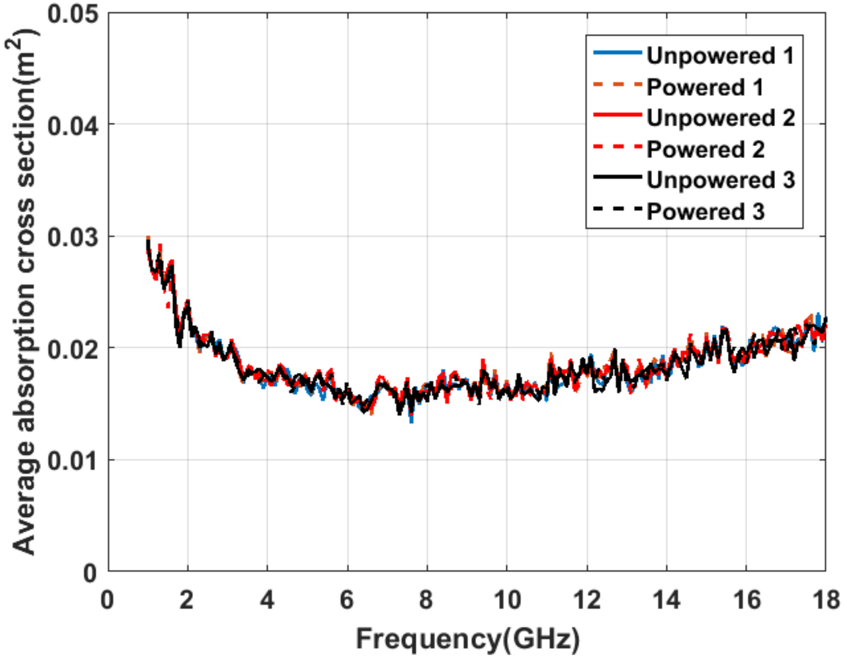


Does the power state matter?

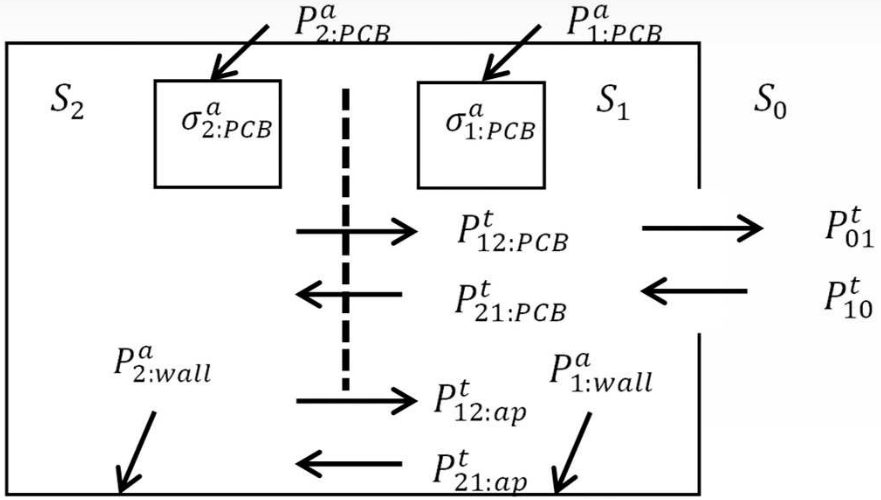
The ACS of the powered and unpowered computer were measured 3 times each for comparison.

Programs running during the measurements:

- Windows system
- Stress test software HeavyLoad
  (CPU hard drive)
- Windows media player (CD-ROM)



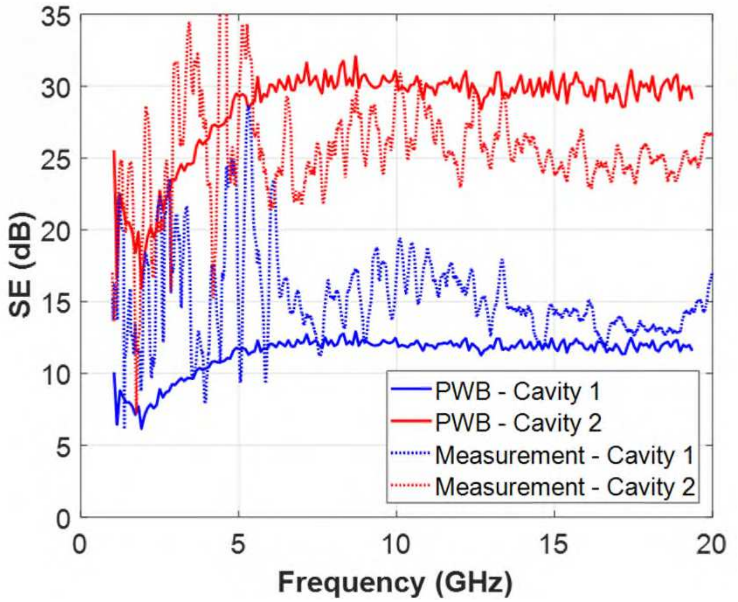
Where Next? Multi-Cavity Shielding?



Power Balance used to evaluate the Shielding of an enclosure divided into two sub-cavities by a circuit card with absorbing surfaces and a gap around the edge.

Two Cavity Shielding

$$\begin{bmatrix} \frac{S_0}{S_1} \\ \frac{S_0}{S_2} \end{bmatrix} = \begin{bmatrix} (\sigma^a_{1:wall} + \sigma^a_{1:PCB} + \sigma^t_{21:ap} + \sigma^t_{10}) & -(\sigma^t_{12:ap}) \\ -(\sigma^t_{21:ap}) & -(\sigma^a_{2:wall} + \sigma^a_{2:PCB} + \sigma^t_{21:ap}) \end{bmatrix}^{-1} \begin{bmatrix} \sigma^t_{10} \\ 0 \end{bmatrix}$$

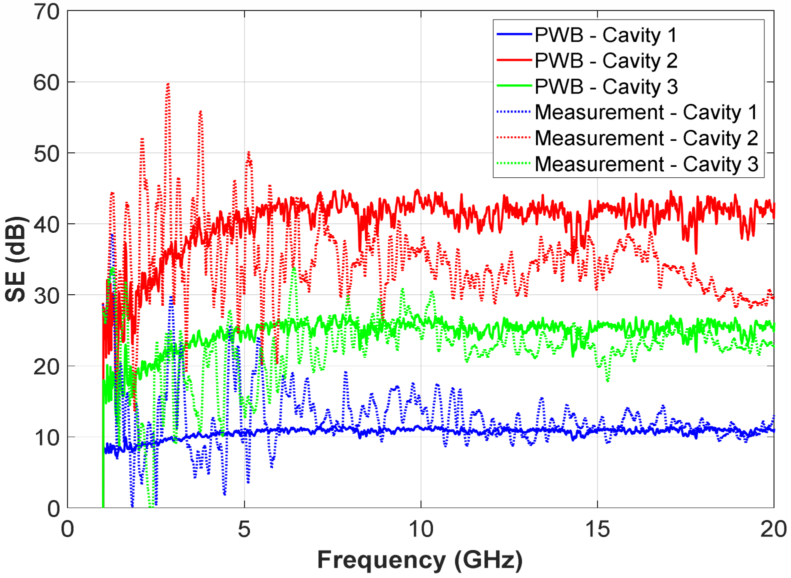


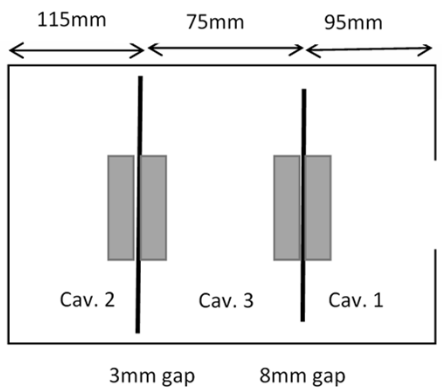
The solid lines are Power Balance predictions using measured ACS data for the circuit card. The dotted lines show the measured SE at a point in each sub-cavity.

In principle the formulation can be extended to any number of sub-cavities.

Three Cavity Shielding

$$\begin{bmatrix} \frac{S_0}{S_1} \\ \frac{S_0}{S_2} \\ \frac{S_0}{S_3} \end{bmatrix} = \begin{bmatrix} (\sigma^a_{1:wall}+\sigma^a_{1:PCB}+\sigma^t_{21:ap}+\sigma^t_{10}) & 0 & -(\sigma^t_{13:ap}) \\ 0 & (\sigma^a_{2:wall}+\sigma^a_{2:PCB}+\sigma^t_{21:ap}) & -(\sigma^t_{21:ap}) \\ -(\sigma^t_{31:ap}) & -(\sigma^t_{32}) & (\sigma^a_{3:wall}+\sigma^a_{3PCB}+\sigma^t_{23:ap}+\sigma^t_{13:ap}) \end{bmatrix}^{-1} \begin{bmatrix} \sigma^t_{10} \\ 0 \\ 0 \end{bmatrix}$$





Where Next? Diffusion?

The Power Balance model gives a good estimate of the average energy density on the enclosure which is assumed to be uniform throughout.

However, if energy enters the enclosure and is absorbed into its walls and contents there must be an energy flow process that will result in a non-uniform energy density.

