State-of-the-art in Determining the Absorption, Scattering and Diffusion Coefficients

by

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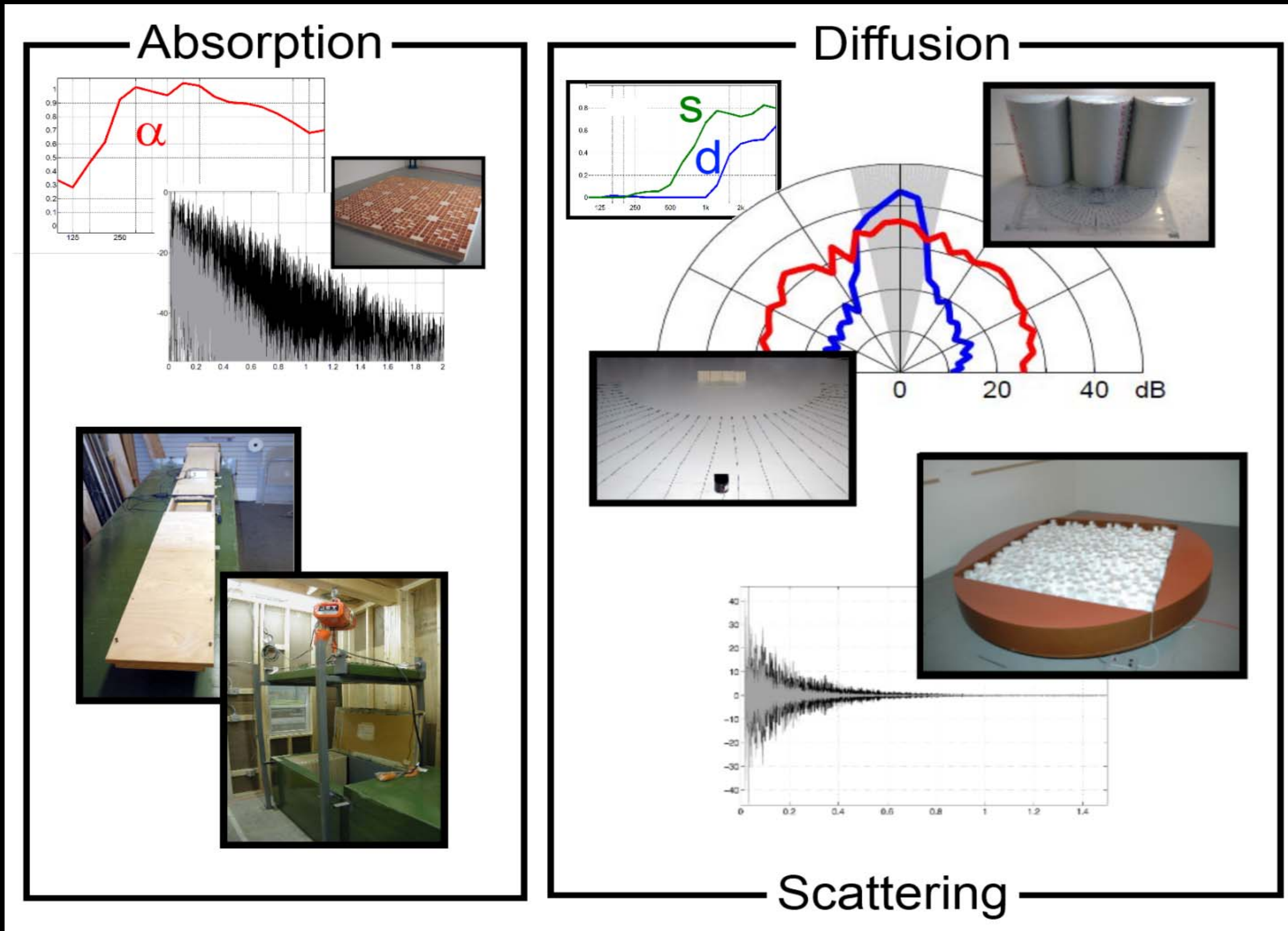
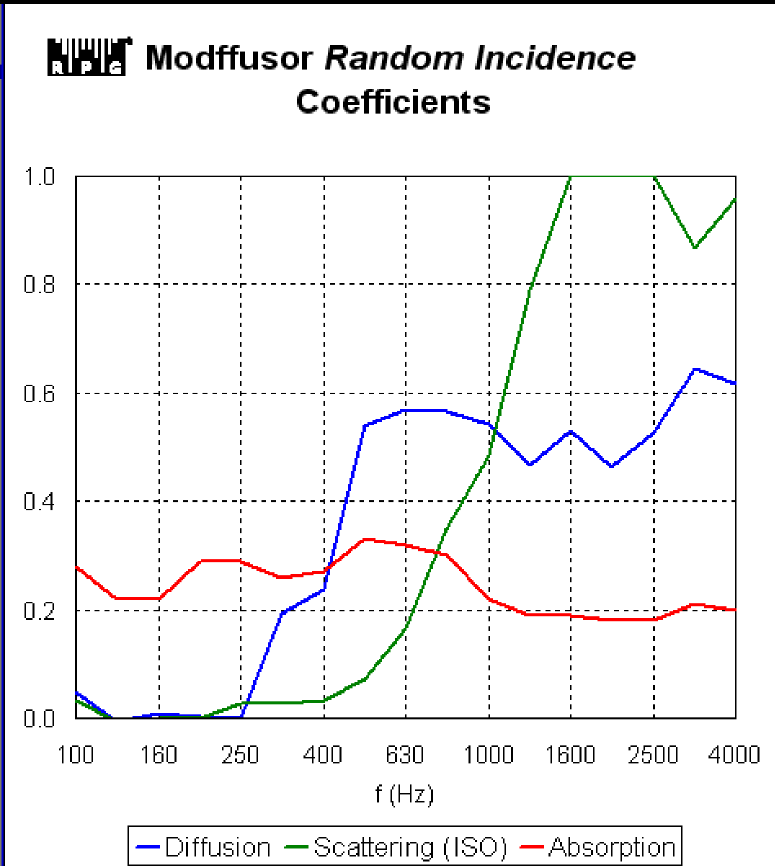
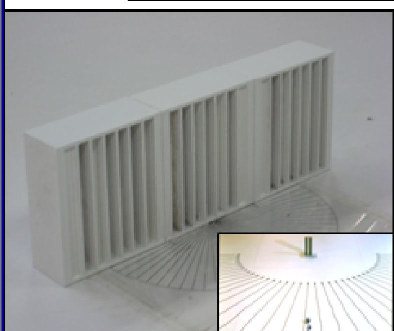
Coefficient Suite



Complete Performance Specs





f (Hz)	Diffusion	Scattering (ISO)	Absorption
100	0.05	0.03	0.28
125	-0.01	-0.01	0.22
160	0.01	0.00	0.22
200	0.00	0.00	0.29
250	0.00	0.03	0.29
315	0.19	0.03	0.26
400	0.24	0.03	0.27
500	0.54	0.07	0.33
630	0.57	0.17	0.32
800	0.57	0.35	0.30
1000	0.54	0.49	0.22
1300	0.47	0.79	0.19
1600	0.53	1.00	0.19
2000	0.46	1.00	0.18
2500	0.53	1.00	0.18
3150	0.64	0.87	0.21
4000	0.62	0.96	0.20

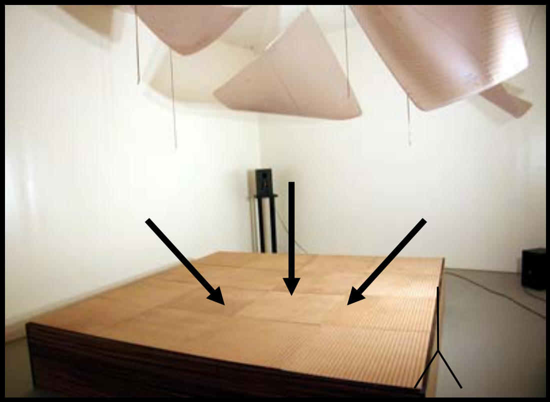
Absorption Coefficient ISO 354: How much of the incident sound is absorbed (Must be measured full scale). Chairman Martijn Vercammen

Scattering Coefficient ISO 17497-1: How much of the incident sound is scattered (Can be measured in scale and calculated). Chairman Trevor Cox

Diffusion Coefficient ISO 17497-2: How uniformly is the incident sound scattered (Can be measured in scale and calculated). Chairman Trevor Cox

ISO 354 / ASTM C423-09

Measurement empty: T_1



Measurement with sample: T_2

Calculation of the equivalent absorption area

$$A = 55.3 \cdot V \left(\frac{1}{c_2 T_2} - \frac{1}{c_1 T_1} \right) - 4V(m_2 - m_1)$$

Calculation of the absorption coefficient :

$$\alpha_s = \frac{A}{S}$$

m_1 = air attenuation empty

m_2 = air attenuation with sample

$c_{1,2}$ = speed of sound

V = room volume

α_s = random-incidence absorption coefficient

S = sample surface area

A = equivalent absorption area

ISO 354 Review of activities TC43/SC2/WG26

- Revision of ISO 354 Chaired by Martijn Vercammen (Peutz consultants, NL)

- Round Robin 2009 (Wide disparity among labs and coefficients exceeding unity)

Topics Under Discussion:

- Excess Absorption

- Correcting Edge Diffraction, primarily at low frequencies
- Evaluate using Eyring instead of Sabine to reduce high frequency excess absorption
- Correct for reduced mean free path (4*V*/*S) caused by suspended diffusers and not accounted for in current calculations*
  - *Proposed boundary diffusors*

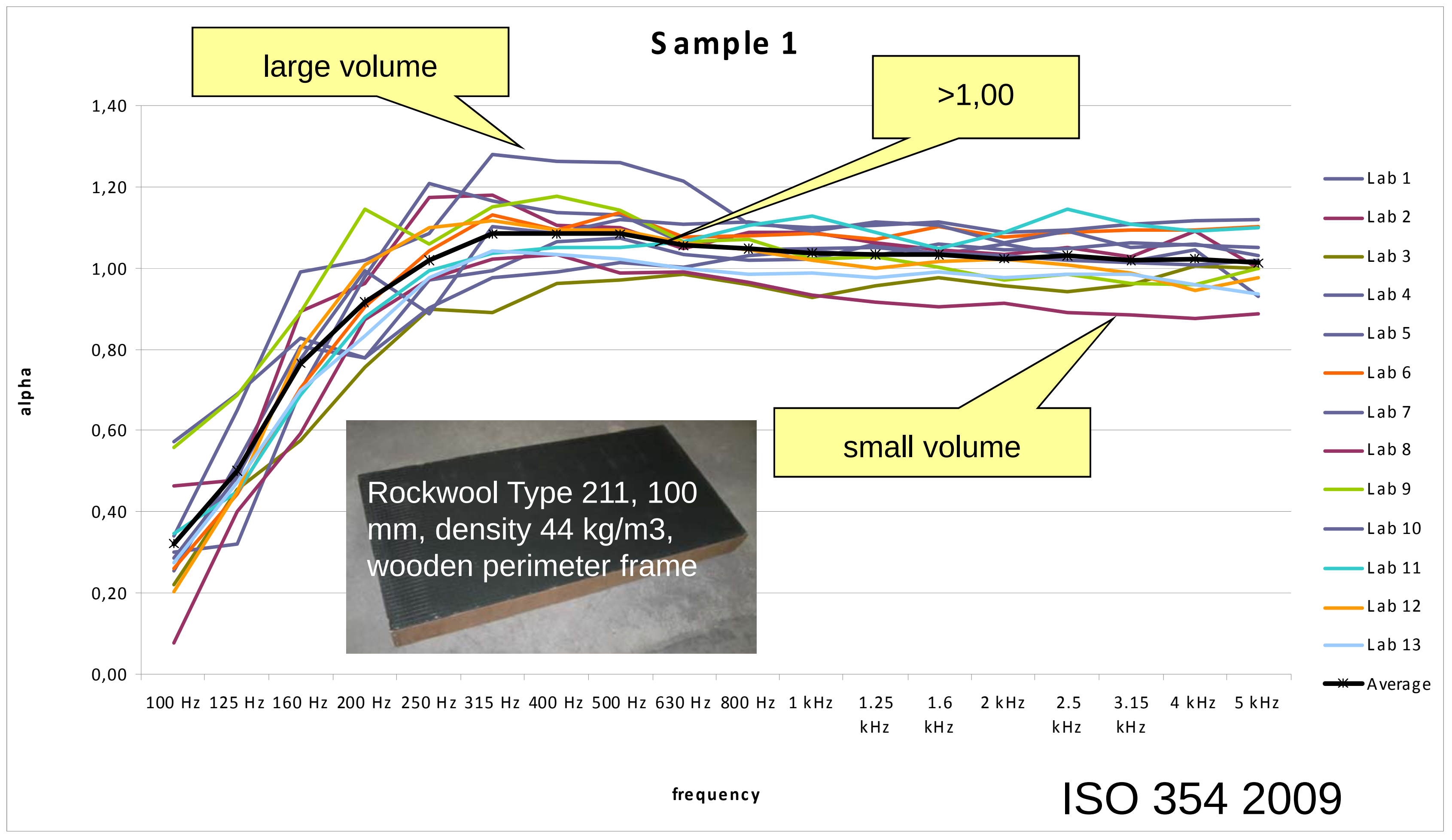
*- **Reproducibility***

- Calibration of rev rooms using a reference absorber (reflector)

