Laboratory and In Situ Sound Absorption Measurement under a Synthetized Diffuse Acoustic Field: a Case Study on Five Materials

Olivier Robin, Celse Kafui Amedin, Alain Berry, Noureddine Atalla, Olivier Doutres and Franck Sgard

GAUS
GROUPE D'ACOUSTIQUE DE L'UNIVERSITÉ DE SHERBROOKE

ÉTS
Le génie pour l'industrie

irsst
Institut de recherche Robert-Sauvé en santé et en sécurité du travail

Introduction - context

- Random-incidence sound absorption coefficients or Sabine absorption coefficients are estimated in reverberant chambers following standards (ASTM C423, ISO 354)
- The reverberation times with and without a sample (T_{sample} and T_0, respectively) are measured, then the absorption coefficient is deduced following

$$\alpha = \frac{55.3\,V}{c_0 S}\left[\frac{1}{T_{sample}} - \frac{1}{T_0}\right]$$

with V the room volume and S the sample area

A first issue…

ASTMC423 : **V=125 m^3 minimum - S=6.7 m^2**

ISO 354: **V=150 m^3 minimum – S=12 m^2**

Introduction - context

A second issue...

This measurement is highly dependent on sample size and arrangement, with possible overestimation of measured coefficient (non-physical result >1) - not to be directly used in room acoustics simulation