Consider a point source in an enclosure;

$$W(\mathbf{r})=1/2\,(\varepsilon_0\langle|\mathbf{E}(\mathbf{r})|^2\rangle+\mu_0\langle|\mathbf{H}(\mathbf{r})|^2\rangle)$$

volumetric loss rate

energy density

diffusivity

$$(D\nabla^2+\Lambda_\mathrm{V})W(\mathbf{r},t) = P^{\mathrm{TRP}}\,\delta^{(3)}(\mathbf{r}-\mathbf{r}_s)$$

isotropic point source

Diffusivity & Mean Free Path

$$D = \bar{l}\mathrm{c}_0/3$$

$$\bar{l}^{\,-1} = \bar{l}_{\mathrm{wall}}^{-1} + \bar{l}_{\mathrm{con}}^{-1}$$

chamber walls

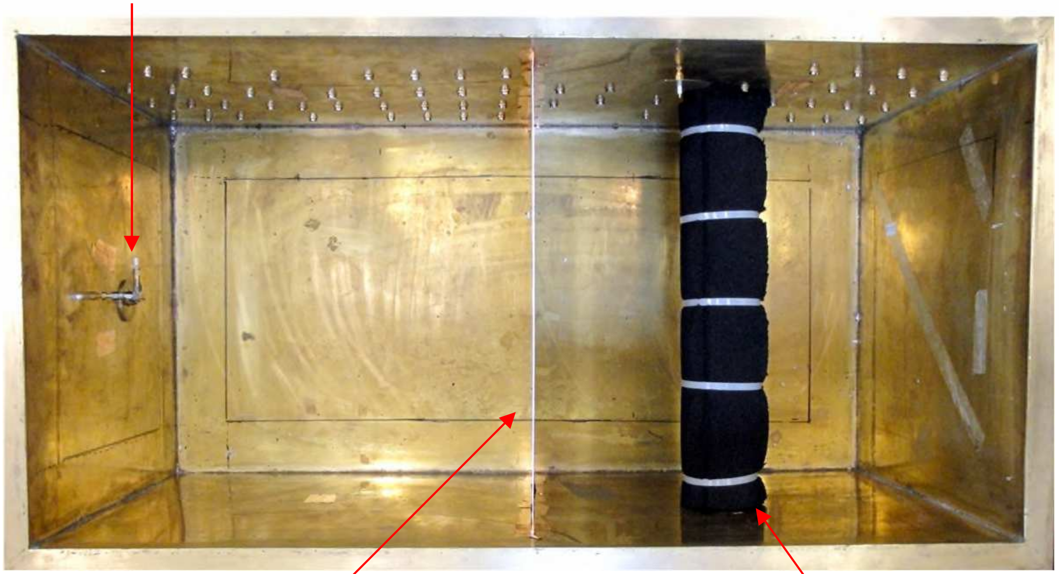
$$\bar{l}_{\mathrm{wall}} = 4V/S_V$$

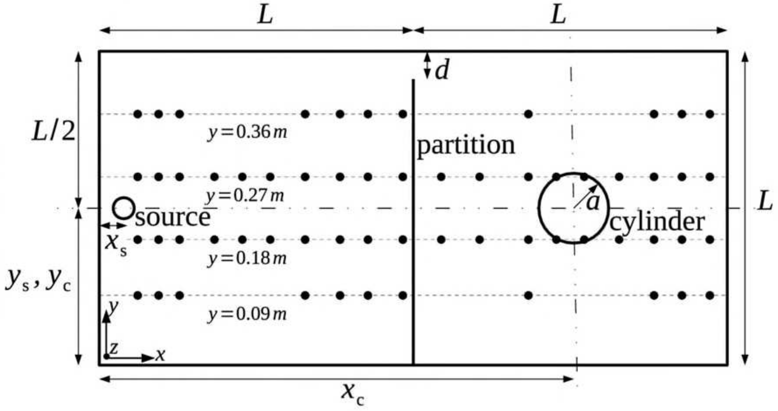
contents

$$\bar{l}_{\mathrm{con}} = 4\,V/S_{\mathrm{con}}$$

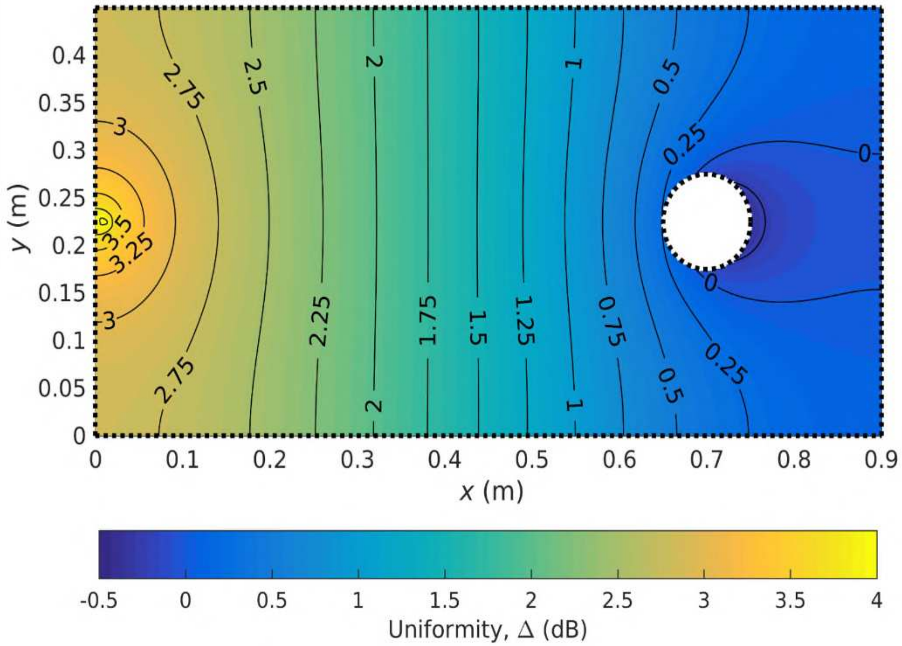
The diffusivity, the rate at which energy diffuses through the enclosure, depends on the mean-free-paths of waves scattering off the walls and the contents. Here, S is the surface area, V the volume and c_0 the velocity of wave propagation.

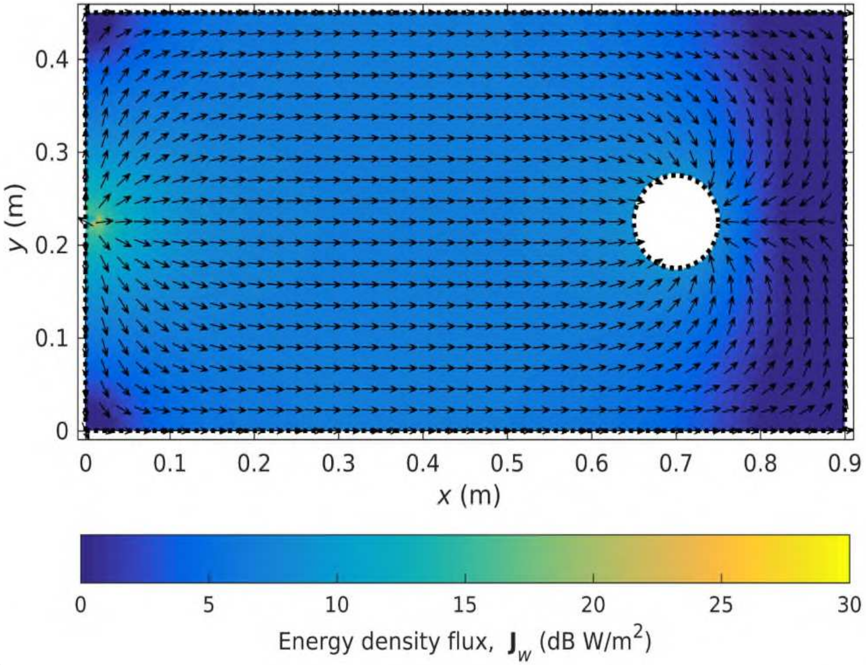
Test Chamber



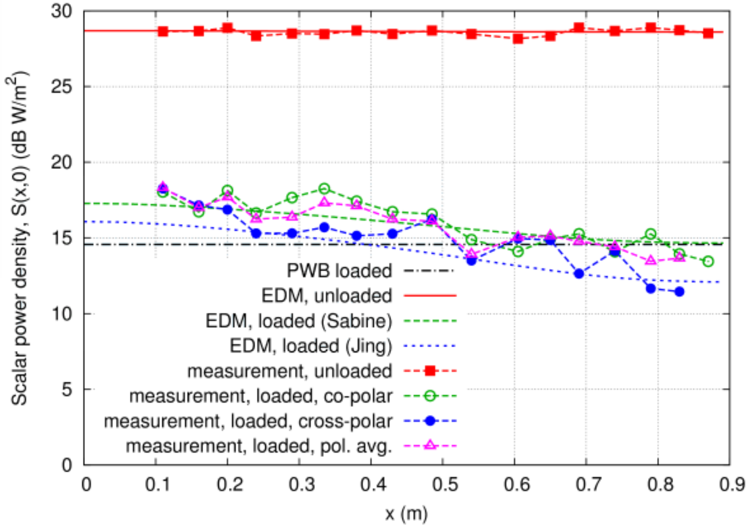


Numerical Diffusion Solutions.

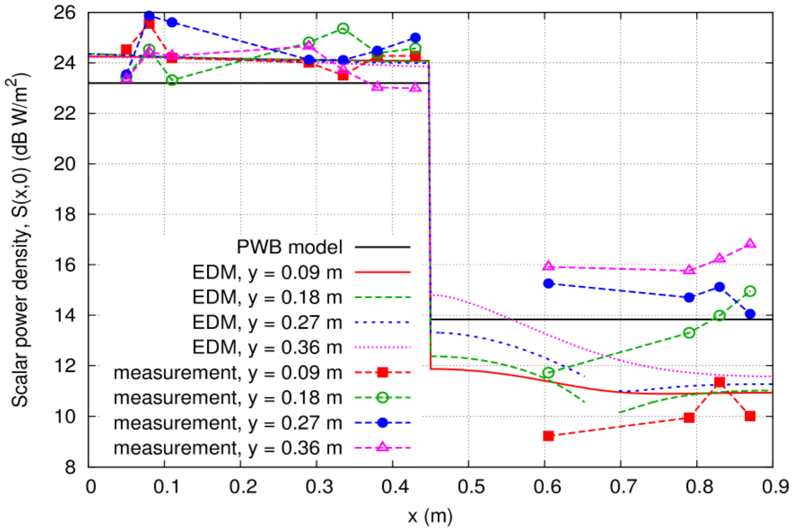




Computed and Measured Data.