M.L.S. Vercammen, ISRA Proceedings 2010, Melbourne, Australia

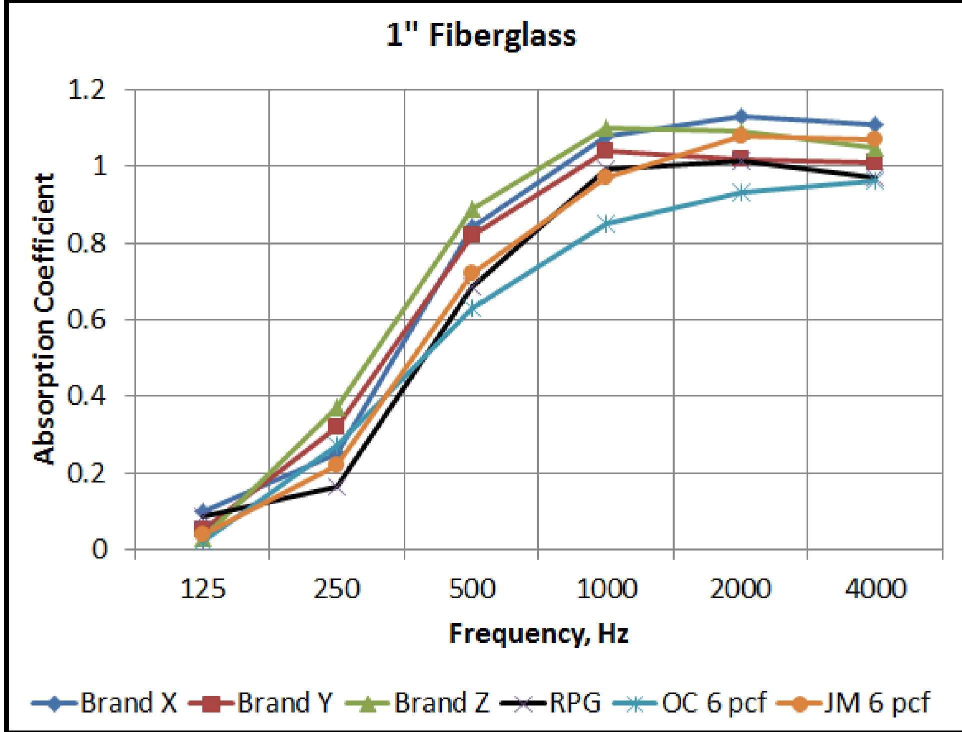
An Inconvenient Truth

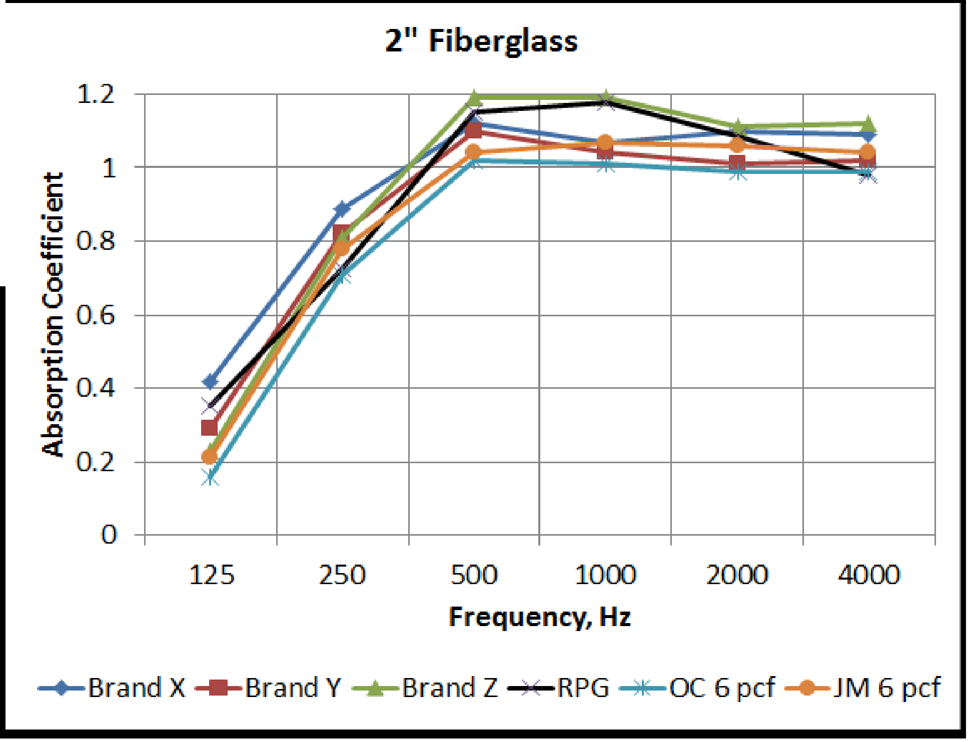
- 13 laboratory round robin



M.L.S. Vercammen, ISRA Proceedings 2010, Melbourne, Australia

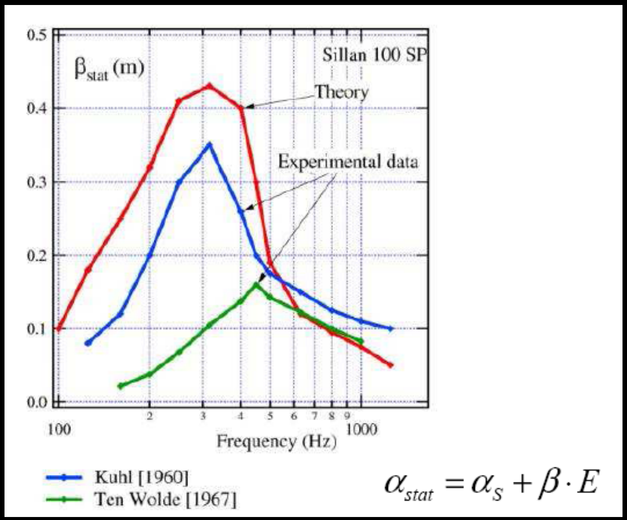
Fiberglass Comparison





Edge Effect

- This is related to the wavelength relative to the dimensions of the sample.
- The absorption of a finite sample is composed of the absorption of an infinite sample α_s and a factor β multiplied by the edge length E.
- The graph shows the beta from experimental and theoretical studies



A. de Bruijn, The edge effect of sound absorbing materials “revisited”, NAG 2007
Y. Kawai and H. Meotoiwa, Acoust. Sci. & Tech. 26, 2 (2005)

Sabine, Eyring and MFP

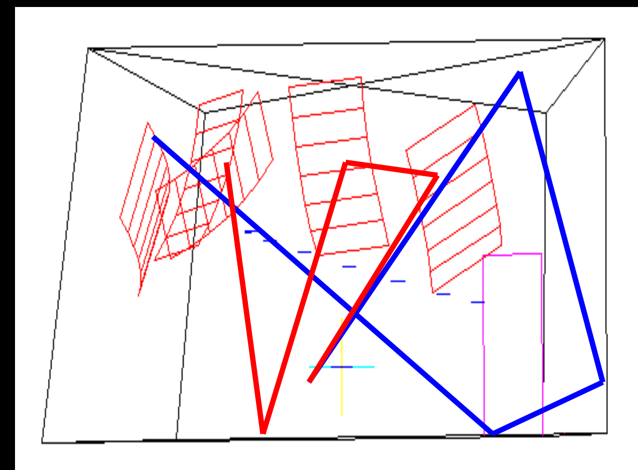
- Clouds reduce the mean free path which is the basis of the Sabine equation
- One may correct the shorter mean free path occurring with clouds using a ray tracing program and correct the volume V = MFP*S/4
- A calculation indicated 12% lower absorption using this reduced volume

$$_s \quad 55.3\frac{V}{S} \quad \frac{1}{c_2T_2} \quad \frac{1}{c_1T_1} \quad \frac{4V}{S} \; m_2 \quad m_1$$

- Use of Eyring instead of Sabine, might prevent the high frequency excess above 1 (Error estimated at 0.03).

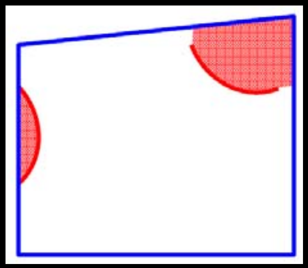
$$_E \quad \frac{S_0}{S} \exp \quad \frac{V}{S_0} \; \frac{55.3}{c_1T_1} \quad 4m_1 \quad \exp \quad \frac{V}{S_0} \; \frac{55.3}{c_2T_2} \quad 4m_2$$

MFP= 4V/S



M.L.S. Vercammen, ISRA Proceedings 2010, Melbourne, Australia

Boundary vs Cloud Diffusers

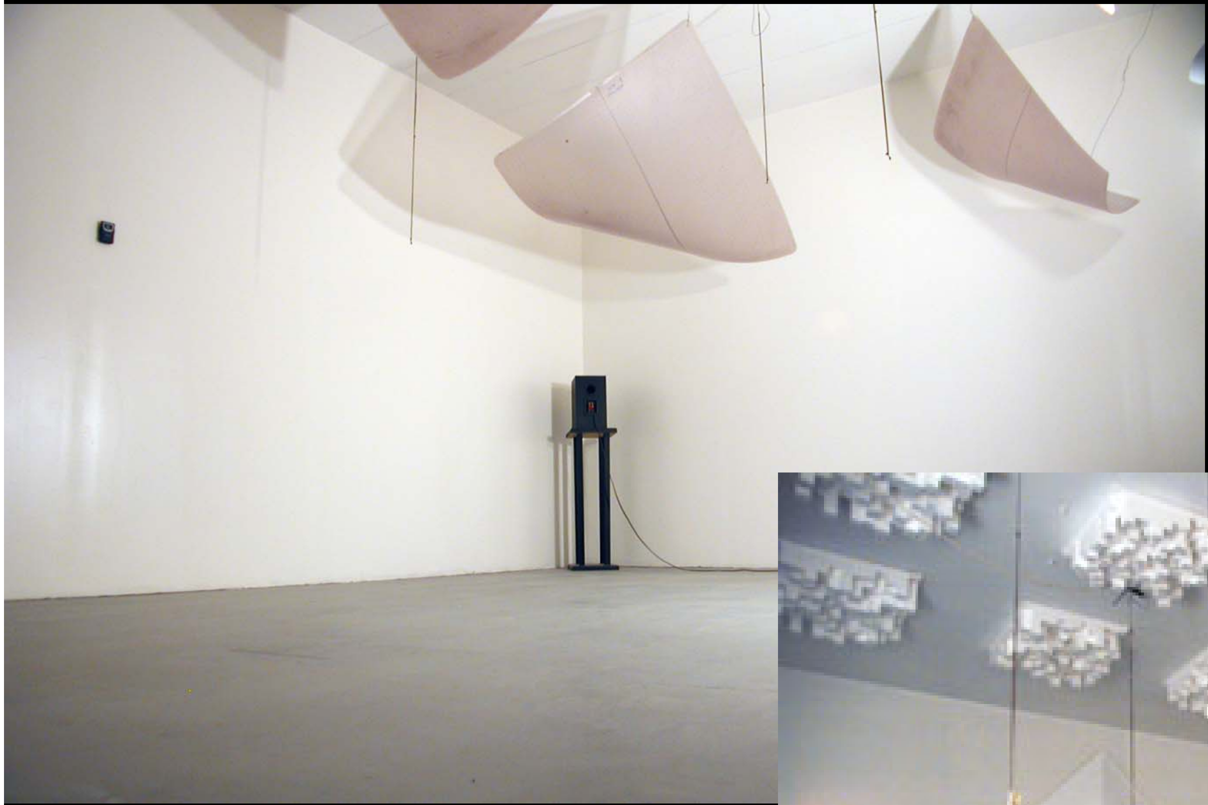


- With boundary diffusers, the known volume behind the diffusers can be subtracted to determine the correct room volume, V
- Shadowing caused by hanging clouds is eliminated
- The correct room surface area, S_0, can be used
- Boundary diffusers result in higher diffusivity and standard deviation between mic-speaker pairs

$$E \quad \frac{S_0}{S} \exp \quad \frac{V}{S_0} \frac{55.3}{c_1 T_1} \quad 4m_1 \quad \exp \quad \frac{V}{S_0} \frac{55.3}{c_2 T_2} \quad 4m_2$$

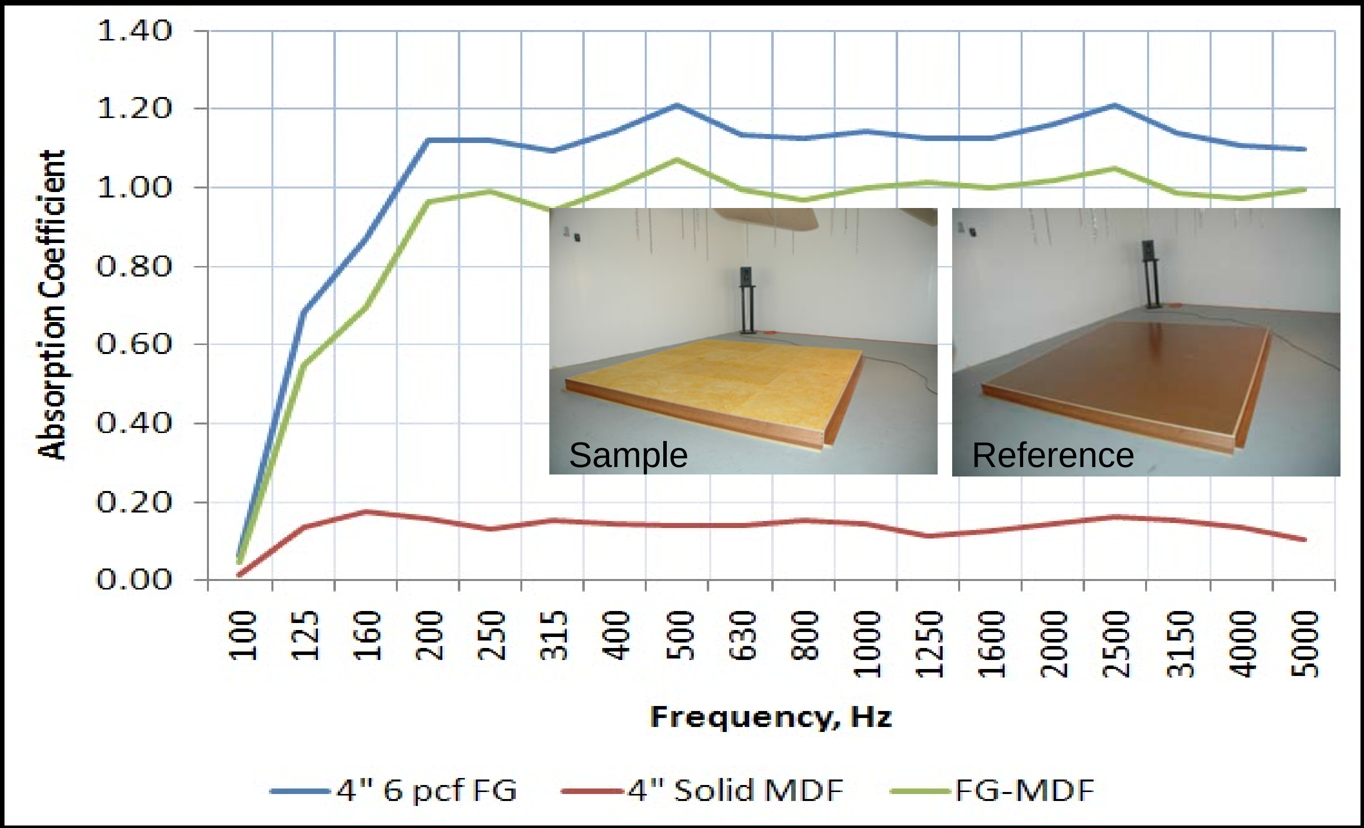
M.R. Lautenbach, M.L.S. Vercammen, Proc. 20th ICA, Sydney, Australia (August 2010)

Ceiling Clouds vs. Boundary Diffusers

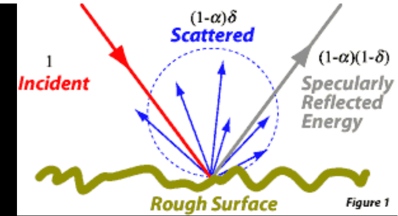


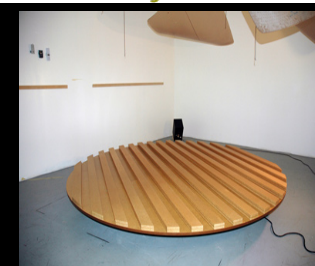
Standard Calibration Reference

- Use of a standard absorber is proposed to calibrate measurement results of other samples and insure reproducibility among labs
- D'Antonio has proposed use of a non-absorbing reference reflector of the same area & perimeter to calibrate a reference zero absorption and the use of Eyring instead of Sabine