DEPENDENCE OF SOUND ABSORPTION UPON THE AREA AND DISTRIBUTION OF THE ABSORBENT MATERIAL

By V. L. Chrisler

Journal of research of the national bureau of standards, RP700, **1934**

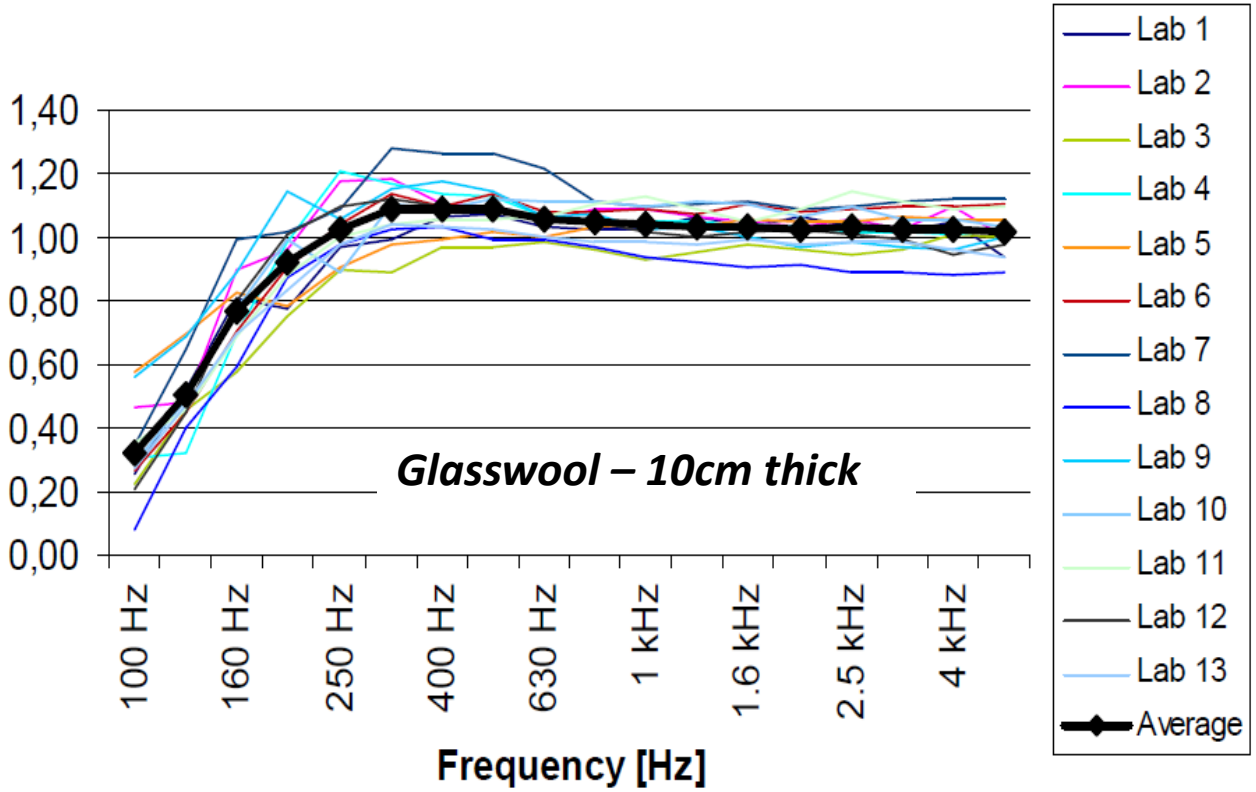
ABSTRACT

This paper contains a report of work on sound absorption where large areas of absorbent material are installed. The measurements show that under these conditions it is impossible to obtain a logarithmic decay, hence the sound absorption is less than would be expected from the absorption coefficient of the material.

Measurements were also made on very small areas. In this case the absorption was more than would be expected from the coefficient determined by measuring the absorption of an area of 72 square feet.

Introduction - context

A third issue... This measurement shows a poor interlaboratory reproducibility (depending on room size, diffusers effect)