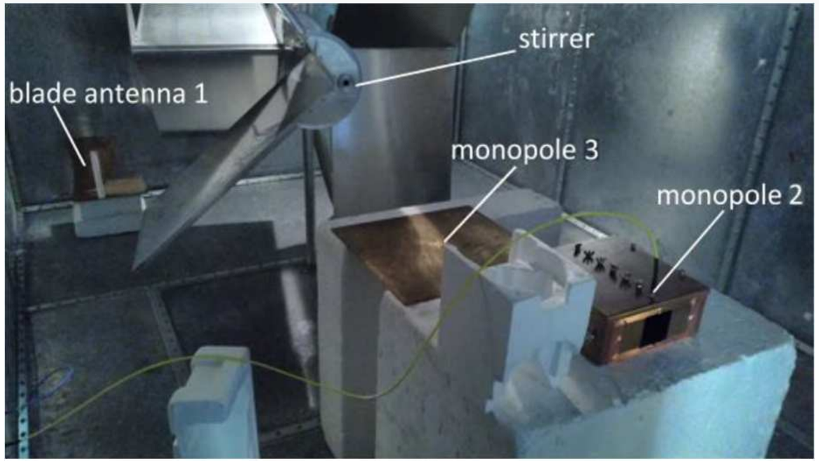


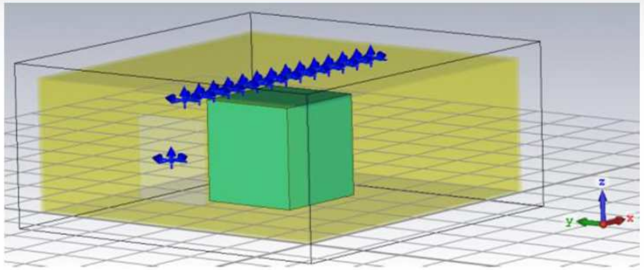
Without the partition.

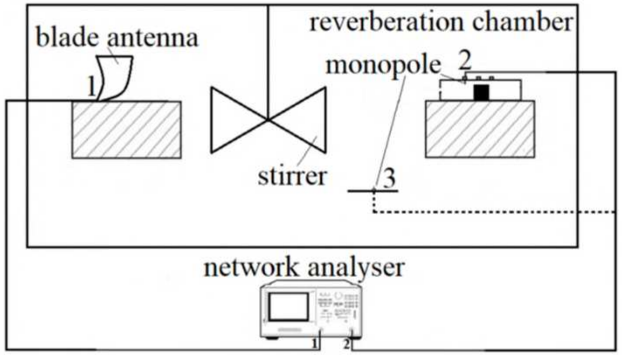


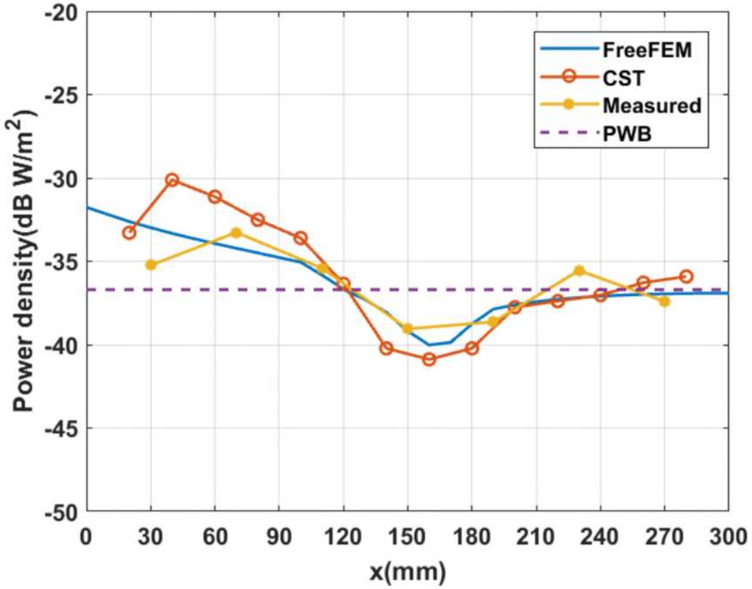
With the partition.

Diffusion in a Loaded Enclosure









What makes Board Level Shields Different?

Typical Board Level Shield installation.

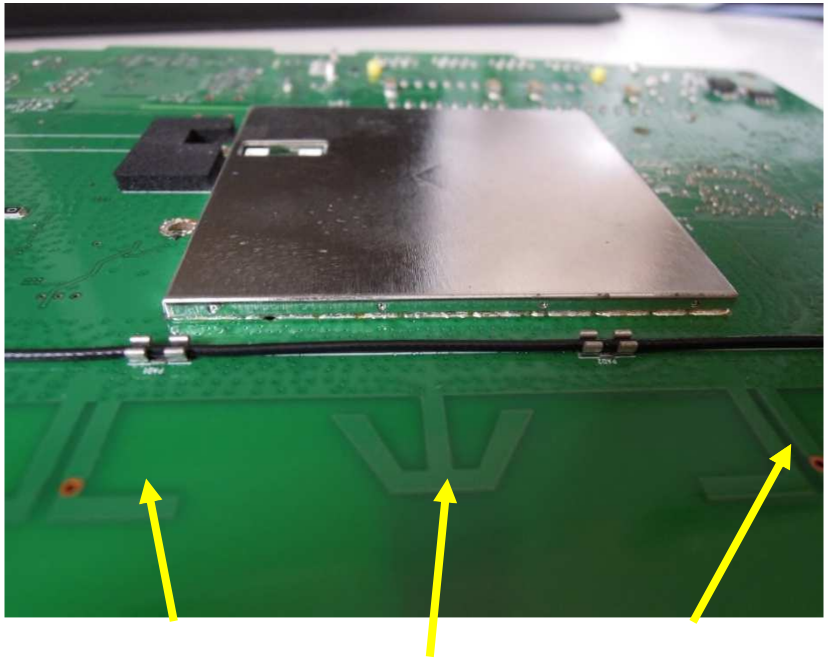
Board Level Shields (BLS) are much smaller than normal Shielded Enclosures. Typical dimensions are 100 mm or less.

They normally have five rather than six sides. The sixth side is the circuit board ground-plane.

Their size makes the installation of internal measurement antennas impractical in most cases meaning that standard Shielding Effectiveness measurements are not applicable.

Their only function is to act as a shield.

Board Level Shield Application External Environments



Antennas on router board.

BLS are installed in various environments. They may be in an outer equipment enclosure which itself is shielded (resonant or reverberant) or they may be in an un-shielded enclosure such as the router opposite left but in close proximity to antennas.

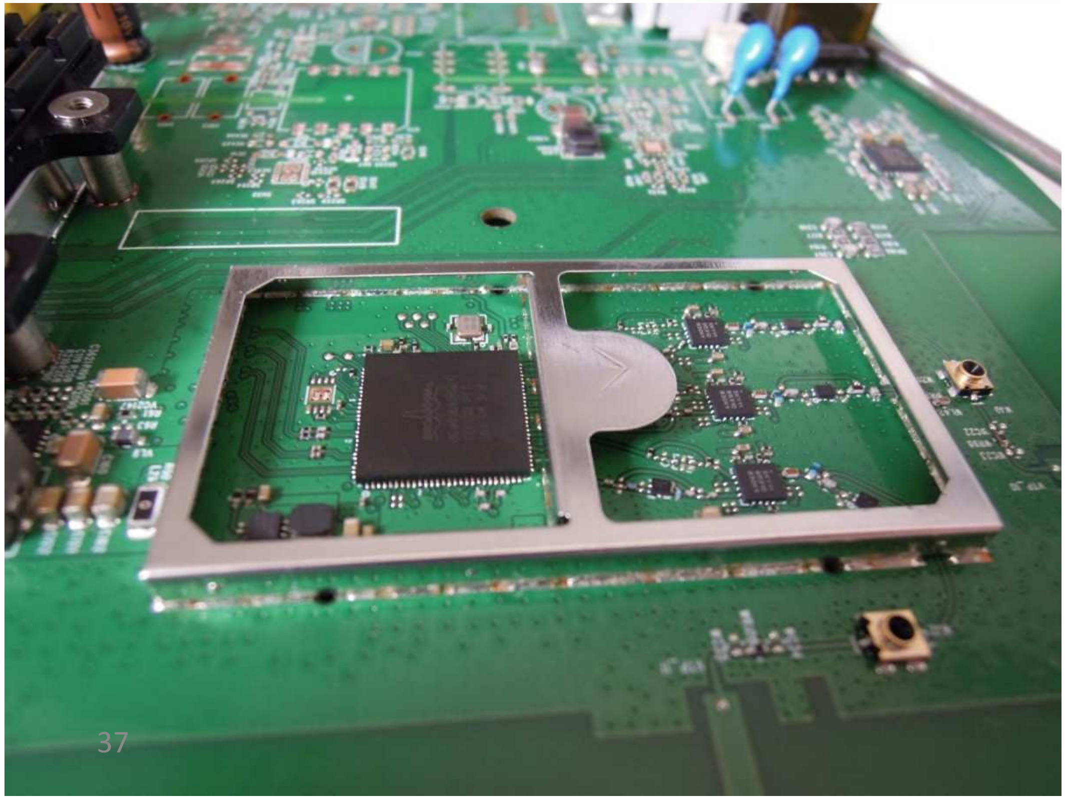
All we can say is that we are dealing with known unknowns.

Board Level Shield Application Internal Environments

The BLS is there to shield something!

The internal components may act as interference sources or they may suffer from external interference.

The shield contents will, in any event, absorb electromagnetic energy and need to be accounted for in any shielding measurement.