Scattering Coefficient Relations: ISO 17497-1





Absorption coefficient on stationary table

$$\alpha_s = 55.3\frac{V}{S}\left(\frac{1}{c_2T_2}-\frac{1}{c_1T_1}\right) - \frac{4V}{S}(m_2-m_1)$$

Absorption coefficient on rotating table

$$\alpha_{spec} = 55.3\frac{V}{S}\left(\frac{1}{c_4T_4}-\frac{1}{c_3T_3}\right) - \frac{4V}{S}(m_4-m_3)$$

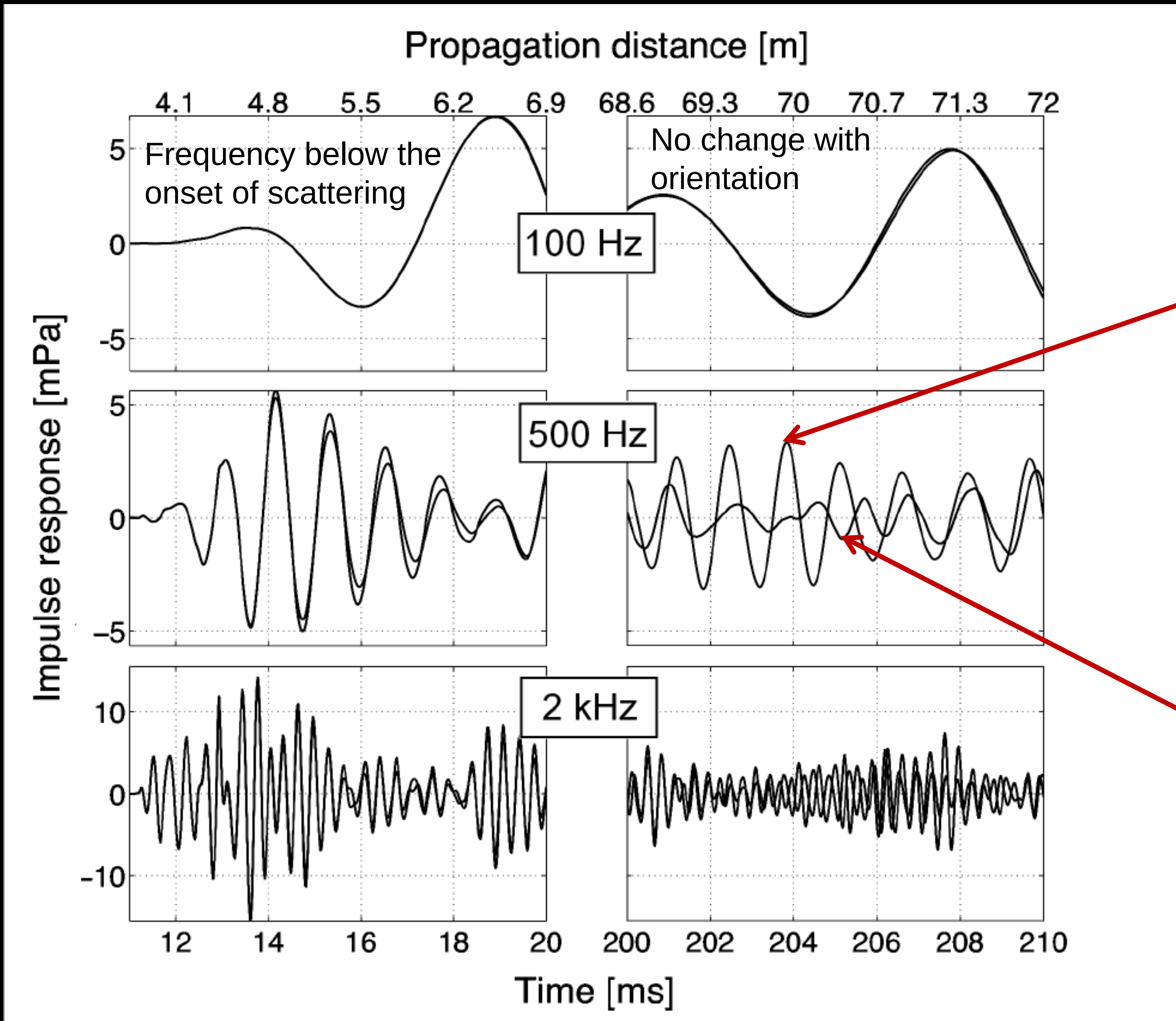
Scattering coefficient

$$s = \frac{\alpha_{spec}-\alpha_s}{1-\alpha_s} = 1-\frac{E_{\text{spec}}}{E_{\text{total}}}$$

- V is the volume of the reverberation room
- S is the area of the test sample
- $C_{1,2,3\ \&\ 4}$ are the speed of sound in air during the measurement of $T_{1,2,3\ \&\ 4}$
- $m_{1,2,3\ \&\ 4}$ are the energy attenuation coefficient of air in m^{-1} during the measurement of T_1, T_2, T_3 and T_4, respectively

Reverberation time	Test sample	Turntable
T_1	not present	not rotating
T_2	present	not rotating
T_3	not present	rotating
T_4	Present	rotating

Specular Separation



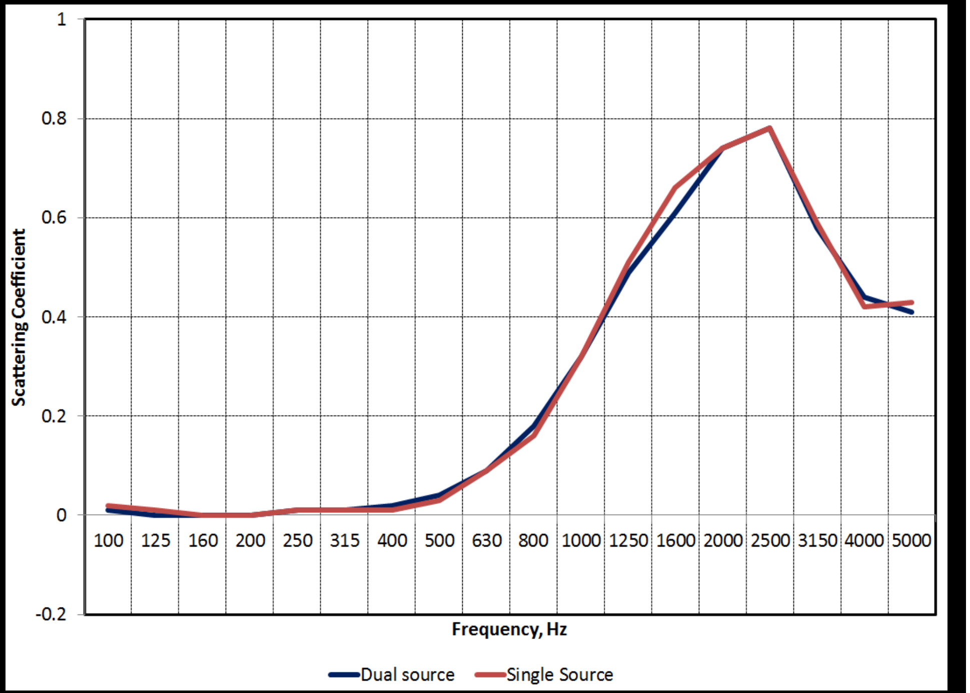
Orientation 1

Orientation 2

Improvements

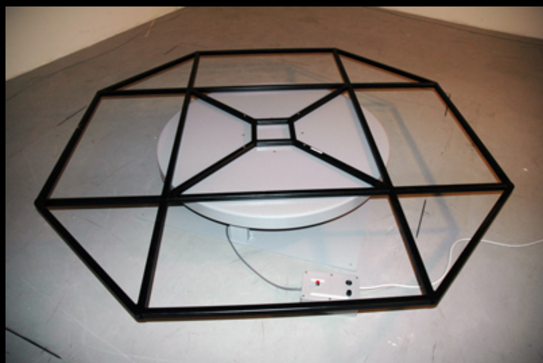
- Dual source/Multiple-mic simultaneous measurement method
  - Conventional measurements with two sources and 6 microphones results in long measurement times
  - If you are using a 3 sec MLS this results in a measurement time of **43 min** (3s x 72 x 2 x 6)/60) for each rotating table measurement with and without sample, plus the traditional stationary table measurements
  - In larger chambers where a longer MLS is required these times are much longer
  - By using a dual source and simultaneously measuring the 6 mics this time is reduced to **3.6 min** (3x72)/60) each

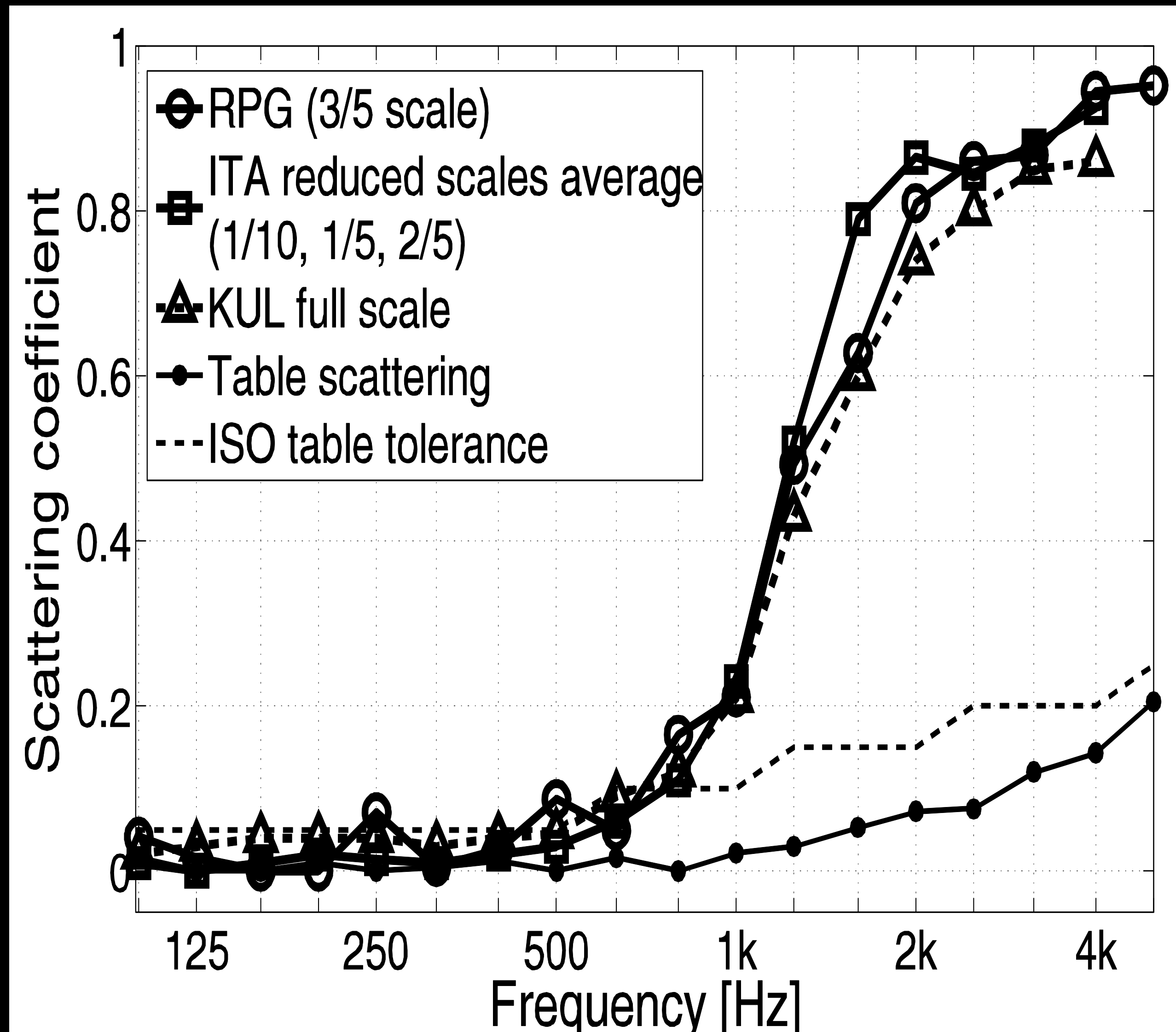
Standard calls for two sources and 6 microphones



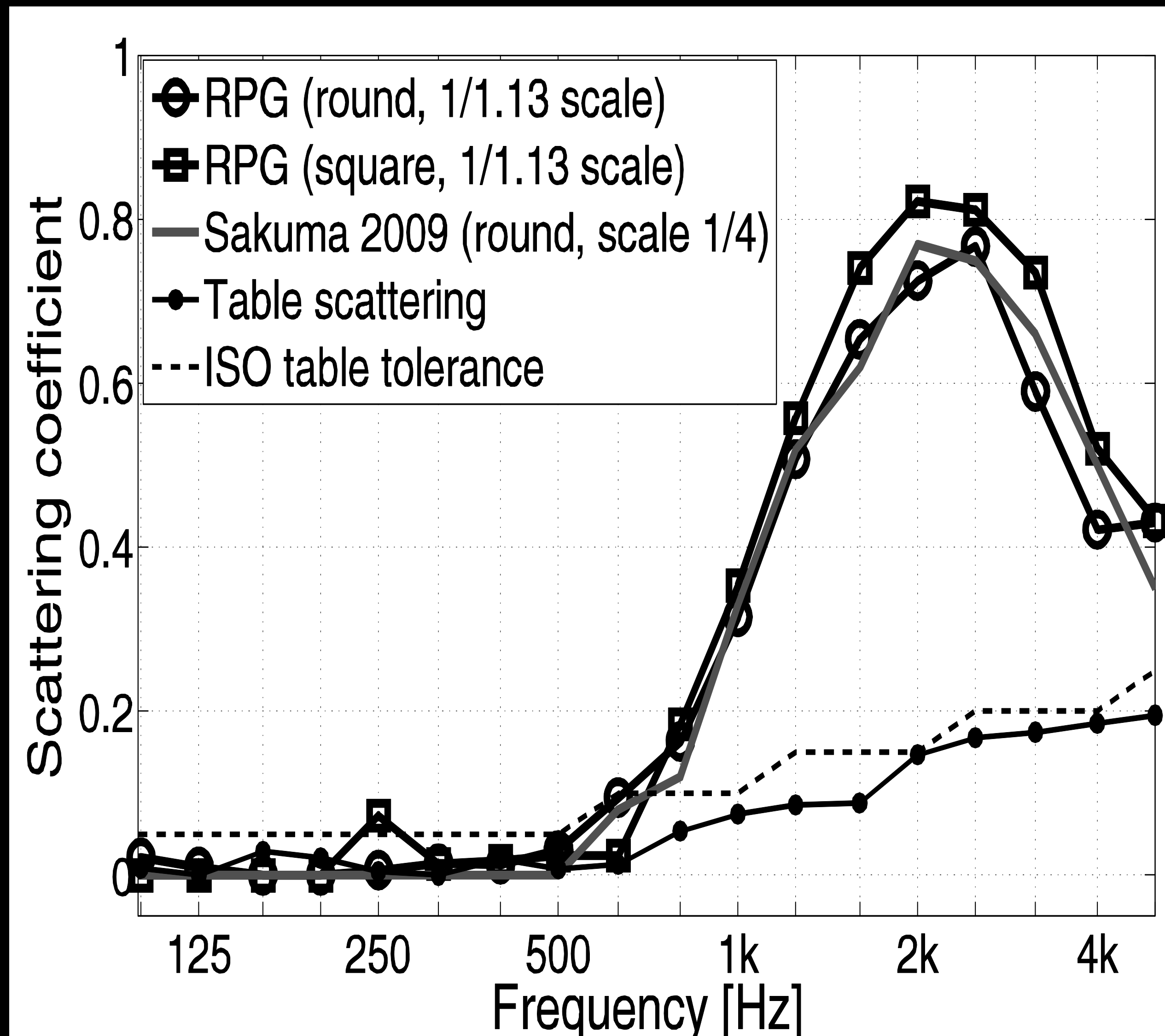
- Brian Rife will describe the dual source theory in a presentation later in the session, as well as the relationship between the scattering and diffusion coefficient