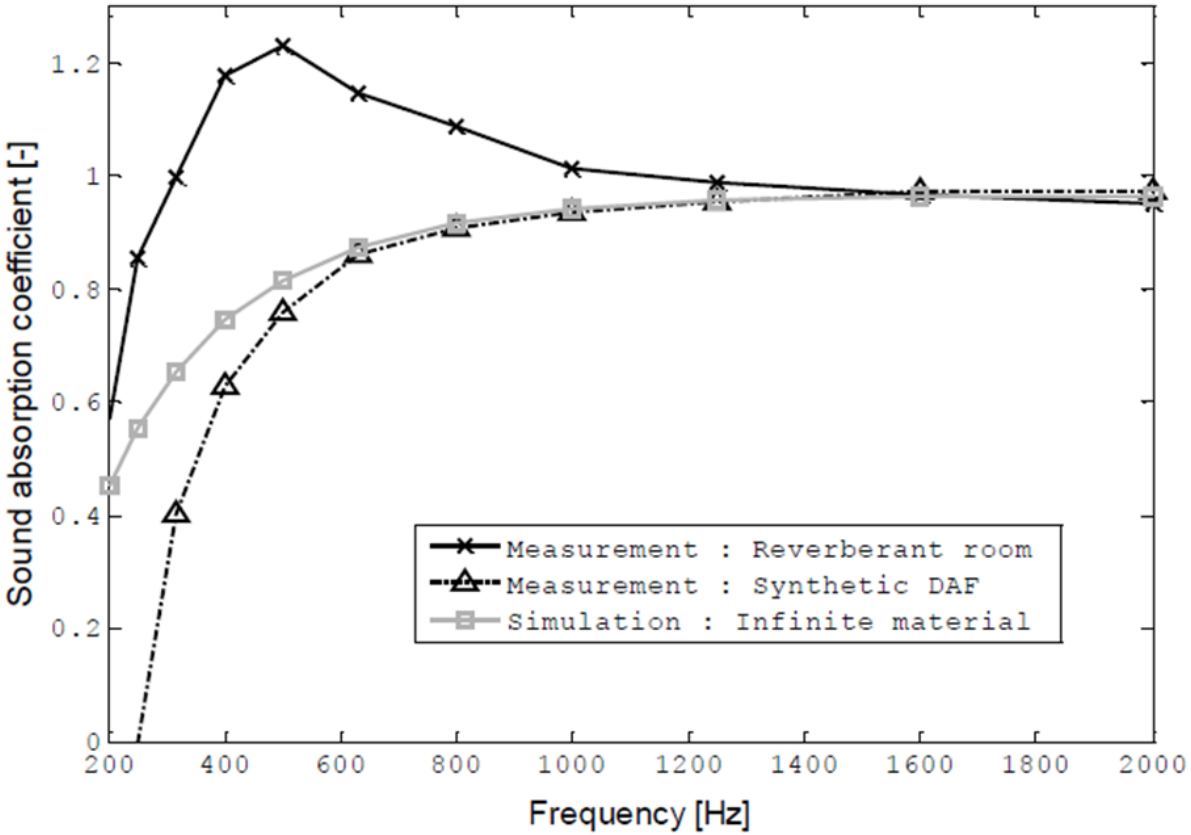


From Vercammen, ISRA2010

A fourth issue... This method can not be applied *in situ*

Introduction - context

A method for estimating the sound absorption coefficient of a material **under a synthesized Diffuse Acoustic Field (DAF)** was recently proposed



Main advantages :

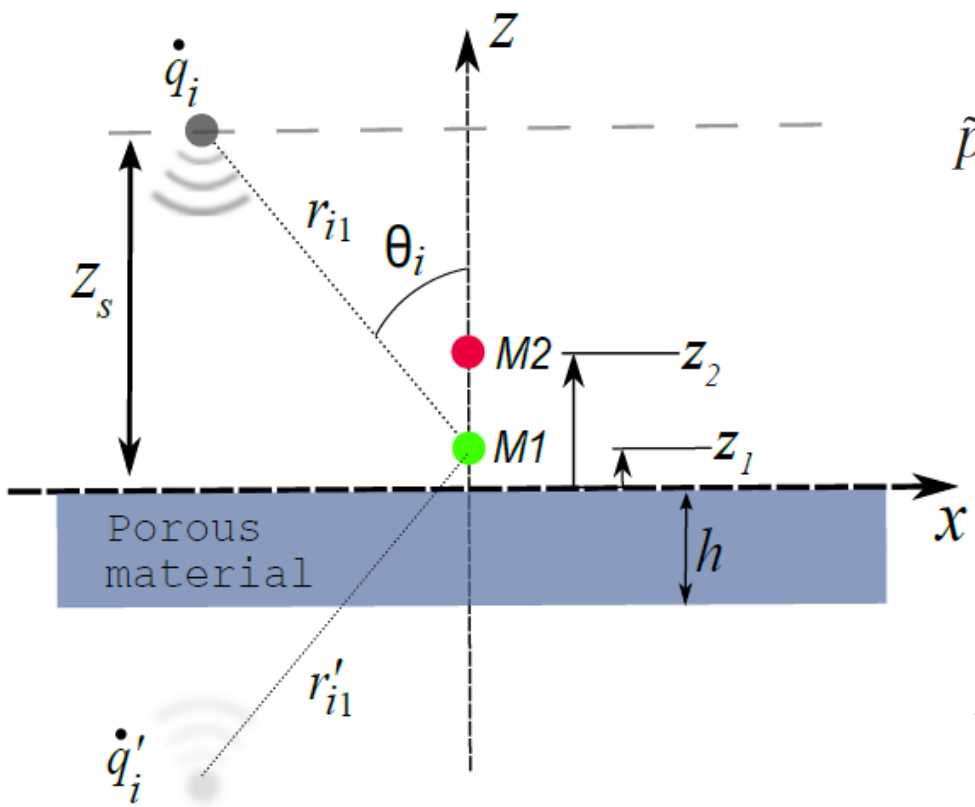
- No need to prepare samples (perimeter sealing)
- Smaller samples can be tested
- Estimation is made at a post-processing step, making it flexible (the excitation can be numerically varied)

Main drawback : a low frequency limitation

Experimental and simulations results concerning the estimation of the sound absorption coefficient of five different materials using this method in laboratory and *in situ* conditions will be summarized.