Energy Coupling Paths

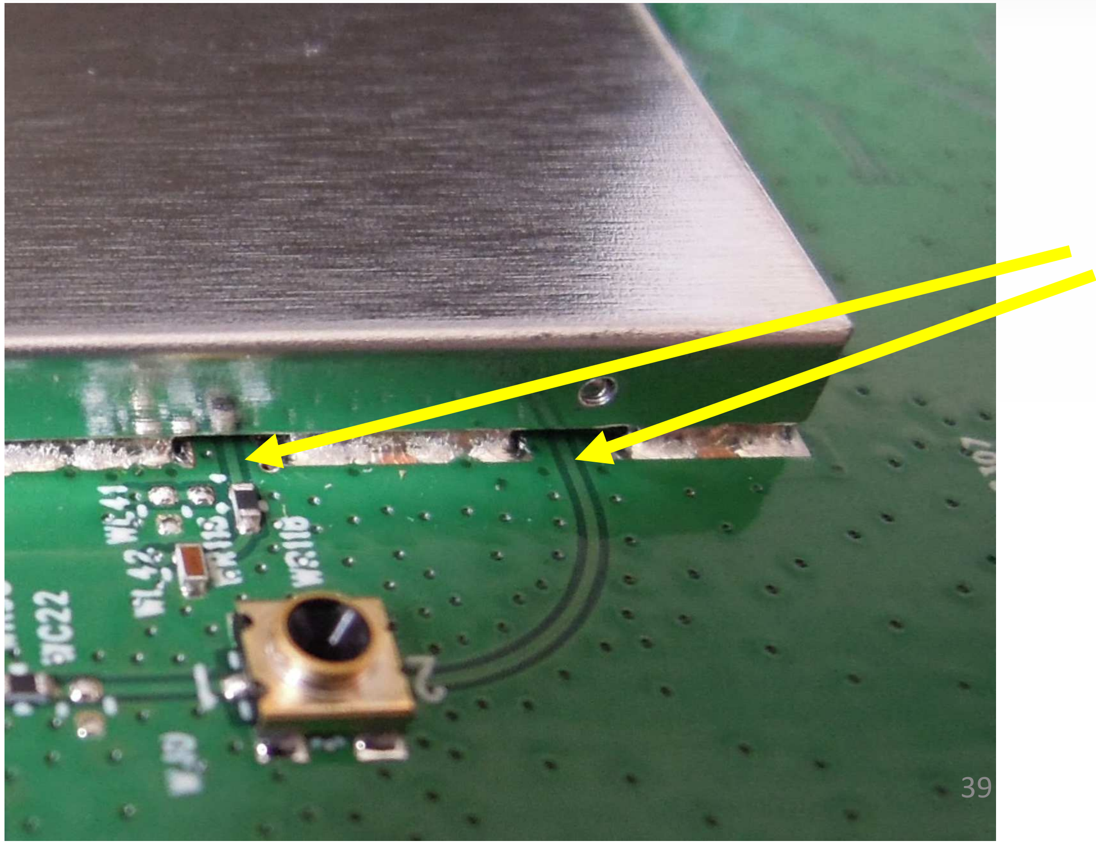
Direct coupling path

Indirect coupling path. Scattered from the external environment

Most interference paths are likely to be from local sources or victims.

External interference is shielded by the equipment enclosure which, if present, will itself produce scattering surfaces for indirect coupling paths.

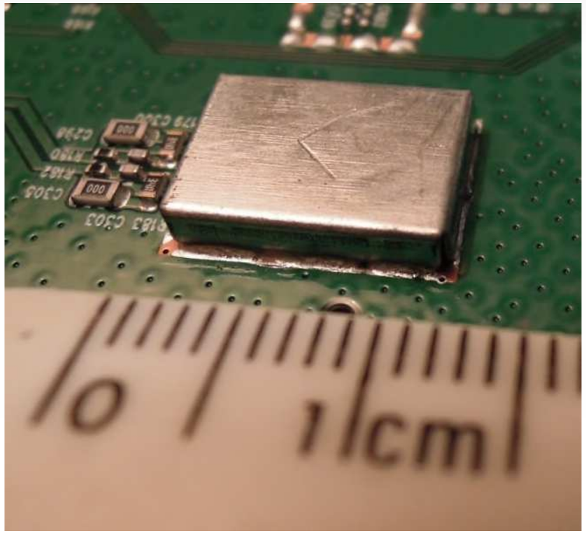
Desired Signal Penetration



The BLS may be installed so as to allow the propagation of desired signals between the interior and exterior of the BLS.

Assessment of the shielding performance of BLS's must exclude these signal paths.

Shielding Effectiveness Measurements

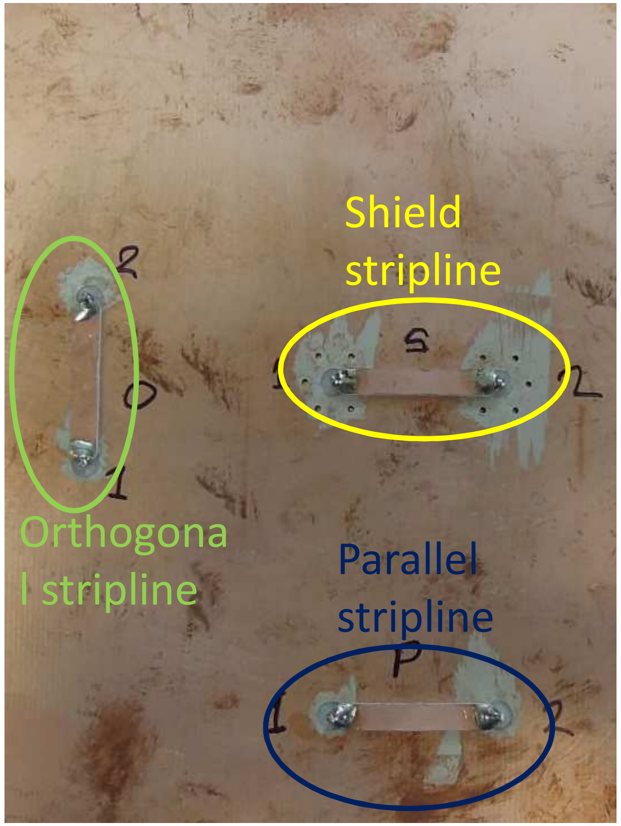


Measurement of the SE of a BLS is challenging due to the small size of the shield. Conventional SE measurement techniques such as IEEE Std 299.1 require the installation of antennas inside the enclosure under investigation.

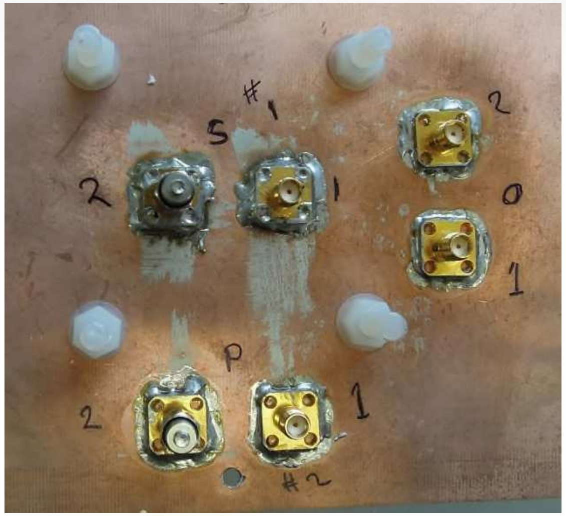
The variable local external environment of the BLS is complex.

The interference source of victim is likely to be on the same circuit board.

Prototype Measurement Jig



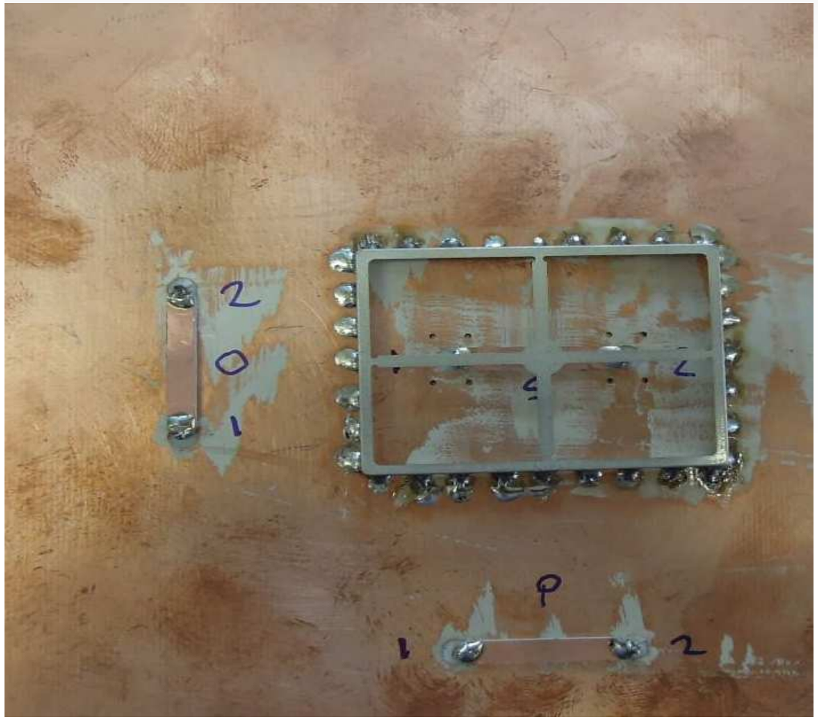
The prototype measurement jig has three 50 Ω striplines on a groundplane to replicate the internal components and the external local interference source or victim components.

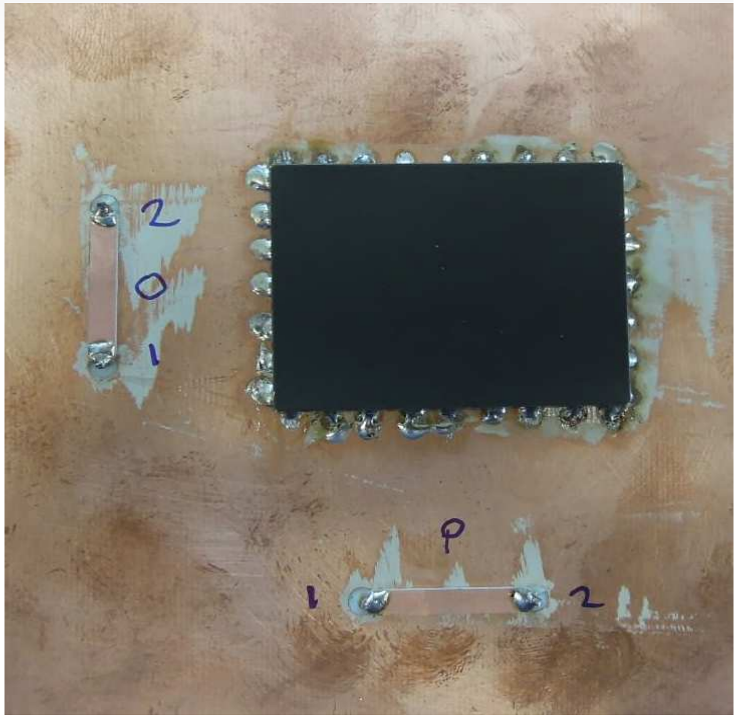


Each stripline is 25 mm long and is separated from the internal stripline by 50 mm.