Commissioning: Sinusoid

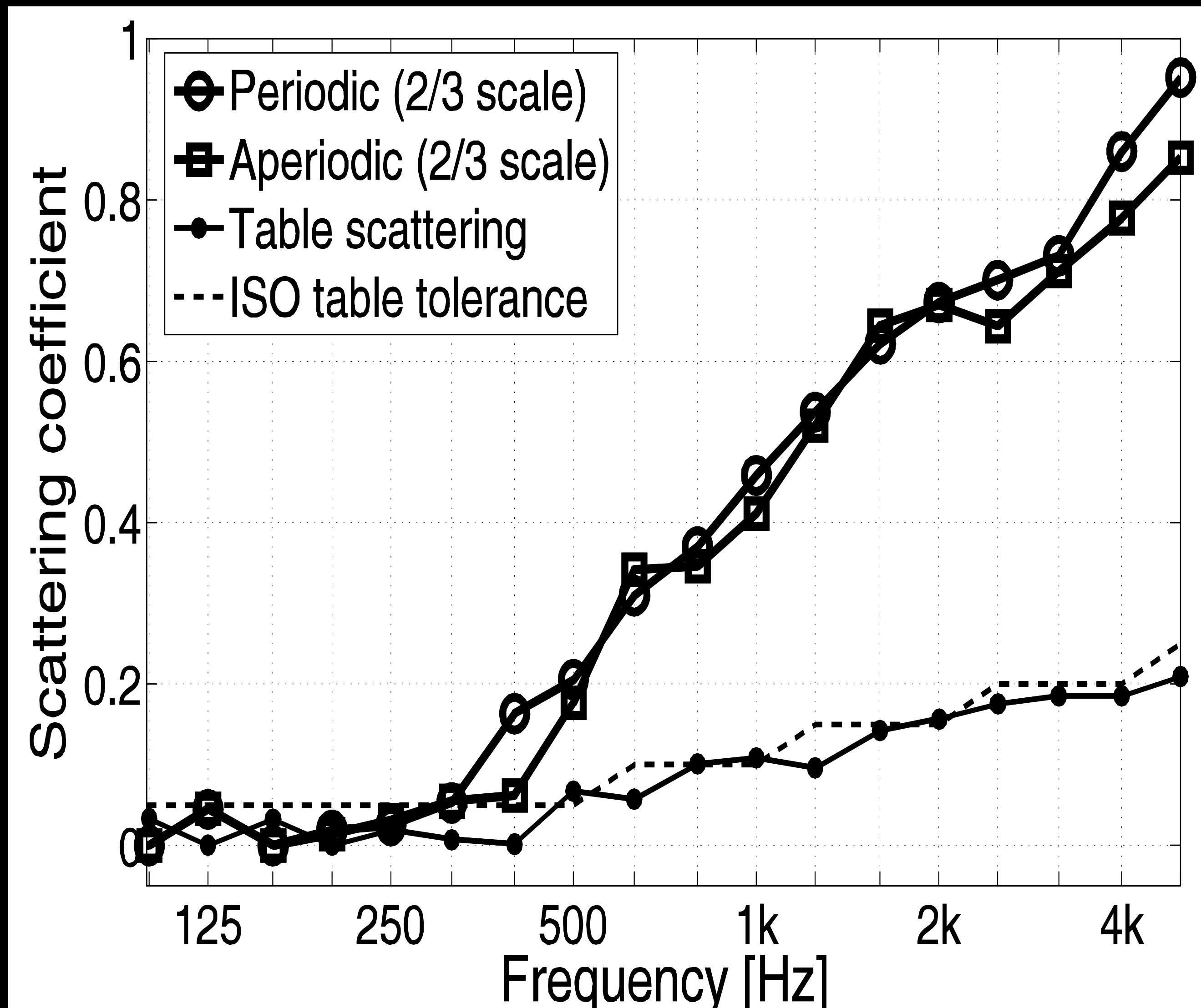




Commissioning: Periodic Battens



Flush 2D Diffusors



Limitations: Fooled By Redirection

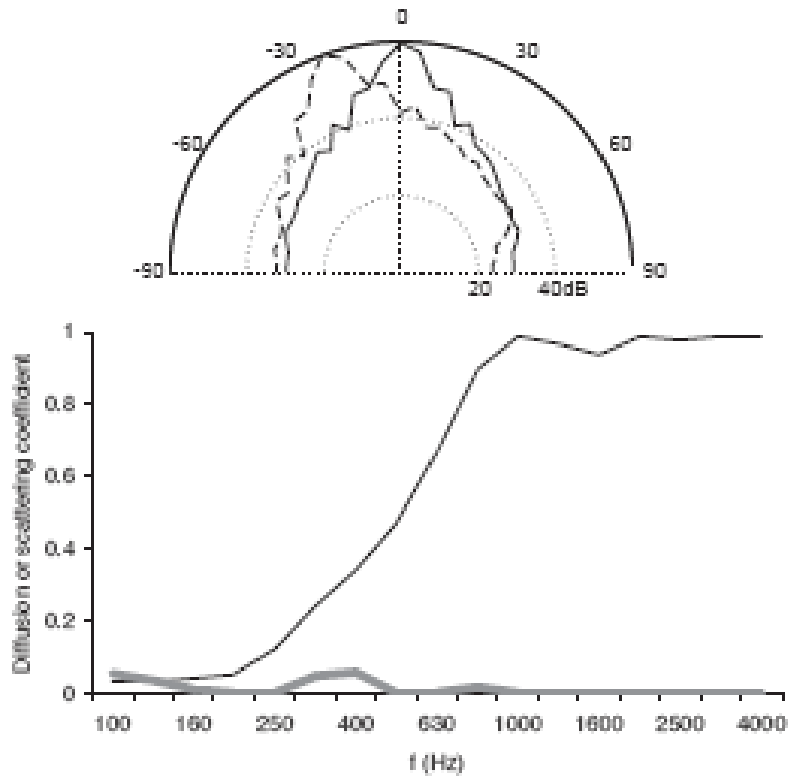
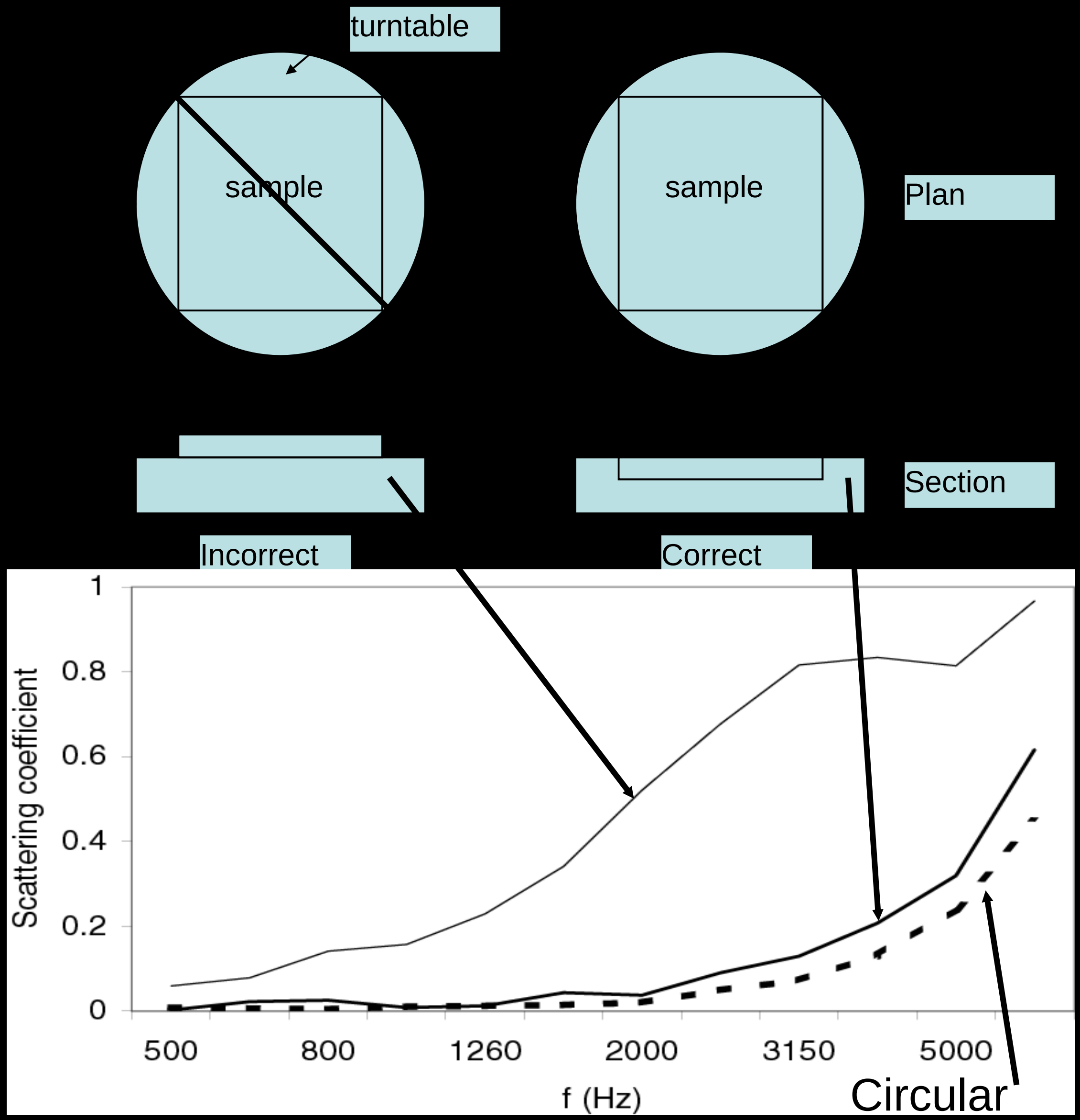


Figure 4.21 Top: the polar responses for ——— a Plane surface and – – – a Rotate plane surface.
Bottom: the diffusion and scattering coefficient frequency responses:
——— Correlation scattering coefficient; and
▬▬▬ Normalized diffusion coefficient rotated plane surface (ad ed from Cox and D'Antonio[35]).

Measure arrays rather than single objects

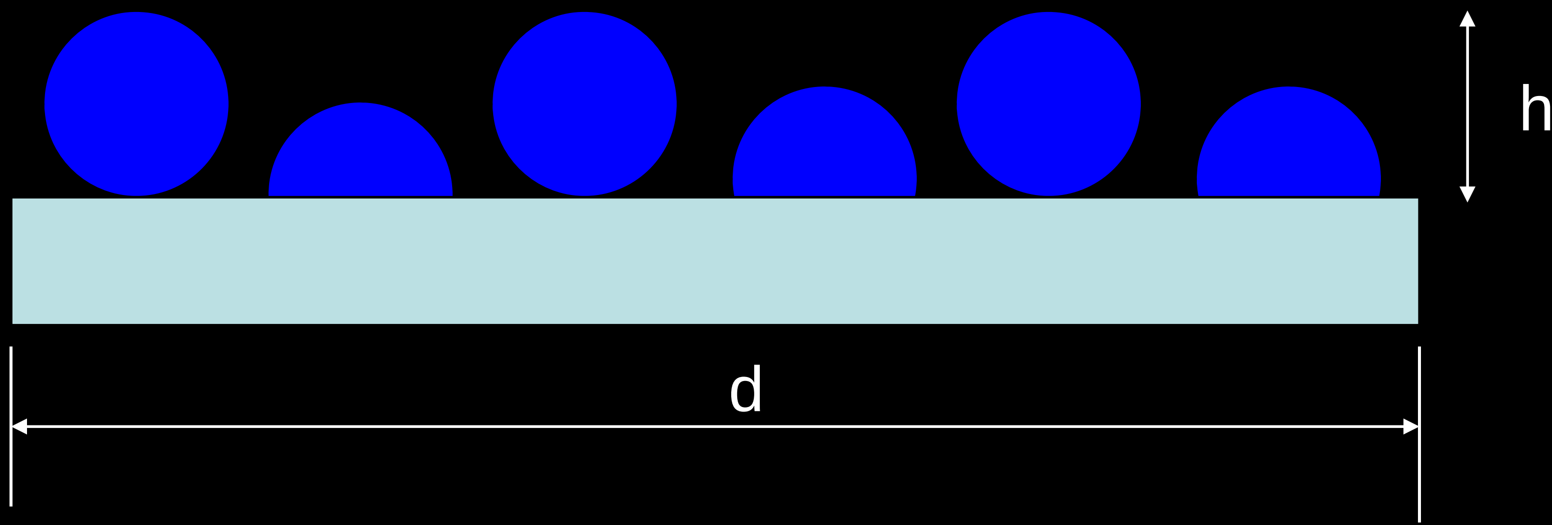
Limitations: Sample Mounting



Measure either a circular sample with a rigid circumference or

A square sample flush with the plane of the rotating table, which is more convenient for full scale commercial samples