Absorption coefficient under a single point source

Using a pair of microphones (*M1* - *M2*) and a point source of volume velocity q_i



- At microphone *j* for a *i*-position of the source, the acoustic pressure p_{ij} is

$$\tilde{p}_{ij}(\theta_i,\omega) = \rho_0 \dot{q}_i(\omega)\frac{e^{-jk_0 r_{ij}}}{r_{ij}} + R(\theta_i,\omega)\rho_0\dot{q}_i(\omega)\frac{e^{-jk_0 r'_{ij}}}{r'_{ij}}$$

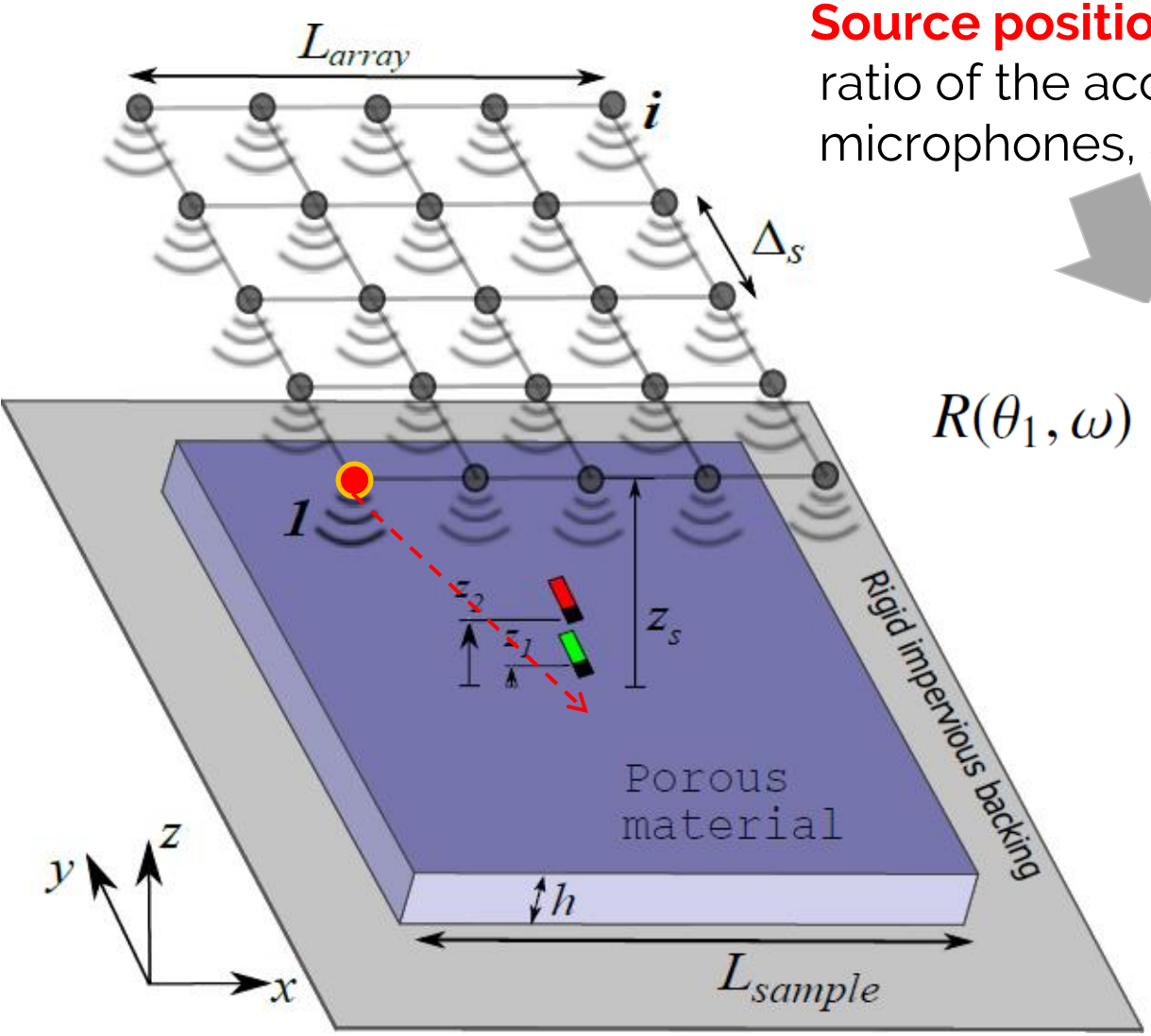
- Measuring $H(\theta_i,\omega)$, the transfer function between the acoustic pressure at each microphone gives