Each stripline is terminated by SMA jacks at each end.

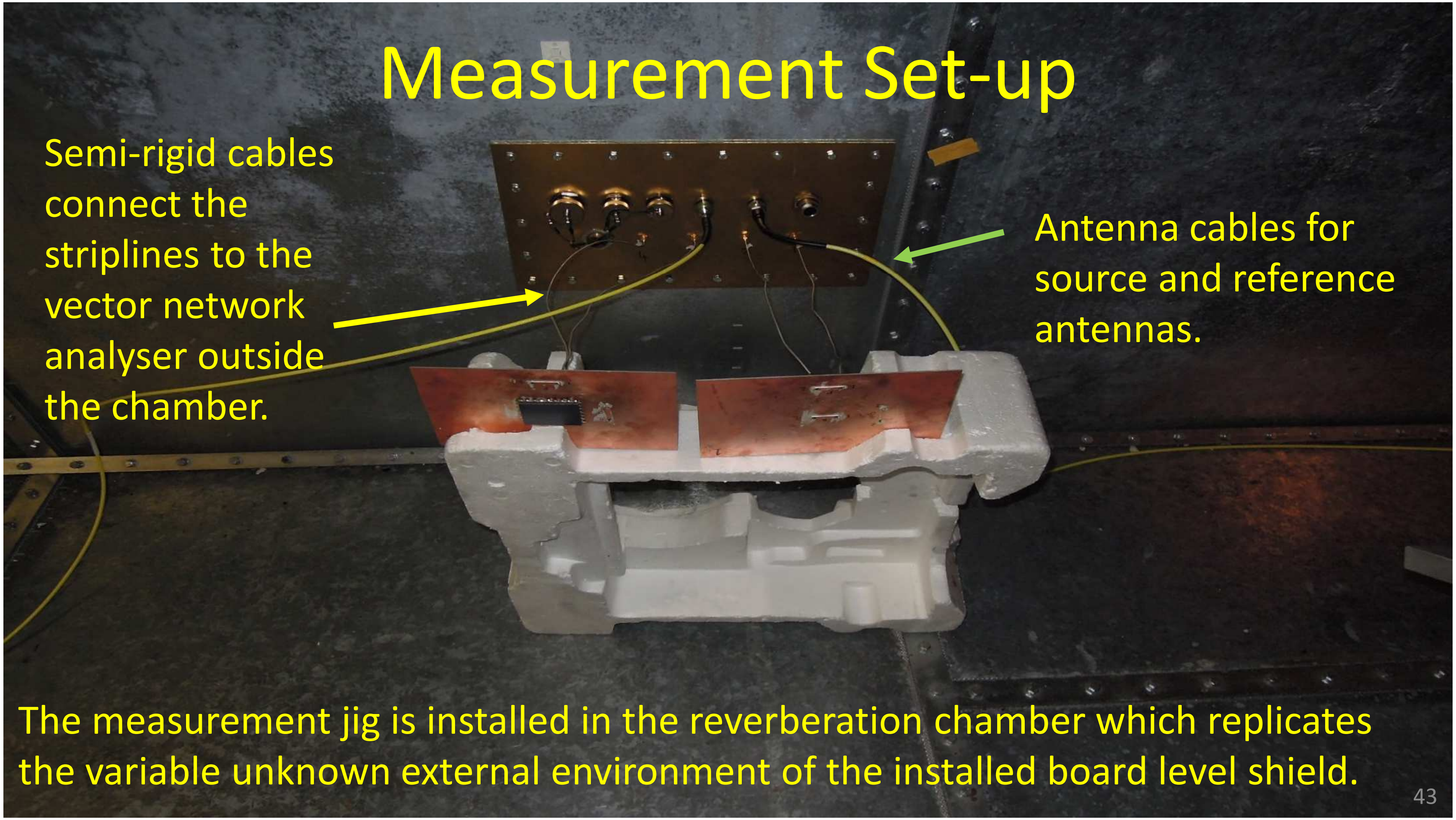
Prototype Measurement Jig





The BLS frame is soldered onto the jig above the S stripline and then the BLS shell is clipped onto the frame.

Measurement Set-up



Semi-rigid cables connect the striplines to the vector network analyser outside the chamber.

Antenna cables for source and reference antennas.

The measurement jig is installed in the reverberation chamber which replicates the variable unknown external environment of the installed board level shield.

So what do we measure?

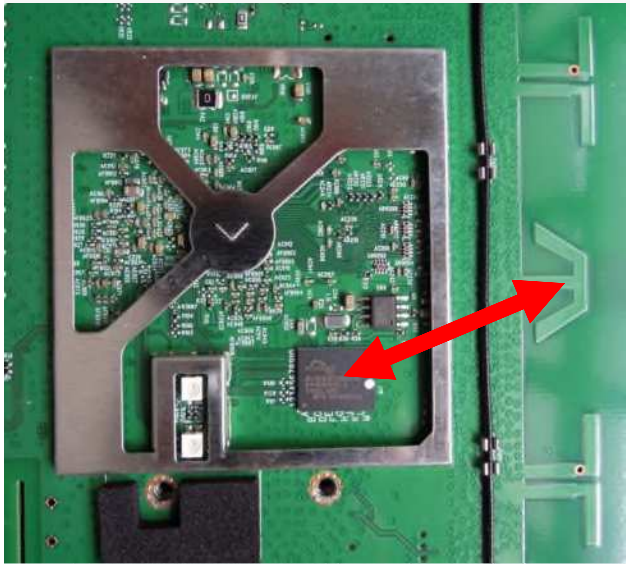
The basic measurement is an *S21* measurement between the shield stripline and an external stripline or antenna in the reverberation chamber. The other end of each stripline is terminated in a 50 Ω load.

The shield stripline mimics the internal components of the shield with energy absorption due to its matched load at either end.

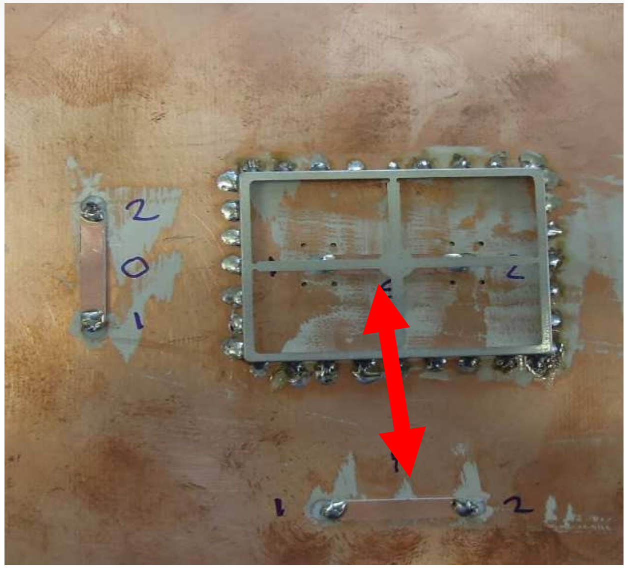
The unknown external environment of the shield is mimicked by the stirring process in the reverberation chamber.

Measurements are made with and without the shield present.

Unstirred Shielding Effectiveness

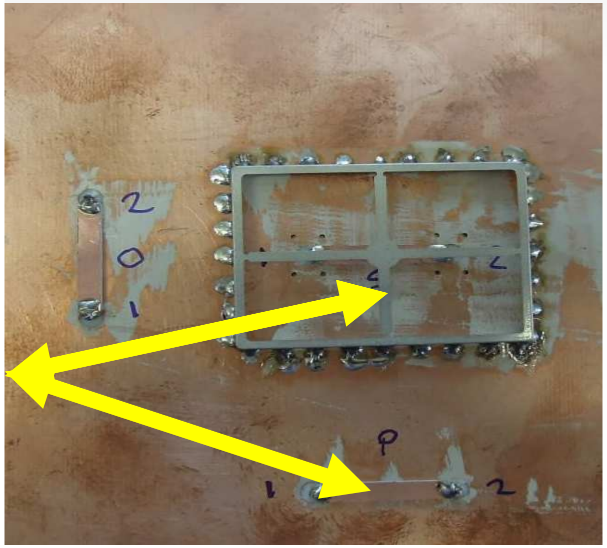


$$SE_{us} = 10\log_{10}\left(\left|\frac{\langle S_{21u}\rangle}{\langle S_{21s}\rangle}\right|\right)^2$$

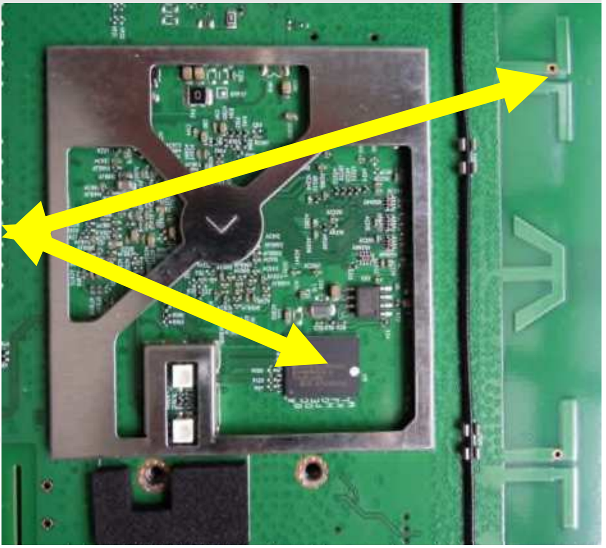


Unstirred Shielding Effectiveness measures the direct coupling between the source and the victim. The averaging process over all the stirrer positions (< >) removes the coupling due to multiple reflections (reverberant coupling) from the measurement result. This is independent of the shield external environment.

Stirred Shielding Effectiveness



$$SE_{st} = 10\log_{10}\left(\frac{\langle|S_{21u}-\langle S_{21u}\rangle|^2\rangle}{\langle|S_{21s}-\langle S_{21s}\rangle|^2\rangle}\right)$$



Stirred Shielding Effectiveness is the shielding of the reflected or reverberant energy in the system. It represents the energy scattered by the external enclosure or other scattering processes. The calculation removes the direct coupled component represented by $<S_{21u}>$ and $<S_{21s}>$ averages.