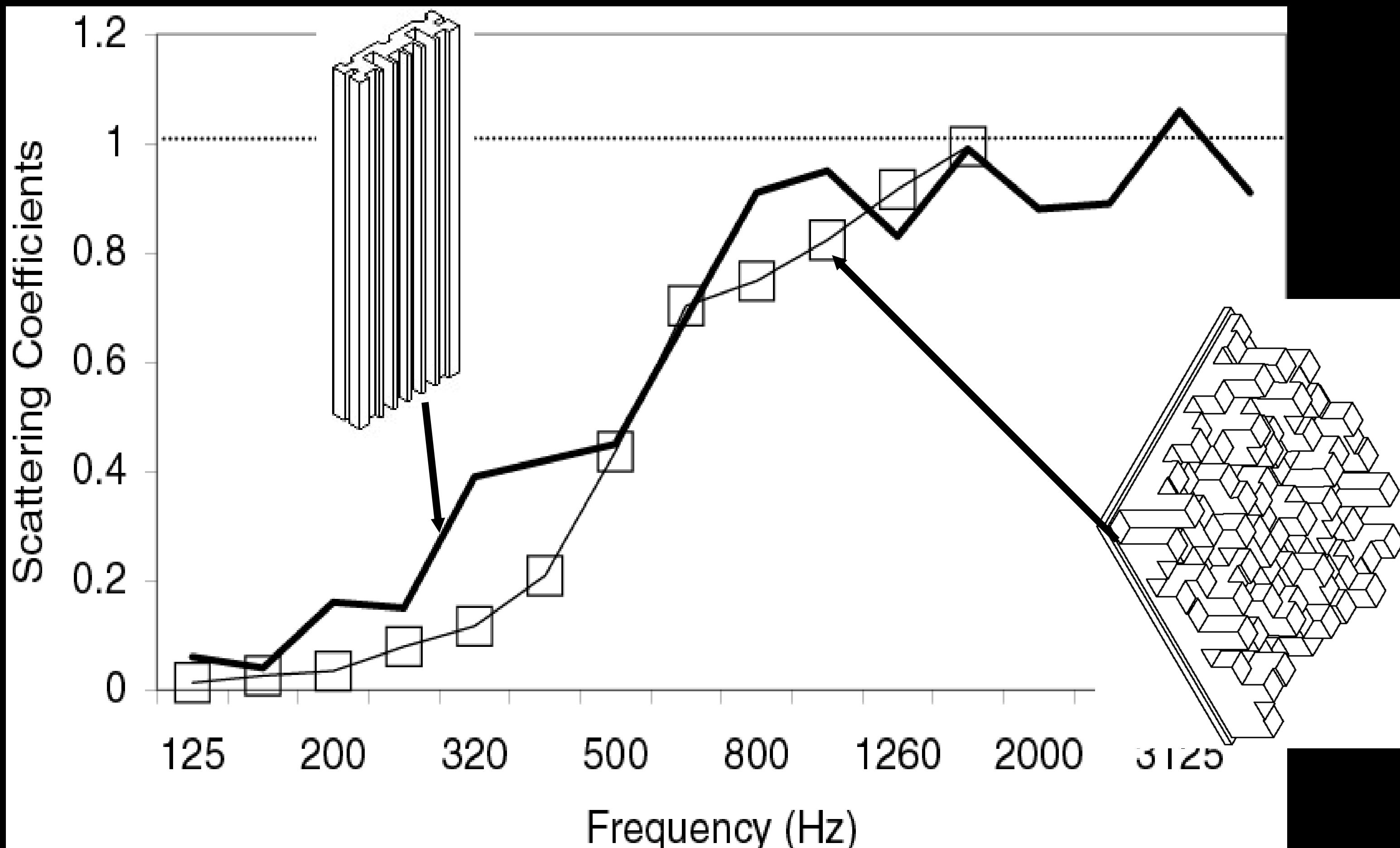
Limitations: Sample height



h <= d/16 Example: If d=24", h=1.5"

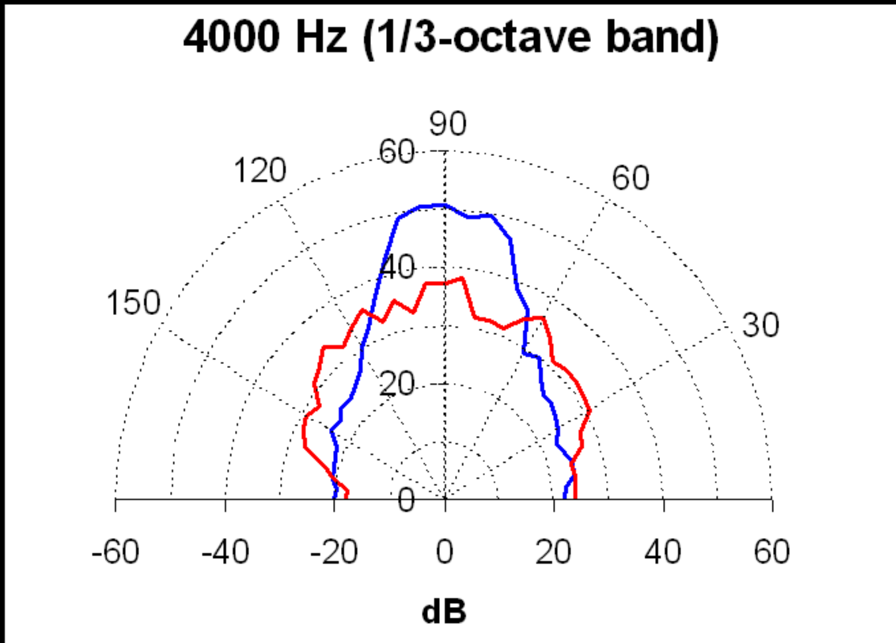
Make sure the height does not exceed the table diameter d/16

Limitations: 1D vs 2D



ISO produces higher values for anisotropic (1D) surfaces and may not differentiate between 1D and 2D surfaces

Correlation Scattering Coefficient



$$s_c = 1 - \frac{\left| \sum_{i=1}^{n} p_1(\theta_i)\, p_0^*(\theta_i) \right|^2}{\sum_{i=1}^{n} \left| p_1(\theta_i) \right|^2 \sum_{i=1}^{n} \left| p_0(\theta_i) \right|^2}$$

s_c can be determined from the cross correlation of the sample (red) and reflector (blue) polar responses

p_1 is the pressure scattered from the test surface

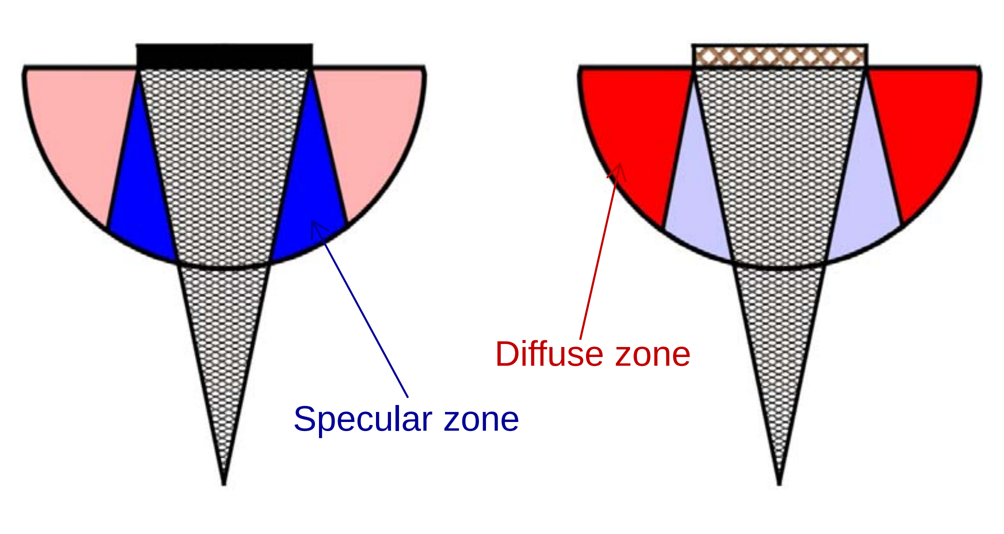
p_0 is the pressure scattered from the flat surface

denotes complex conjugate

θ_i the receiver angle of the i^{th} measurement position, and

n is the number of measurements in the polar response

Specular Zone- Energetic Scattering Coefficient



$$s_{sz} = 1 - \frac{E_{specular\ zone}}{E_{total}}$$

$$s_{n,sz} = \frac{s_{sz}(d) - s_{sz}(r)}{[1 - s_{sz}(r)]}$$

The specular zone or energetic scattering coefficient, s_{sz}, can be obtained from polar responses

E_{spec} is the energy in the specular zone of a polar response

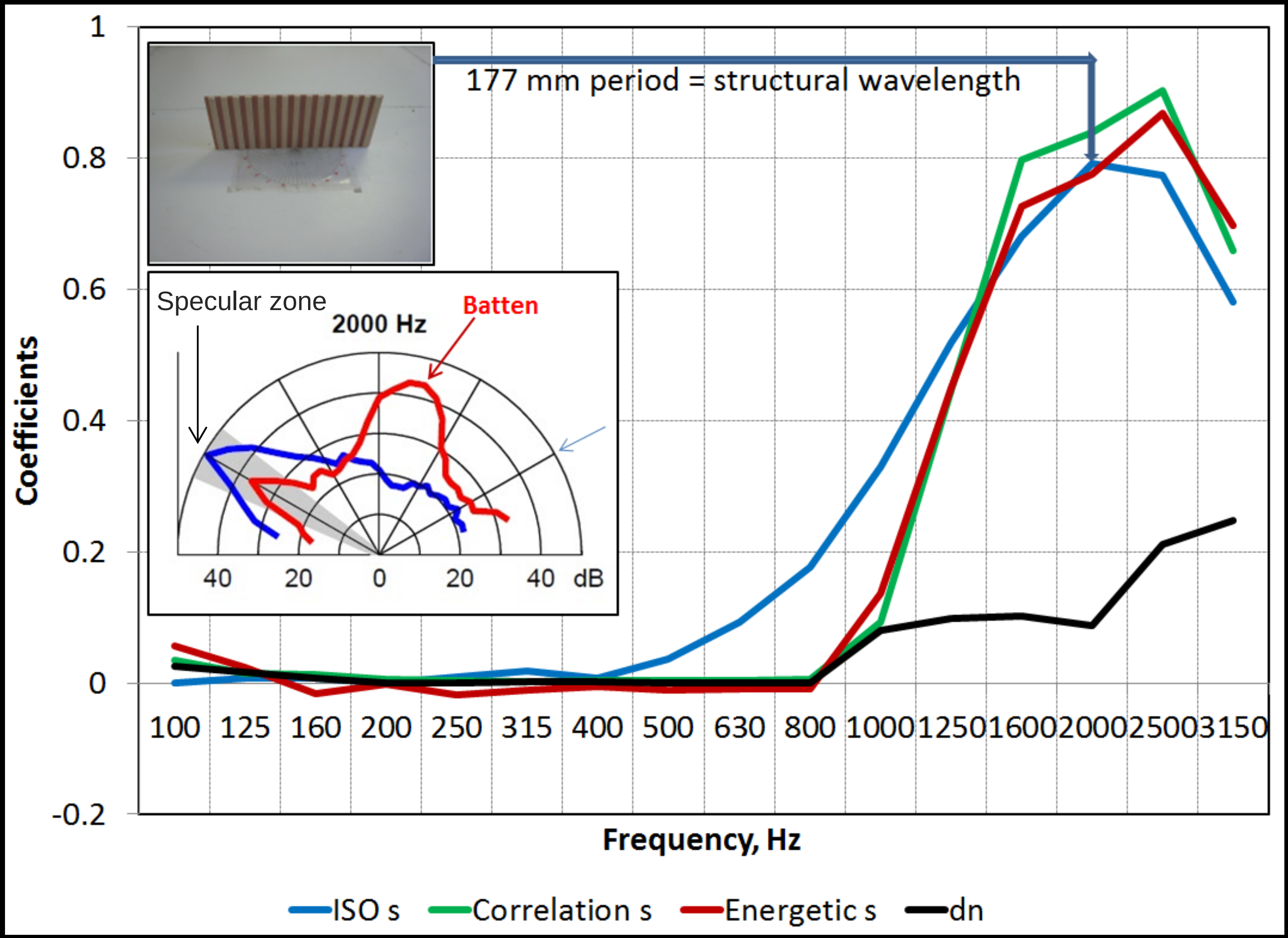
E_{total} is the total energy under the polar response

s_{sz} will consider edge diffraction and surface roughness as diffusion

To eliminate the edge diffraction, one can subtract $s_{sz}(r)$ of a reflector of similar size from $s_{sz}(d)$ of a diffusing surface

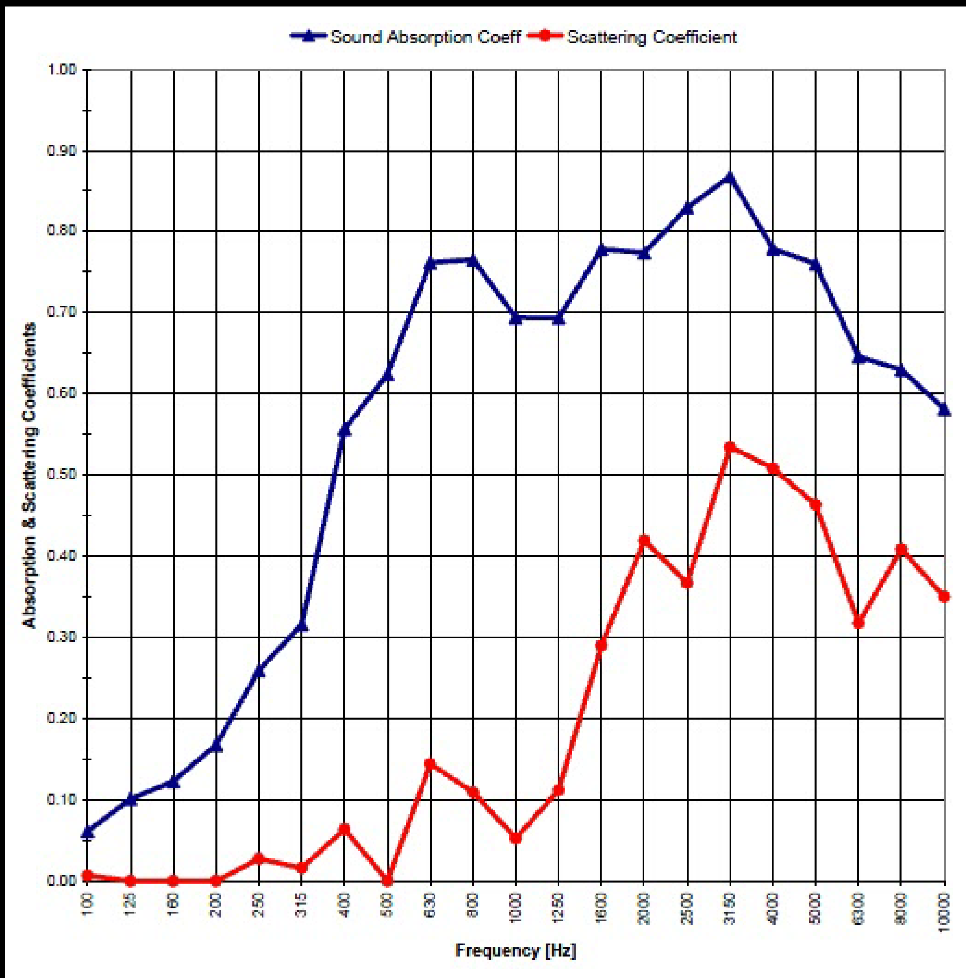
Then normalize by $[1-s_{sz}(r)]$, to provide a normalized specular zone scattering coefficient, $s_{n,sz}$

Scattering vs Diffusion



The batten polar response at the structural wavelength frequency of 2000 Hz illustrates why the scattering coefficient is high in that energy is scattered away from the specular zone. It also shows why the diffusion coefficient is poor and non-uniform