$$R(\theta_i,\omega) = \frac{\frac{e^{-jk_0 r_{i2}}}{r_{i2}} - H(\theta_i,\omega)\frac{e^{-jk_0 r_{i1}}}{r_{i1}}}{H(\theta_i,\omega)\frac{e^{-jk_0 r'_{i1}}}{r'_{i1}} - \frac{e^{-jk_0 r'_{i2}}}{r'_{i2}}}$$

➡ The absorption coefficient $\alpha(\theta_i,\omega) = 1 - |R(\theta_i,\omega)|^2$

Reflection coefficient under a virtual array

With a <u>fixed</u> microphone doublet and a <u>mobile</u> point source

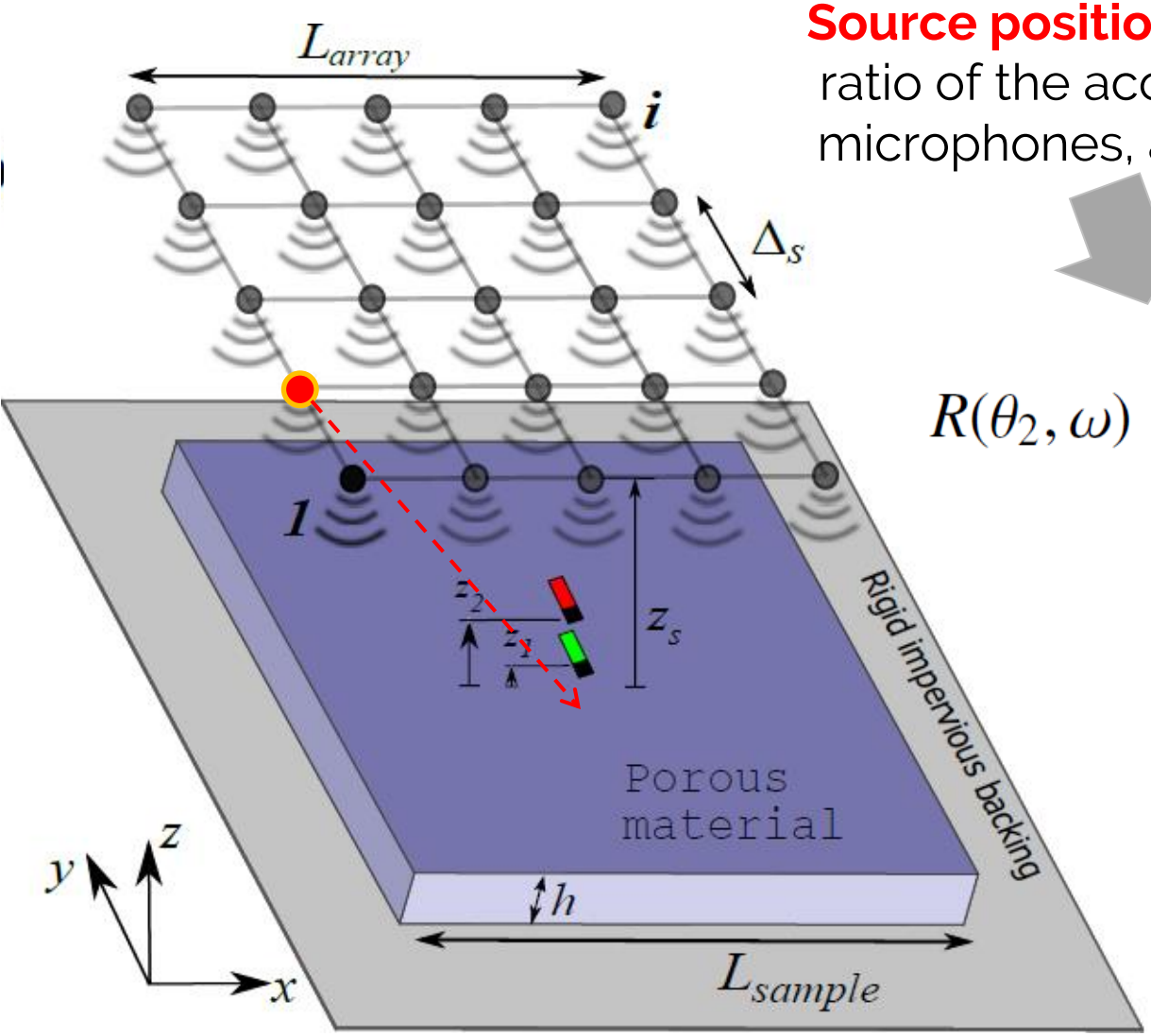


Source position # 1 : Measuring $H(\theta_1,\omega)$, ratio of the acoustic pressure at the two microphones, allows estimating $R(\theta_1,\omega)$

$$R(\theta_1,\omega) = \frac{\dfrac{e^{-jk_0 r_{12}}}{r_{12}} - H(\theta_1,\omega)\dfrac{e^{-jk_0 r_{11}}}{r_{11}}}{H(\theta_1,\omega)\dfrac{e^{-jk_0 r'_{11}}}{r'_{11}} - \dfrac{e^{-jk_0 r'_{12}}}{r'_{12}}}$$