Point Shielding Effectiveness

The stationary *Unstirred SE* is modified by the scattered energy due to the shield's external environment, the *Stirred SE*. This is unknown.

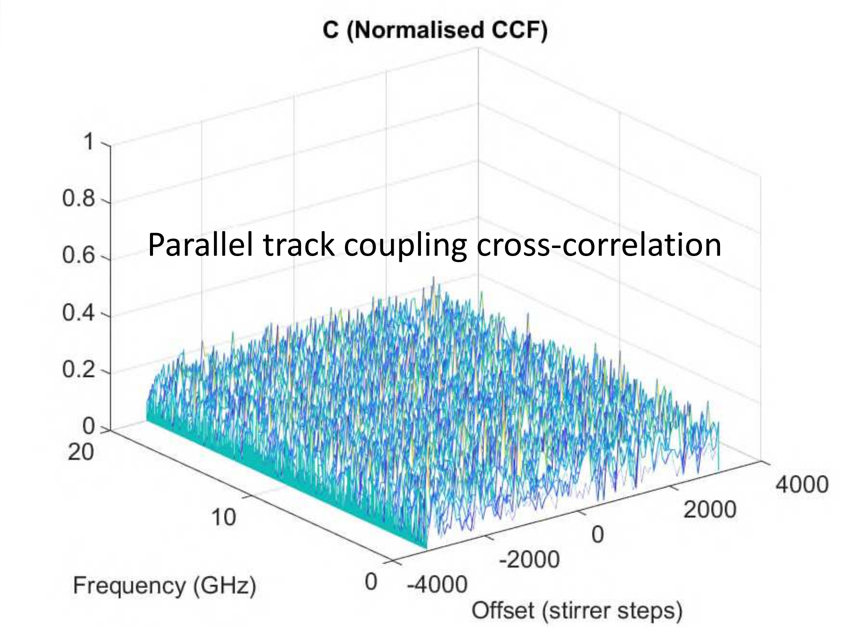
We need a metric that explores the range of variability of the external environment and the effect it has on the SE. The reverberation chamber allows us to do this.

The *Point SE* is the SE of the shield at each of *n* stirrer positions with both direct and scattered energy included. This shows the range of variability of the SE that may be encountered in a range of external environments.

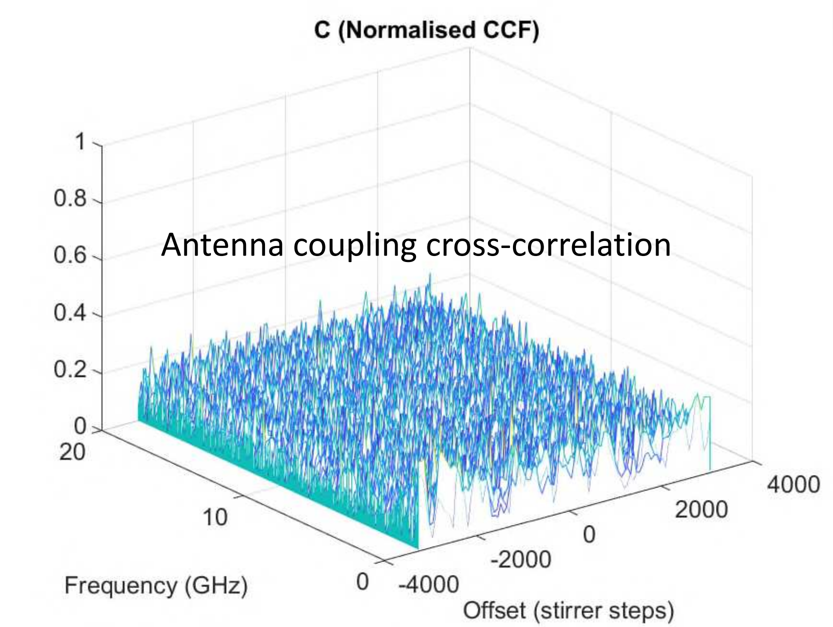
$$SE_n = 10log_{10}\left|\frac{S_{21u(n)}}{S_{21s(n)}}\right|^2$$

$$SE_{point(mean\ dB)} = \left\langle 10\log_{10}\left|\frac{S_{21u}(n)}{S_{21s}(n)}\right|^2\right\rangle$$

Coupling Correlation



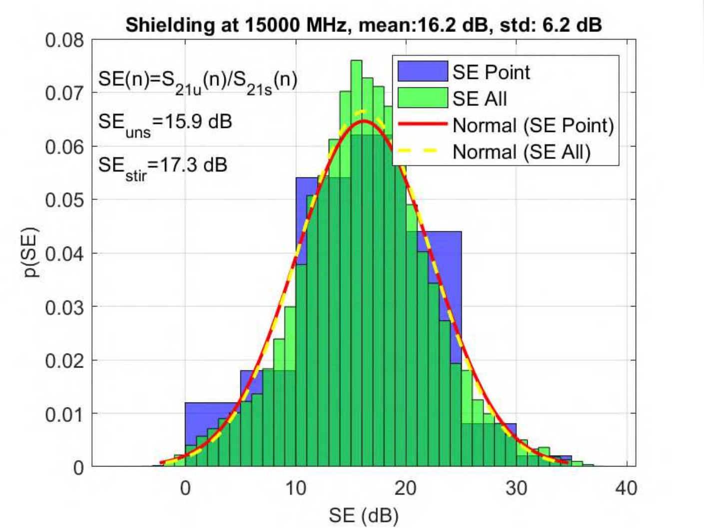
Parallel track coupling cross-correlation

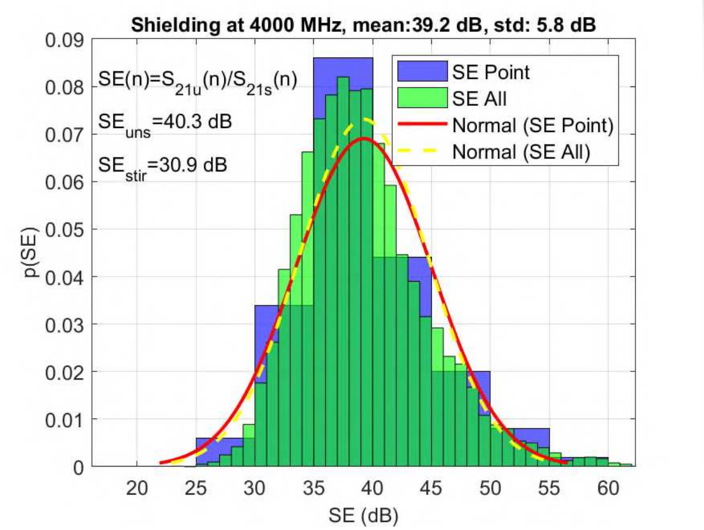


Antenna coupling cross-correlation

There appears to be no cross-correlation between the shielded and unshielded measurements. So the stirrer position by position registration is not necessary.

Point SE and SE All



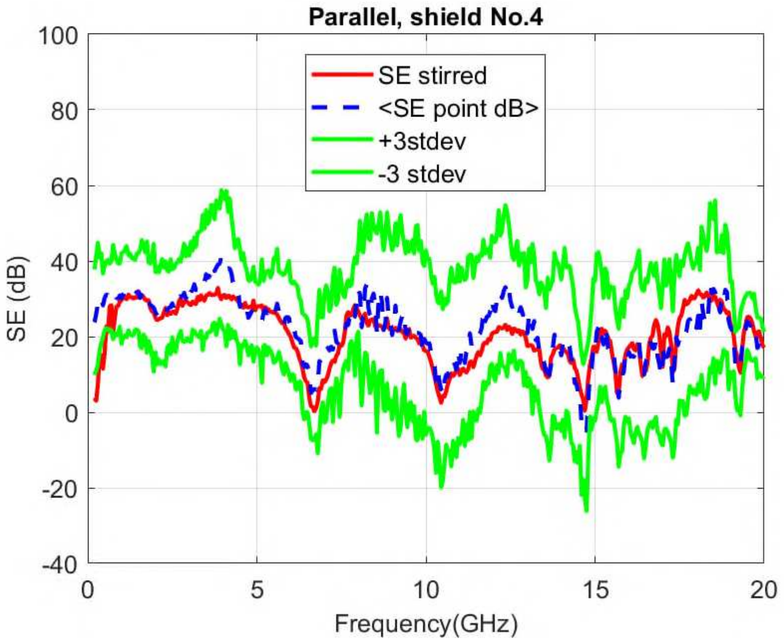


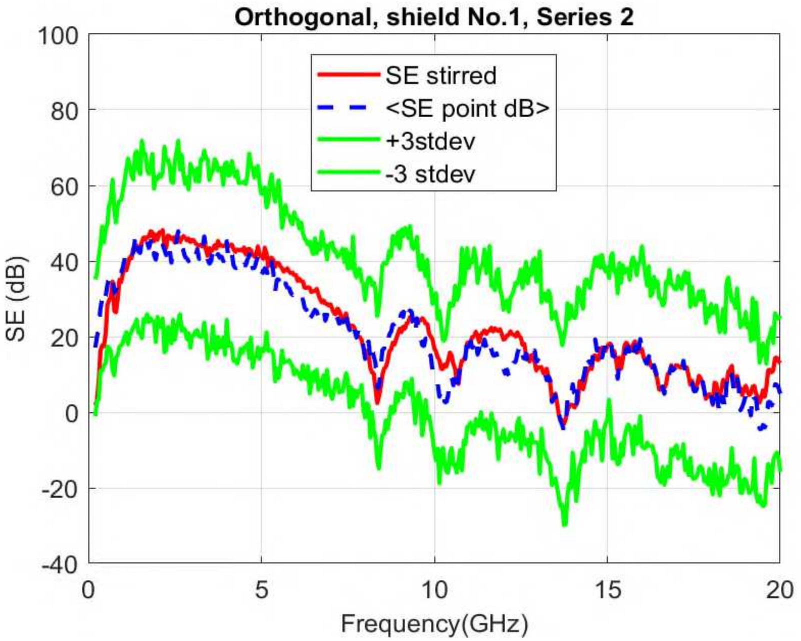
The PDFs show the *Point SE* for a shield with *SE All* which are the SE values derived by ratioing every shielded measurement with every unshielded measurement.