Scattering silliness



Here is an example of data presented in a specification

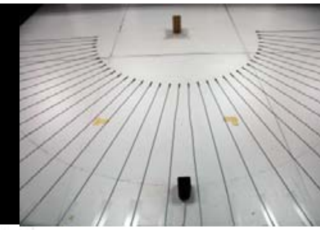
At 3150 Hz, the absorption coefficient is 0.87, which means there is 13% of the incident energy left to be scattered

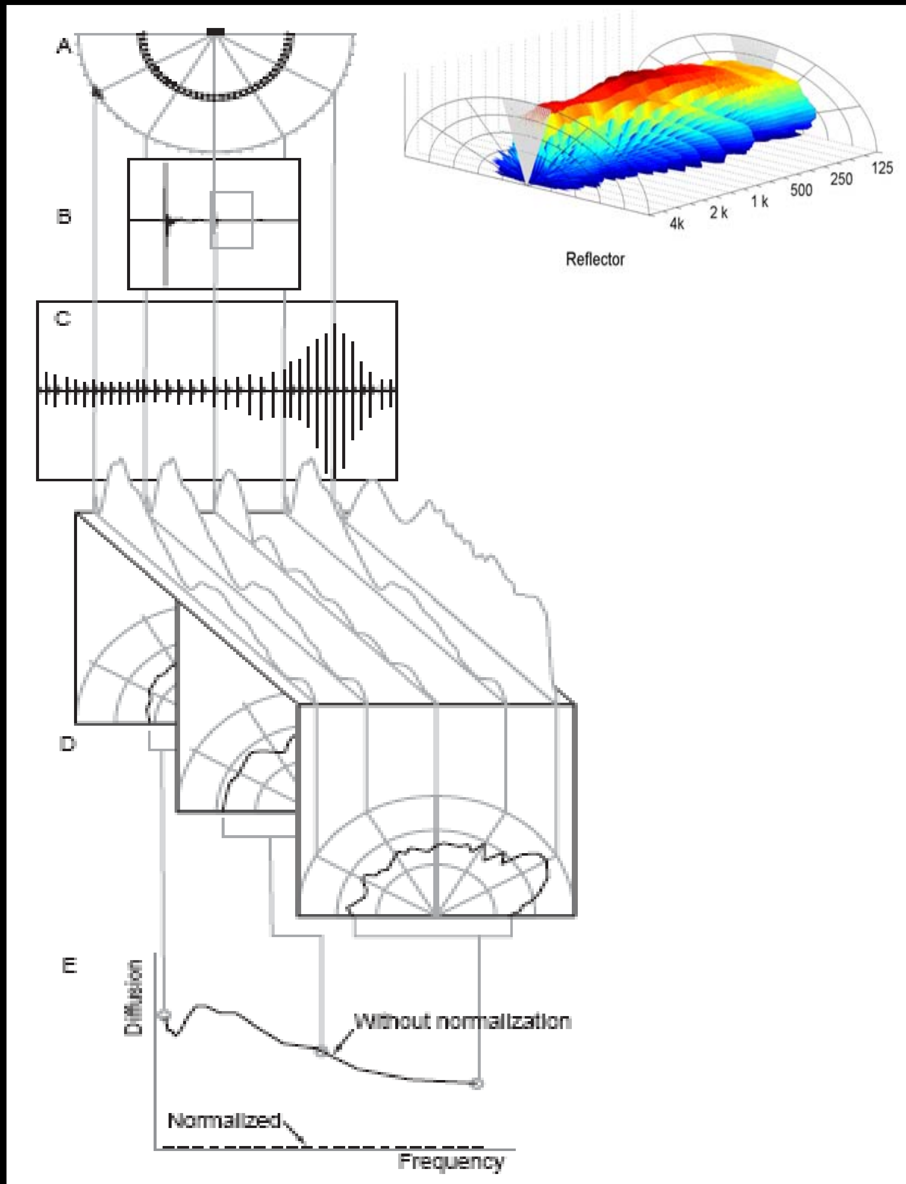
The scattering coefficient, which is incorrect according to ISO 17497-1 because absorption is greater than 0.5, is 0.53

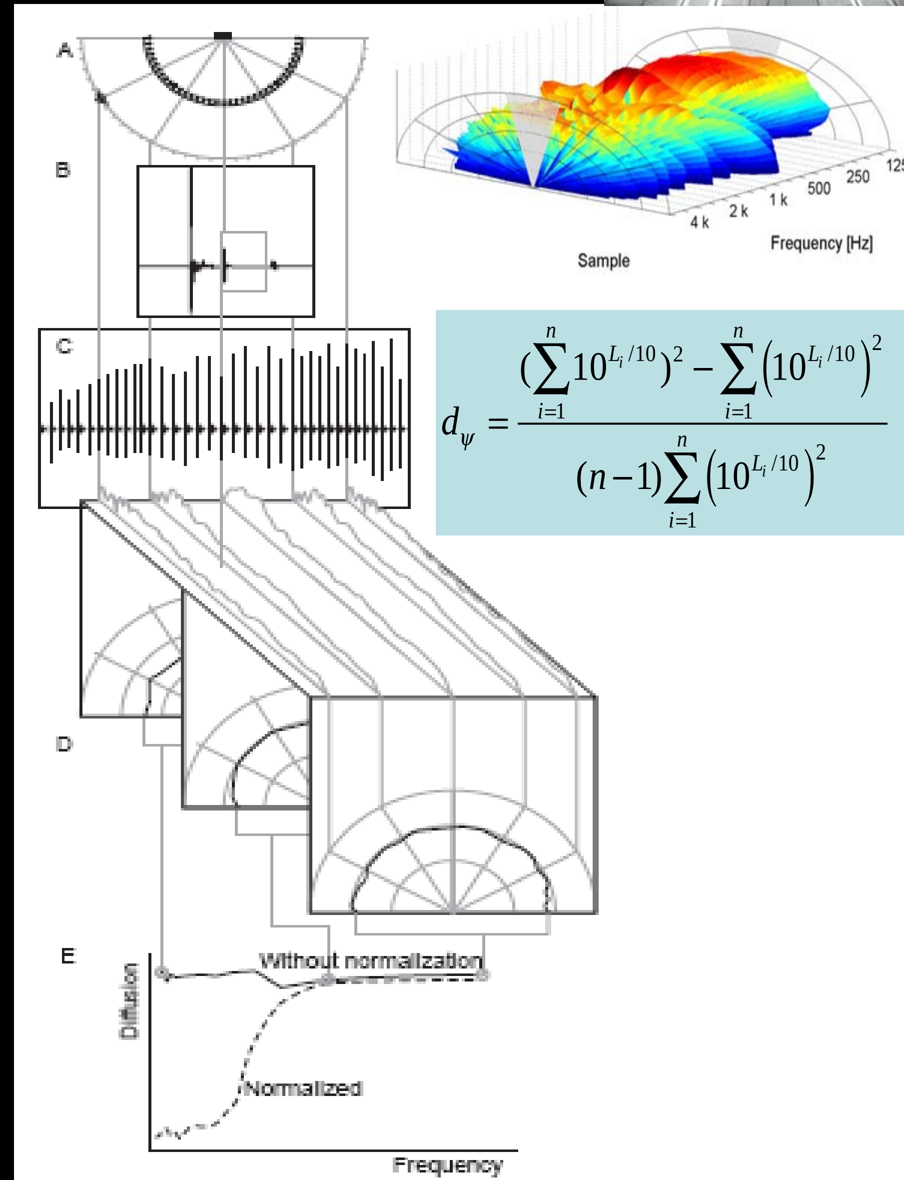
Therefore, 6.9% of the energy is scattered in non-specular directions

And the product is called an absorber and diffuser!

Diffusion Coefficient: ISO 17497-2



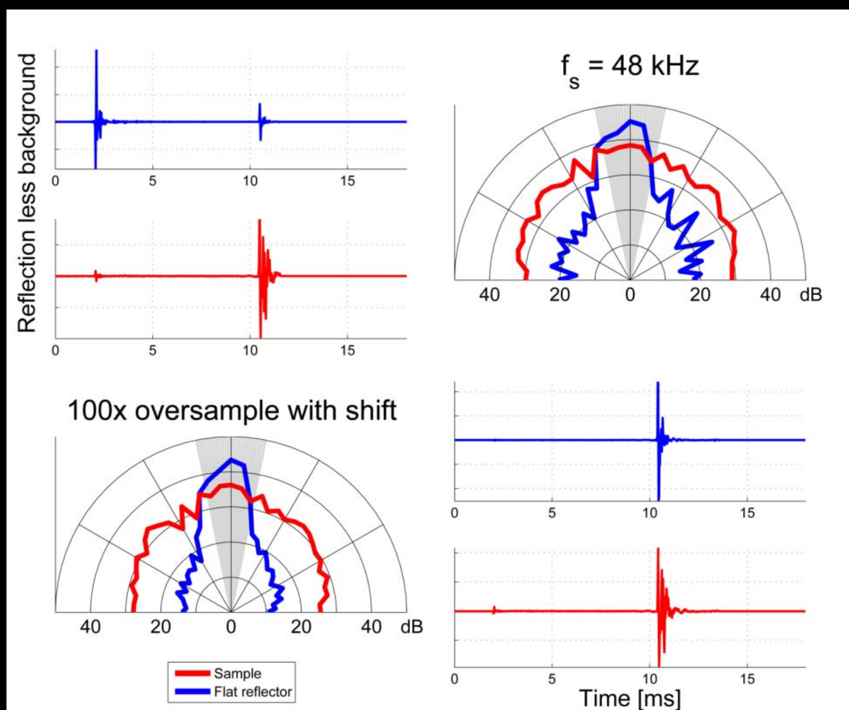




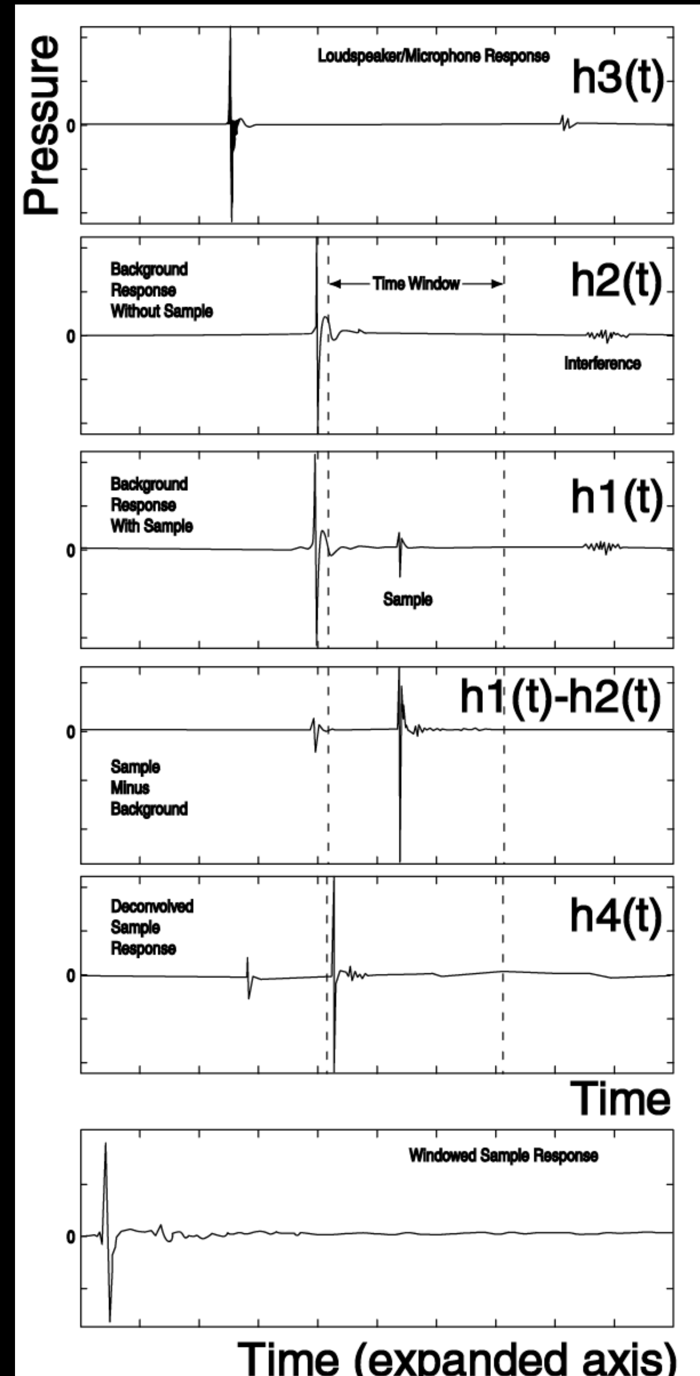
$$d_\psi = \frac{\left(\sum_{i=1}^{n} 10^{L_i/10}\right)^2 - \sum_{i=1}^{n}\left(10^{L_i/10}\right)^2}{(n-1)\sum_{i=1}^{n}\left(10^{L_i/10}\right)^2}$$

Extraction of scattered sound

$$h_4(t) = IFT\left\{\frac{FT\left[h_1(t) - h_2(t)\right]}{FT\left[h_3(t)\right]}\right\}$$



Sample background subtraction with oversampling suggested by Robinson

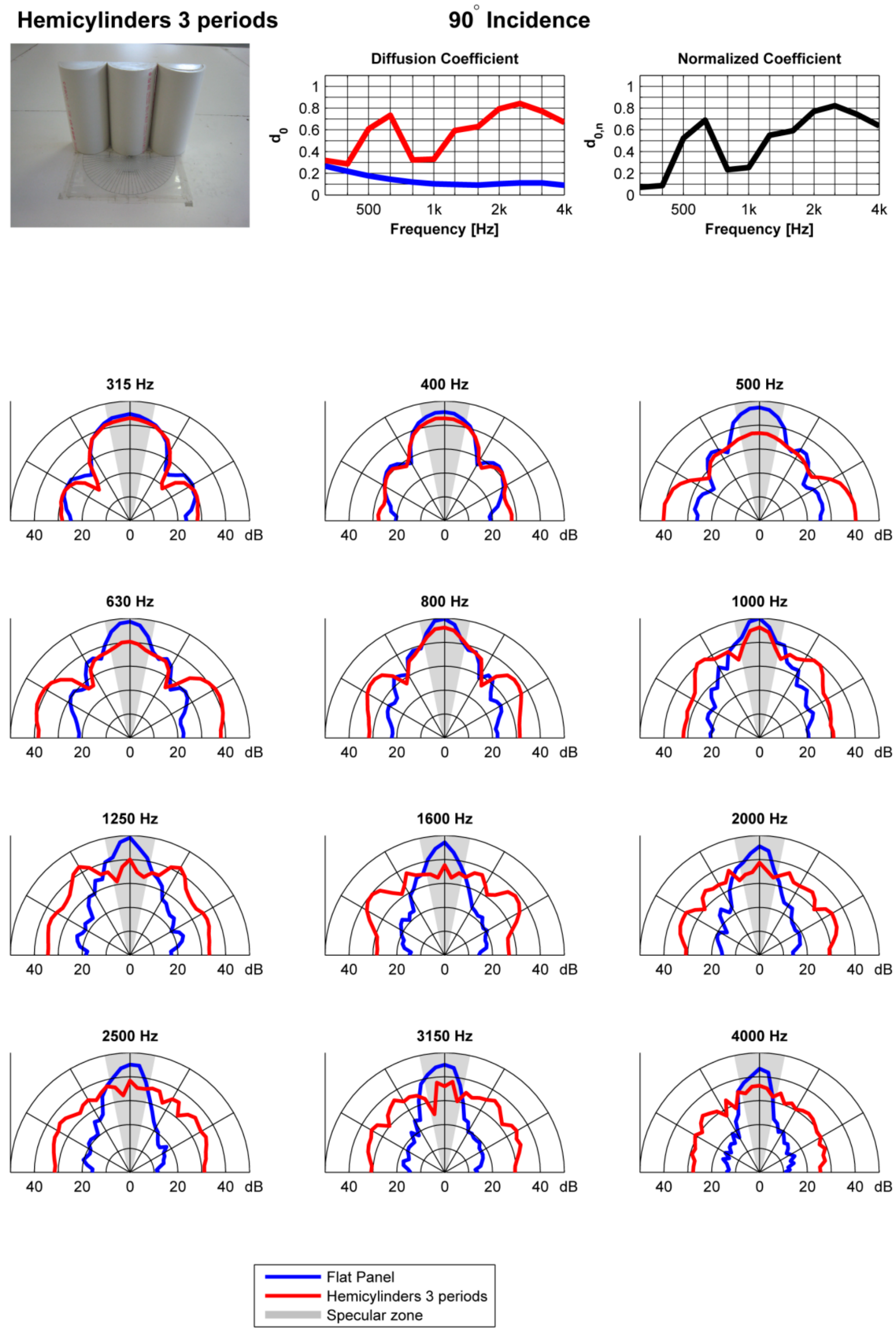


- Presentation template

- The Diffusion Coefficient measured in free space includes contribution from:
  - Surface topology
  - Edge Diffraction