Reflection coefficient under a virtual array

With a fixed microphone doublet and a mobile point source

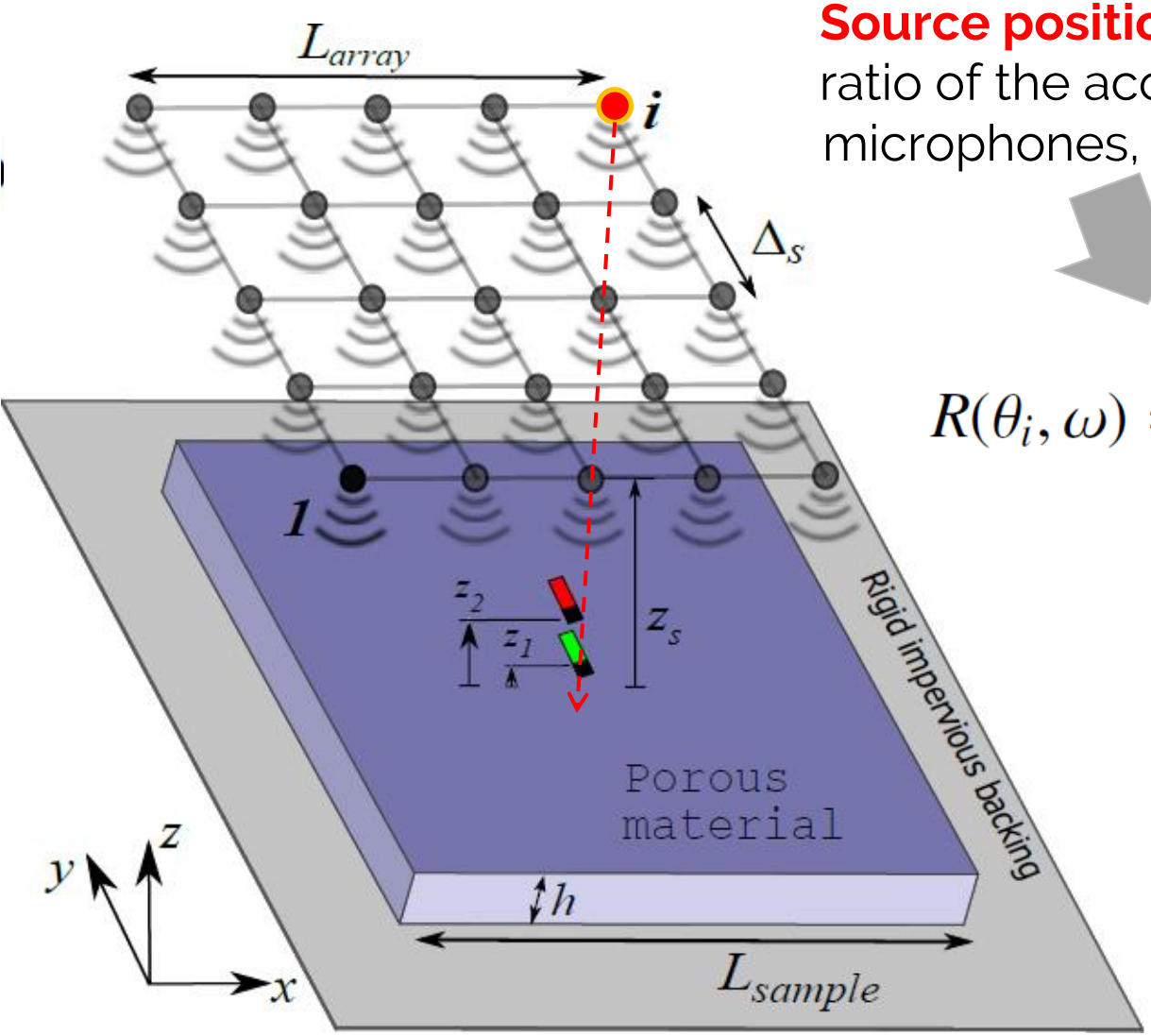


Source position # 2 : Measuring $H(\theta_2,\omega)$, ratio of the acoustic pressure at the two microphones, allows estimating $R(\theta_2,\omega)$

$$R(\theta_2,\omega) = \frac{\frac{e^{-jk_0 r_{22}}}{r_{22}} - H(\theta_2,\omega)\frac{e^{-jk_0 r_{21}}}{r_{21}}}{H(\theta_2,\omega)\frac{e^{-jk_0 r'_{21}}}{r'_{21}} - \frac{e^{-jk_0 r'_{22}}}{r'_{22}}}$$

Reflection coefficient under a virtual array

With a <u>fixed</u> microphone doublet and a <u>mobile</u> point source



Source position # *i*: Measuring $H(\theta_i,\omega)$, ratio of the acoustic pressure at the two microphones, allows estimating $R(\theta_i,\omega)$

$$R(\theta_i,\omega) = \frac{\frac{e^{-jk_0 r_{i2}}}{r_{i2}} - H(\theta_i,\omega)\frac{e^{-jk_0 r_{i1}}}{r_{i1}}}{H(\theta_i,\omega)\frac{e^{-jk_0 r'_{i1}}}{r'_{i1}} - \frac{e^{-jk_0 r'_{i2}}}{r'_{i2}}}$$

↳ **a database of measured reflection coefficients at various incidence angles is generated**

↳ **a virtual array of monopoles is created in front of the material**

Reflection coefficient under a virtual array

Coupling a **calculated** matrix of source amplitudes $\mathbf{S}_{\dot{Q}\dot{Q}}$ to the previously **measured** reflection coefficients database in a post processing phase allows estimating the absorption coefficient under a synthetic DAF