The distributions are almost identical. Both appear to be log-normal.

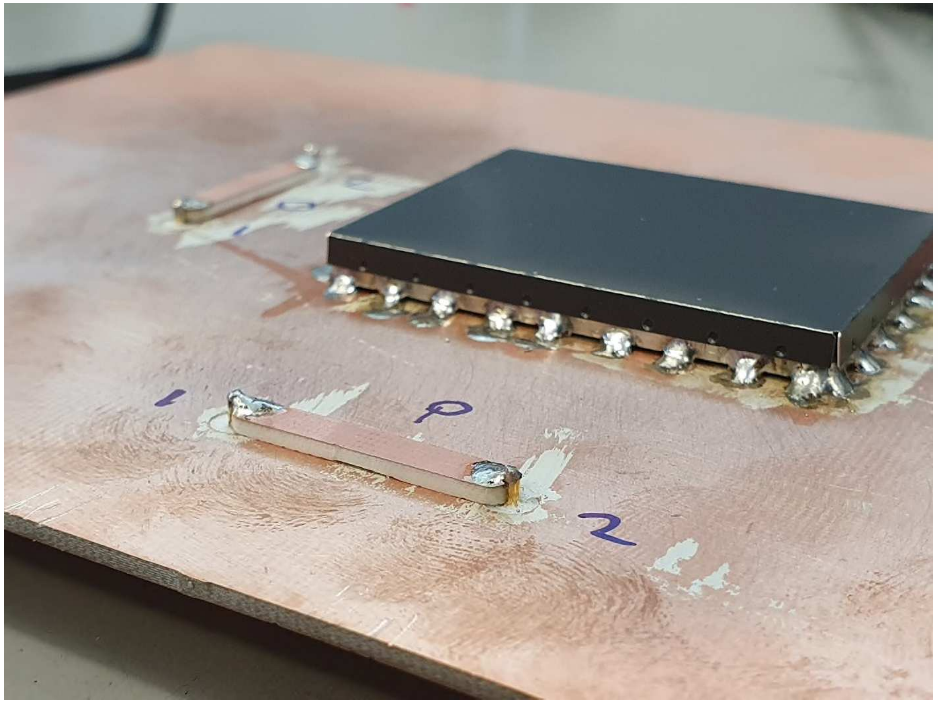
SE All Statistics

The plots show the SE All data for two shield samples along with the ± 3 standard deviation data. These give estimated bounds to the SE variation due to external factors.





BLS Installation Issues



We now have a measurement metric that enables the environment derived SE variability to be estimated and bounded.

However, the BLS still has to be installed on the measurement jig. Soldering the BLS to the jig takes time and un-soldering it takes even longer and often results in damage to the fragile BLS.

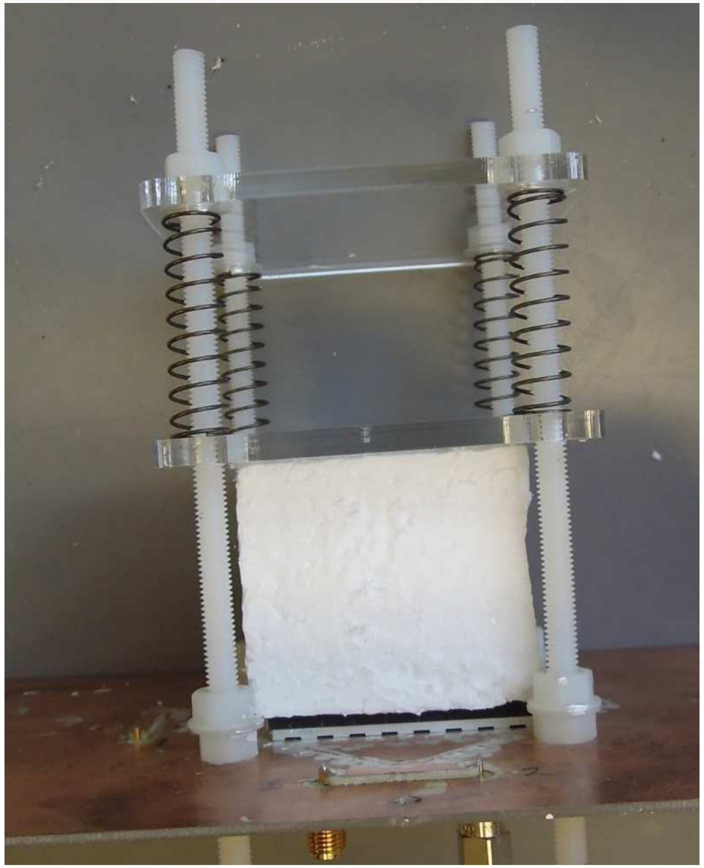
Is there simpler way?

Spring Loaded Pressure Contact Jig

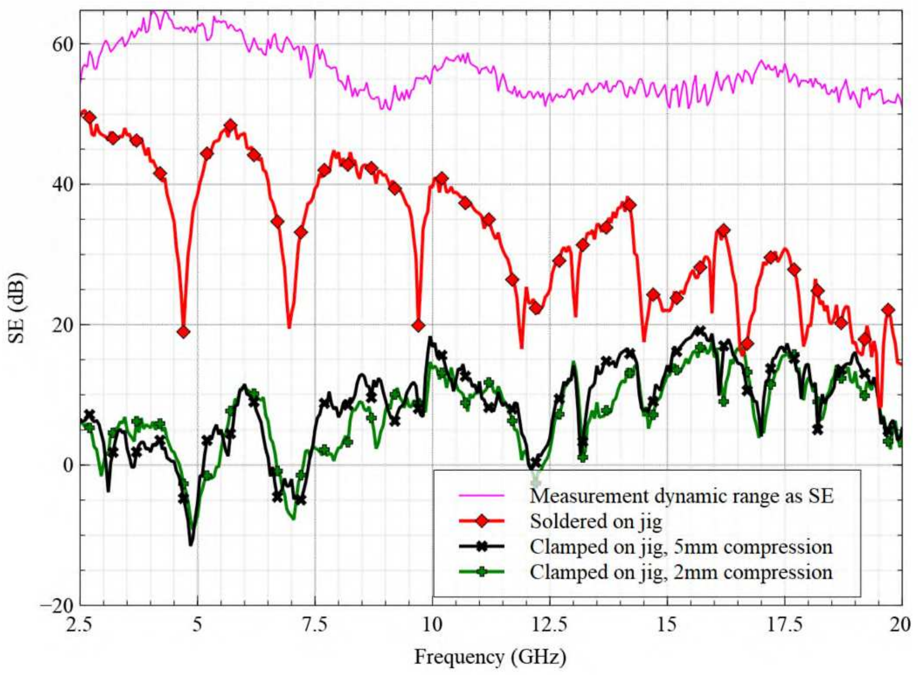
Our initial plan was to use spring pressure to press the BLS onto the groundplane of the jig.

Each spring has a spring constant of 0.49 N/mm so four springs give ~ 2 N/mm contact pressure, equivalent to a weight of ~ 0.2 kg/mm.

The 50 mm cube polystyrene block keeps the metal springs away from the BLS on the jig. The distance is a quarter wavelength at 1.5 GHz.



Spring Loaded Measured Results

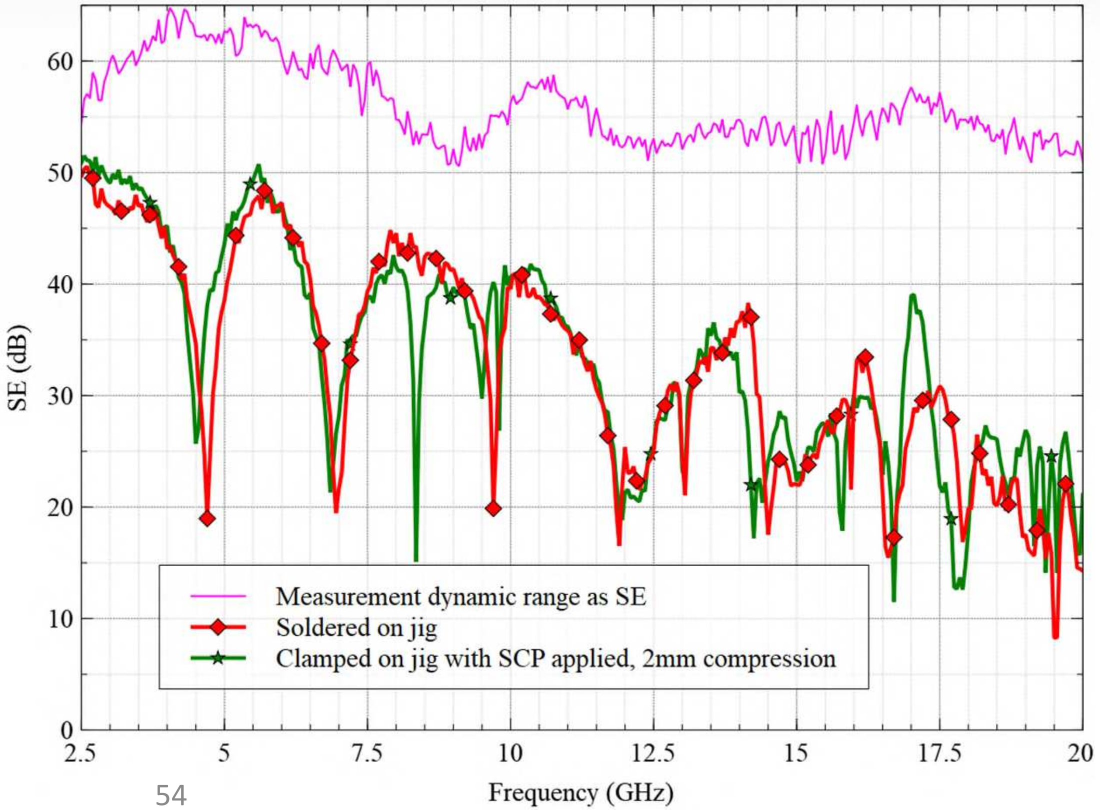


The measured SE with the spring loaded contact jig were disappointing with spring compression of 2 mm a contact force of 4 N (~ 0.4 kg weight) and 5 mm a contact force of 10 N

(~ 1 kg weight). Increased contact forces made no improvement.