- To remove the edge diffraction, we calculate

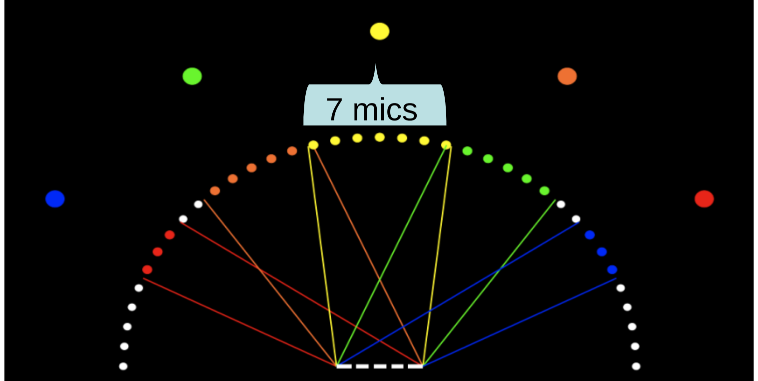
$$d_n = \frac{(d_d - d_r)}{(1 - d_r)}$$

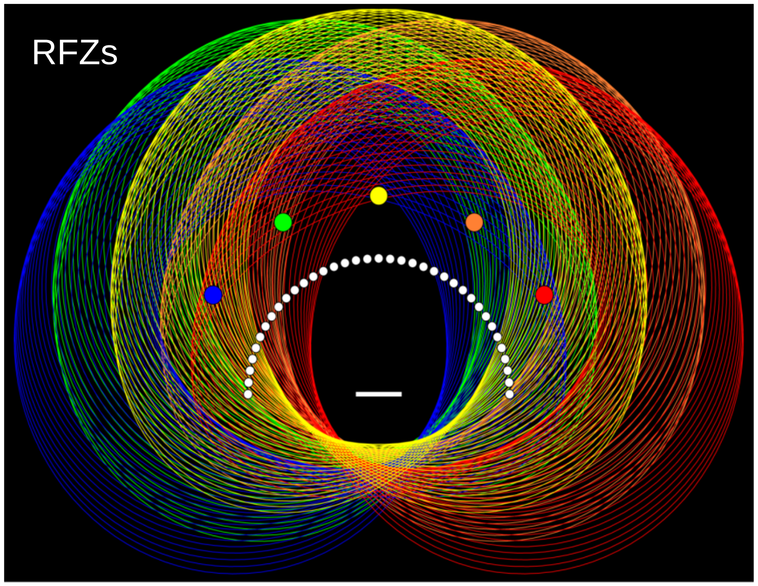


Improvements:

Goniometer Optimization

Specular zones for 30, 60, 90, 120 & 150^{o}





Given:

- L, W, H of measurement room
- (5) 120x120 mm samples
- 36^{0} specular zone
  (7 mics normal incidence)
- 4 ms minimum reflection free zone in impulse response

Find:

- Specular Zone for all angles of incidence
- Reflection Free Zone (RFZ) for all angles of incidence
- Optimal Speaker radius
- Optimal Mic radius

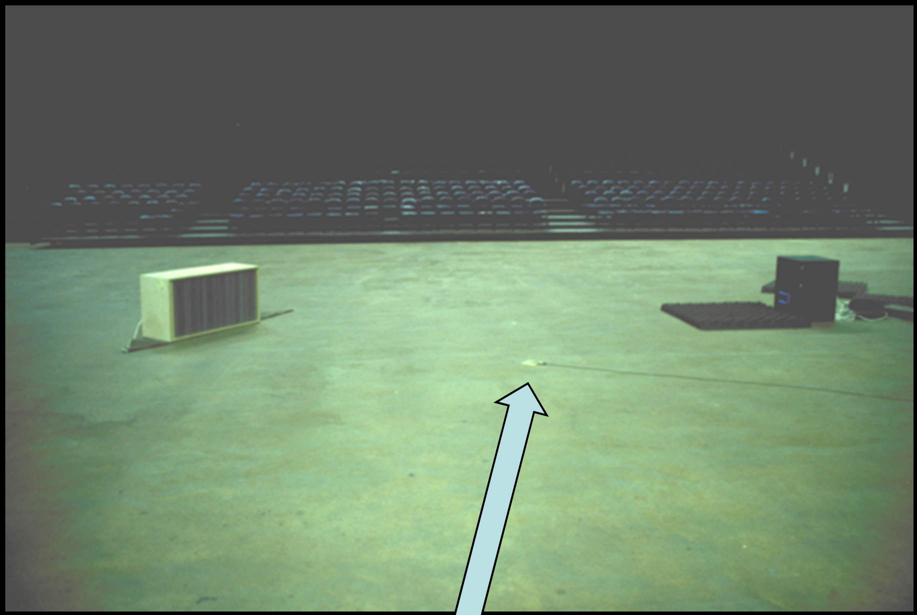
Result:

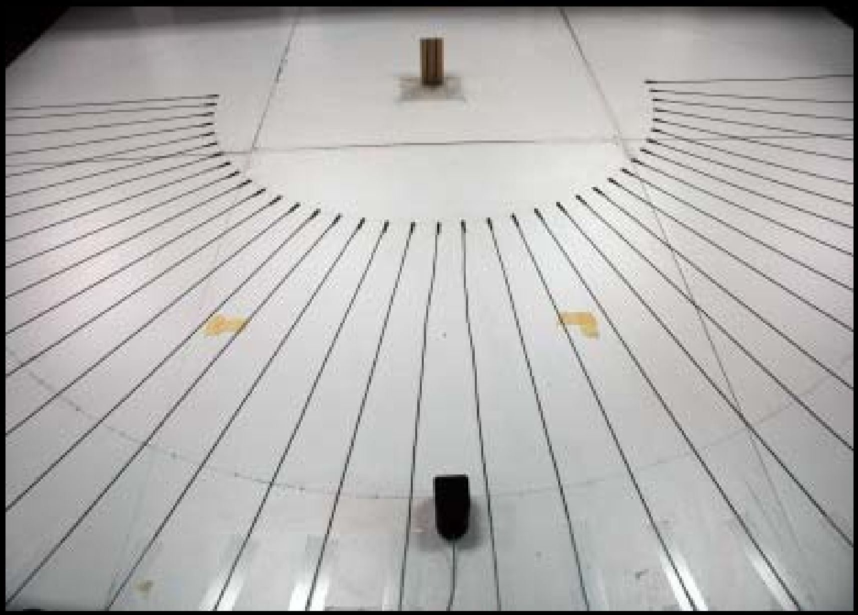
- Allowable sample width increased by 40% with no widening of specular zone
- Reflection arrivals are balanced to arrive at least 2 ms after direct sound and approximately 2 ms before room reflections

Improvements:

1983-1993: Single Mic, Full Scale

1994: Multiple Mics, 1:5 Scale





Single microphone was moved 37 times at 5 degree angular increments to collect 37 impulse responses.

TEF was set to automatic delay and operator had to run into the reflection free zone, move the mic and run out of the RFZ!! The precursor to P90X!

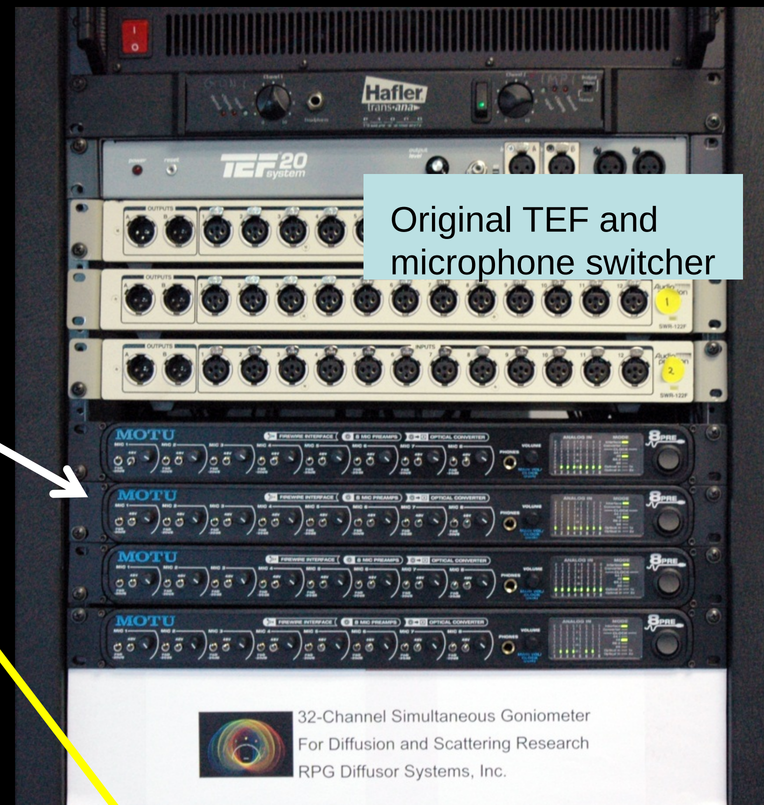
MLS stimulus emitted 37 times with automatic sequential microphone switcher

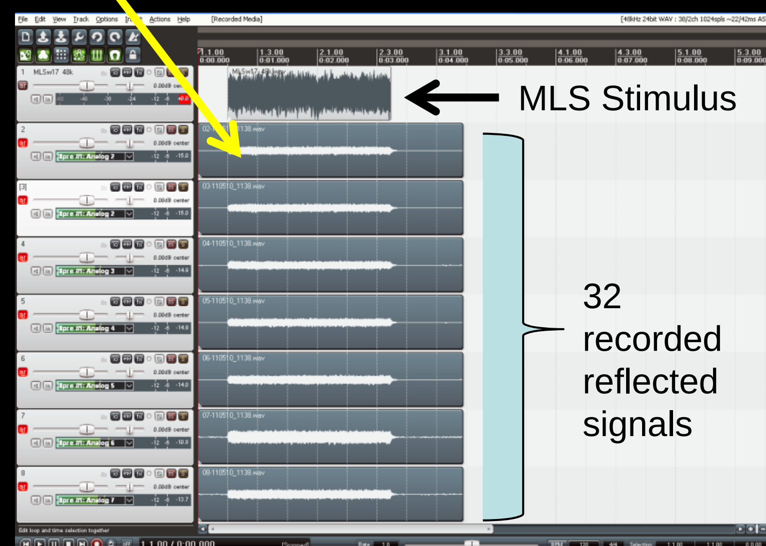
RPG

Improvements:

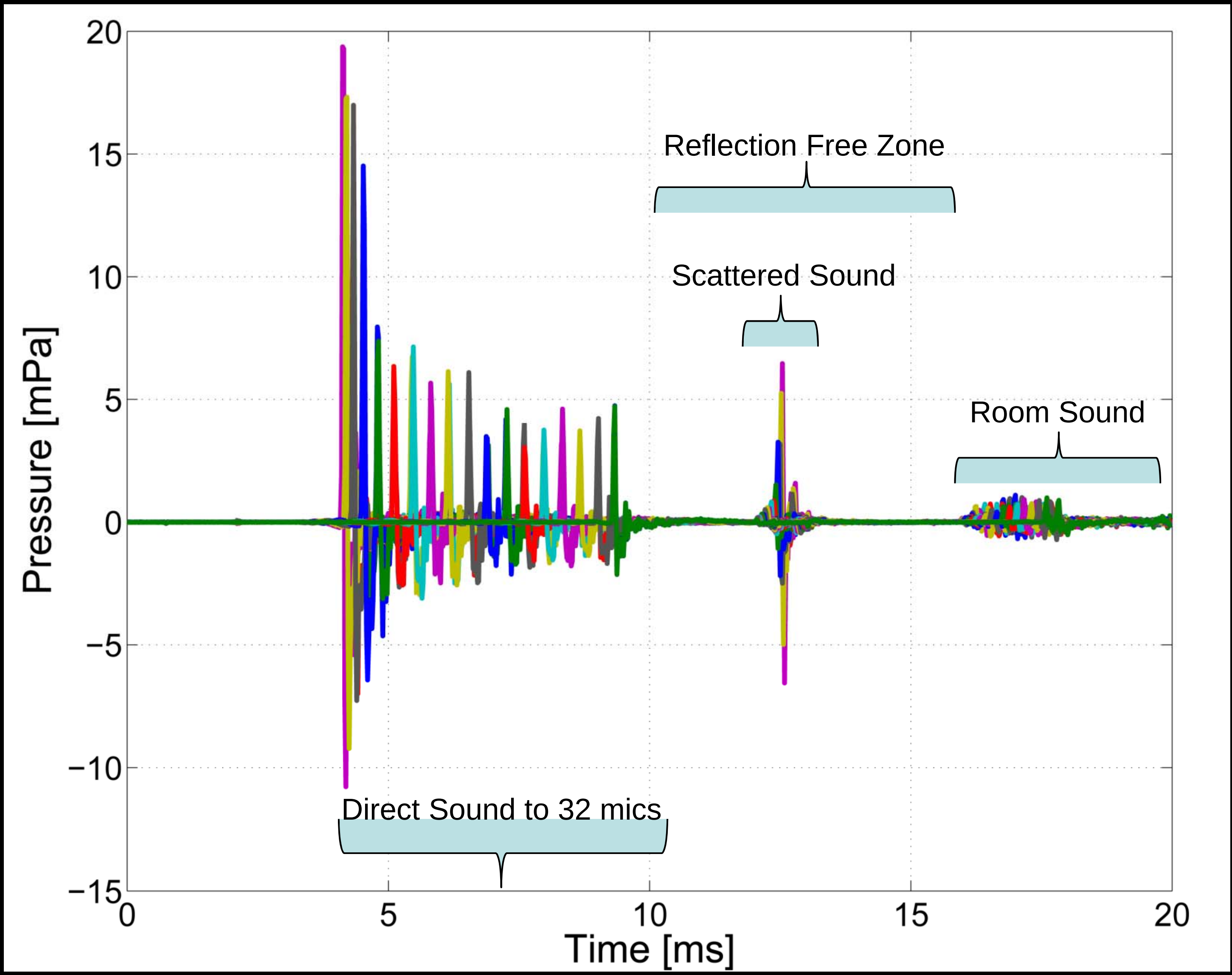
2011: Simultaneous Measurements

- 32 channels of preamps
- 32 channel simultaneous hard disk recording of scattered sounds, using an MLS stimulus
- 32 simultaneous MLS measurements reduces measurement time to 3 s for each sample, background and reference reflector
- Impulse responses are obtained by deconvolution with MLS stimulus
- Automatic data reduction to subtract background, deconvolve mic/speaker response, gate scattered sound and generate polars and diffusion coefficient

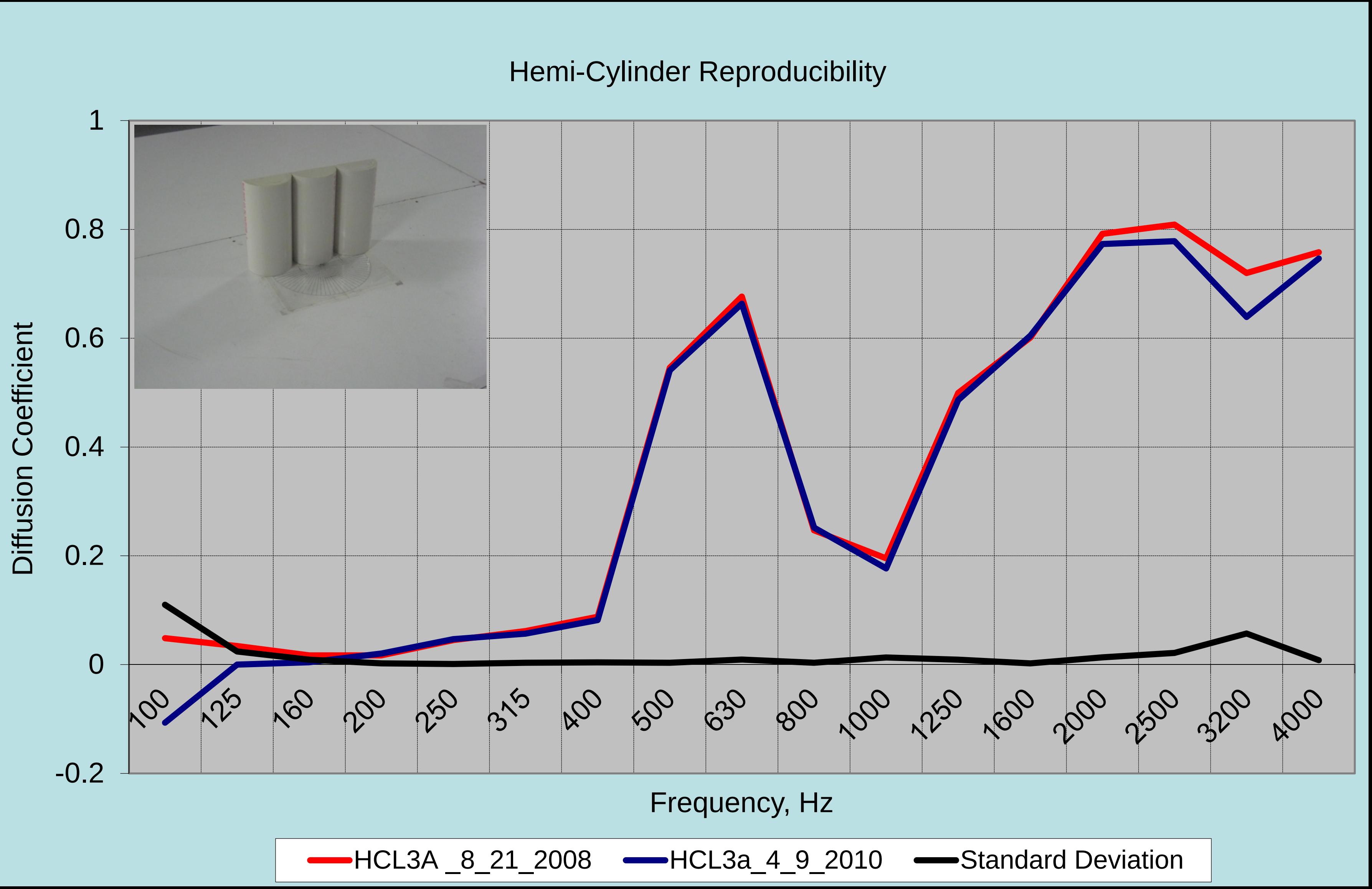




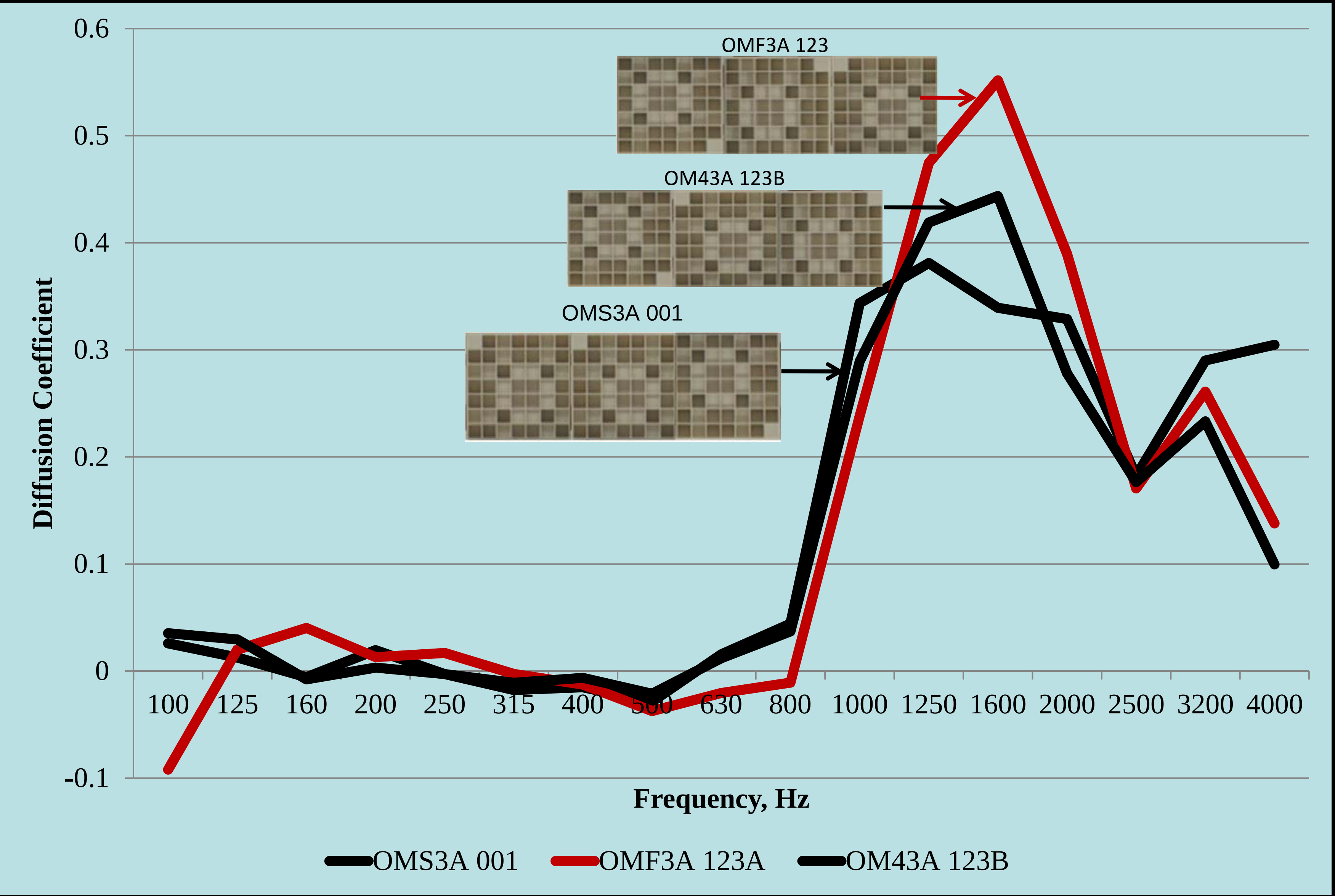
Deconvolved Impulse Responses



Reproducibility



Sensitivity



Limitations: Specular Zone

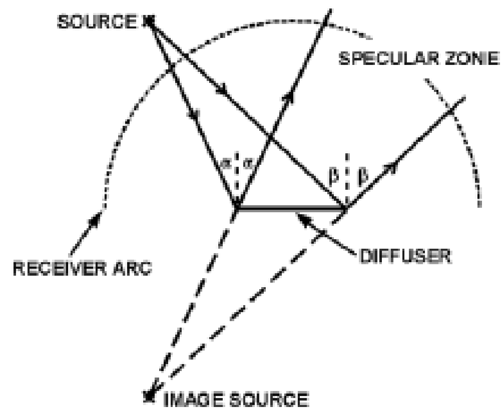
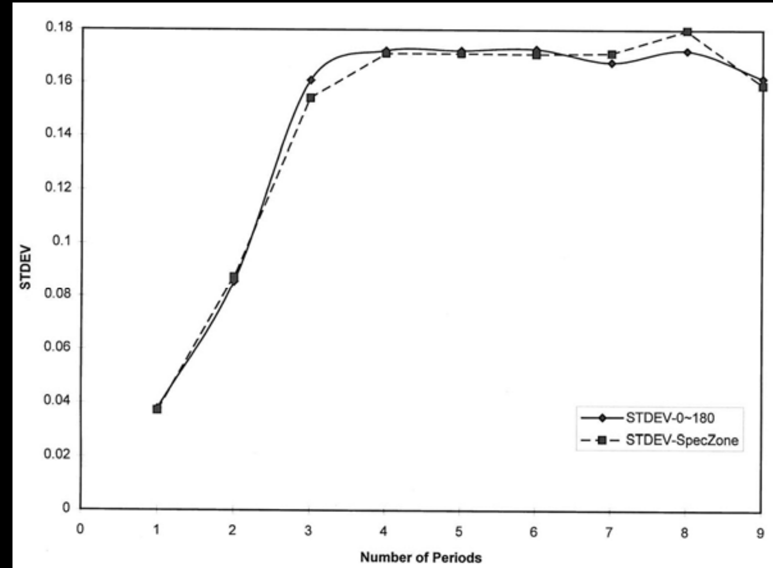


Figure 4.14 Definition of the specular zone – the region over which a geometric reflection occurs. (Although the specular zone is strictly a high frequency construction, practice has shown it to be a useful concept for the geometries and frequencies typically used in diffuser design) (after Hargreaves *et al.*[14]).



A specular zone occurs because we can never practically be in the far field

There is a compromise between minimizing the specular zone and measuring a sufficiently large array to account for grating lobes

After 4 periods, periodicity effects are minimized

Goniometers should be designed to measure 4 periods and maintain 80% of the mics outside the specular zone (36^0 specular zone)

Limitations: Boundary Plane Measurement

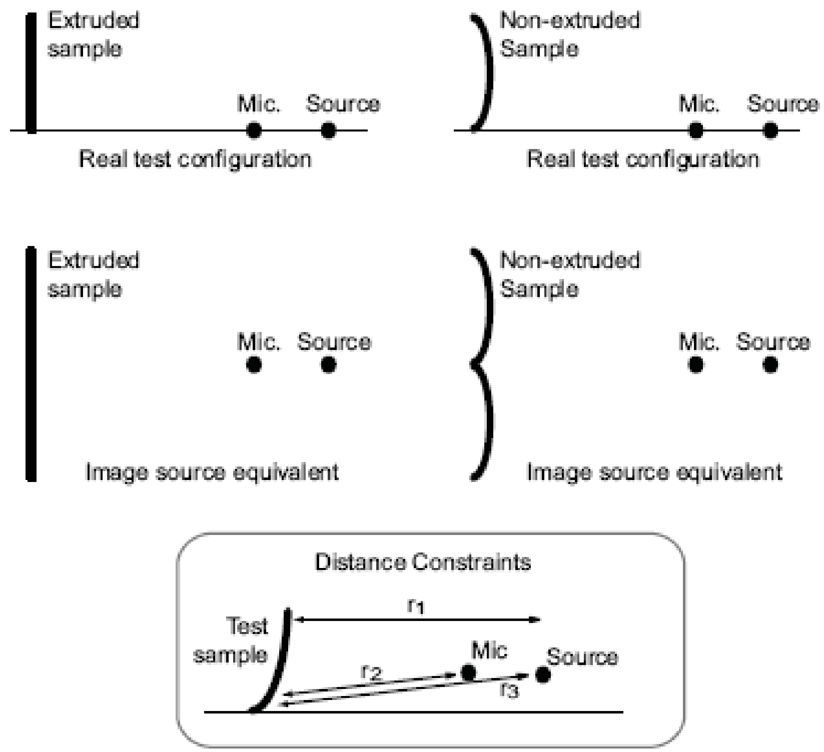


Figure 4.7 Top row: boundary plane measurement and below that the equivalent image source configuration. Left column: extruded sample; right column: non-extruded surface. The insert shows distances used for calculating maximum frequency.

Boundary measurement includes mirror image sample. Not a problem in anechoic chamber

Diffusion deception

- The diffusion industry has grown since the early 1980s and there are many products on the market claimed to be diffusers

- There is evidence, however, that some published diffusion coefficients are fabricated and/or polars are improperly interpreted

- If polars are actually measured, it is for 1 unit, instead of an array as required in the standard to account for grating lobes

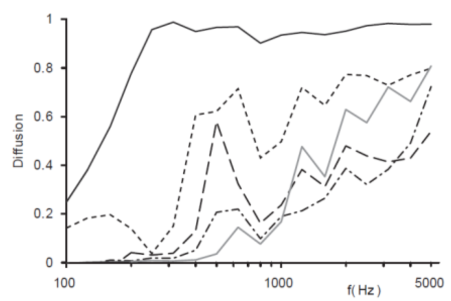


Figure 4.18 The normalized diffusion coefficient for various sets of semicylinders. The number of cylinders in each set is:
- ——— 1;
- ------- 2;
- – – – 4;
- -·-·- 6;
- ——— 12.

- Therefore, you should request the complete normalized diffusion coefficients, with polars for 4 samples and reference reflector and a <u>photo</u> of the measurement setup!

...This is only the beginning!