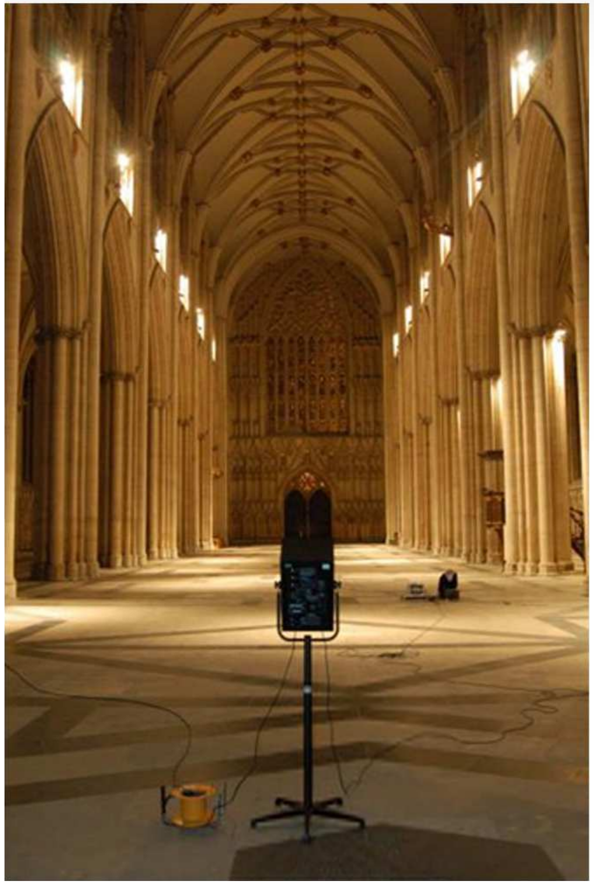
Silver Conducting Paint Comparison

The measured results are very similar to those obtained with a soldered connection.



York Minster - A Very Large Acoustic Reverberation Chamber

Fun with Reverberation Chambers

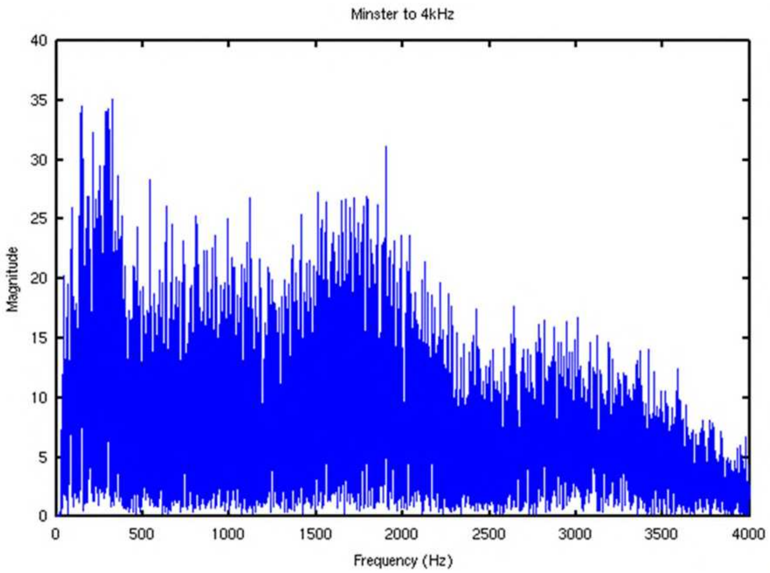


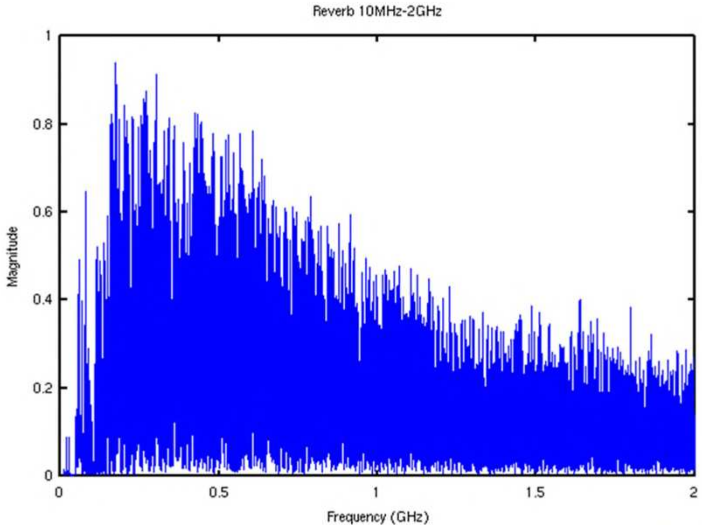
In York Minster the coupling between a microphone and a loudspeaker was recorded with a frequency swept sound, a “chirp” up to 4kHz.

In the reverberation chamber the coupling (S_{21}) between two wideband antennas was recorded from 10MHz to 2GHz at a single stirrer position.

Measured Frequency Responses

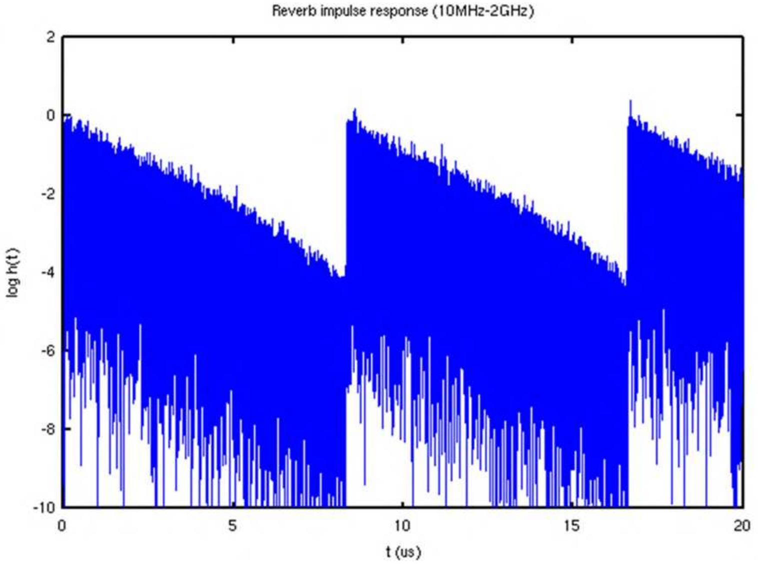
York Minster (0 – 4kHz)



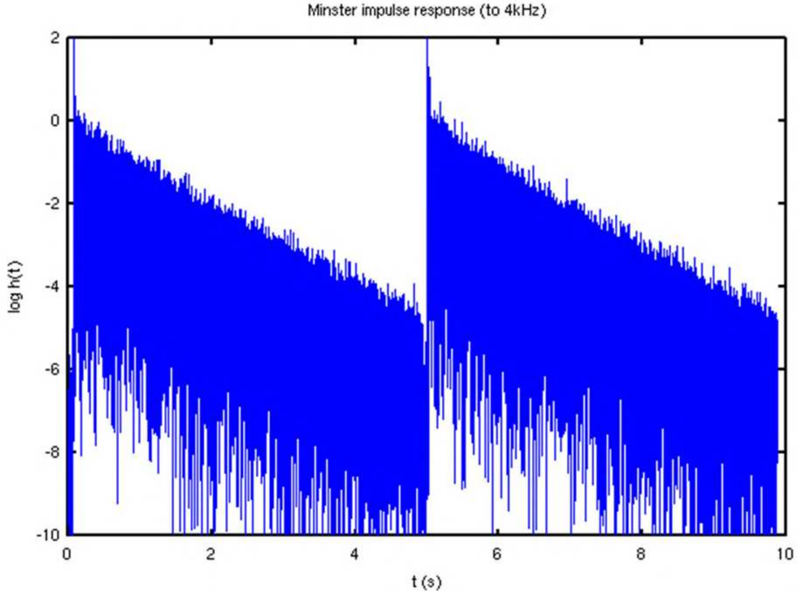


York Reverberation Chamber (10MHz – 2GHz)

Impulse Responses computed from Measured Frequency Responses



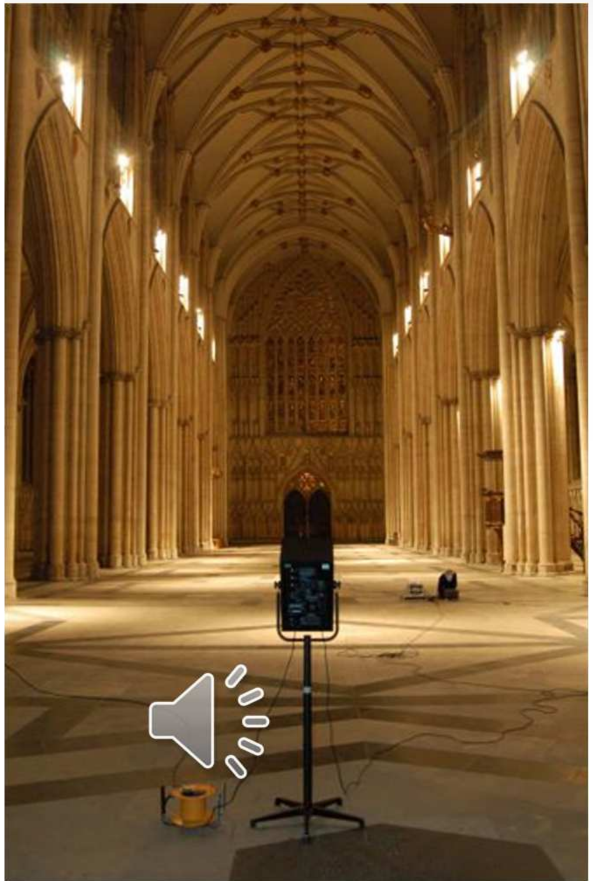
York Reverberation Chamber (0 – 20μsec)



York Minster (0 – 10sec)

Note that the log amplitude scale constant gradient responses indicate exponential decays.

Fun with Reverberation Chambers



The computed impulse responses are recorded in a wav file for audio presentation.

The reverberation chamber response was sonified using about a factor one million time expansion.