Measurement *of* $\boldsymbol{R}(\theta_i,\omega)$
(coefficients included in the $\mathbf{h_1}$ term below)

+

$\mathbf{S}_{\dot{Q}\dot{Q}}$ ***calculation***
(target = DAF on material surface)

Squared reflection coefficient under a synthetic pressure field

$$|R_{synth}(\omega)|^2 = \frac{\mathbf{h_1}^H \mathbf{S}_{\dot{Q}\dot{Q}} \mathbf{h_1}}{\mathbf{g_1'}^H \mathbf{S}_{\dot{Q}\dot{Q}} \mathbf{g_1'}}$$

Absorption coefficient under a synthetic pressure field

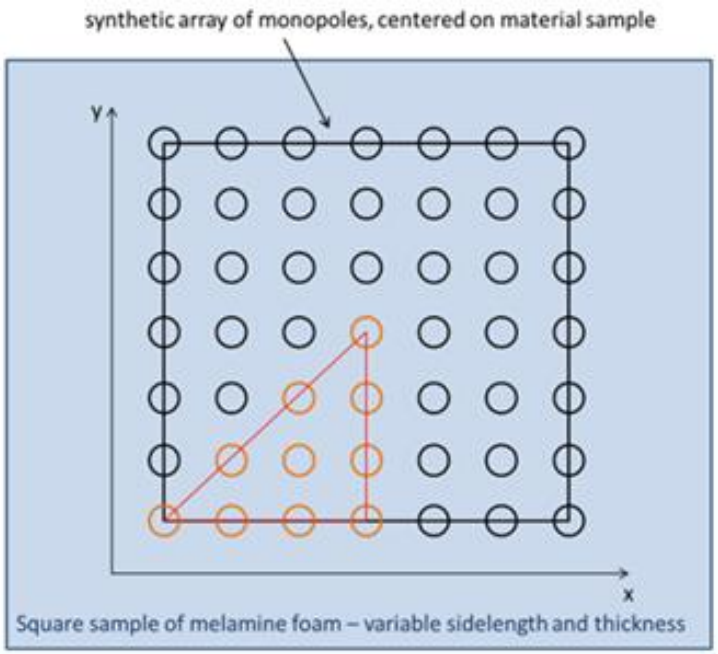
$$\alpha_{synth}(\omega) = 1 - |R_{synth}(\omega)|^2$$

Numerical simulations : summary

- **Main objective: Studying sample size effect, and array size and height effect**

- A finite element model is used to calculate the complex acoustic pressure at positions z_1 and z_2 (microphones positions), under a monopole source positioned at various heights

- Reflection coefficients for ten source positions are calculated (deduced for other source positions by simple symmetry considerations)



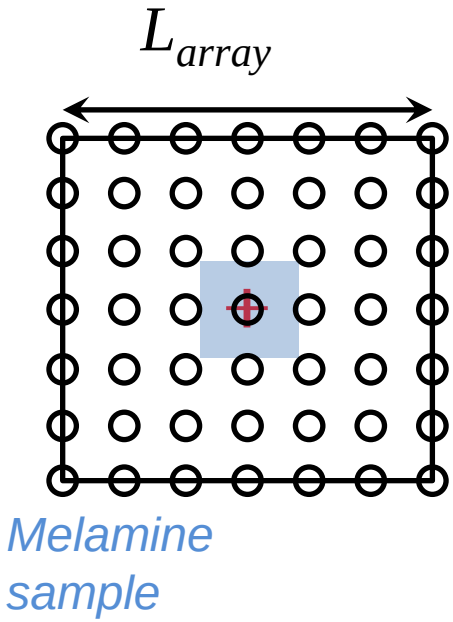
- A melamine foam with similar parameters as the one experimentally tested is considered

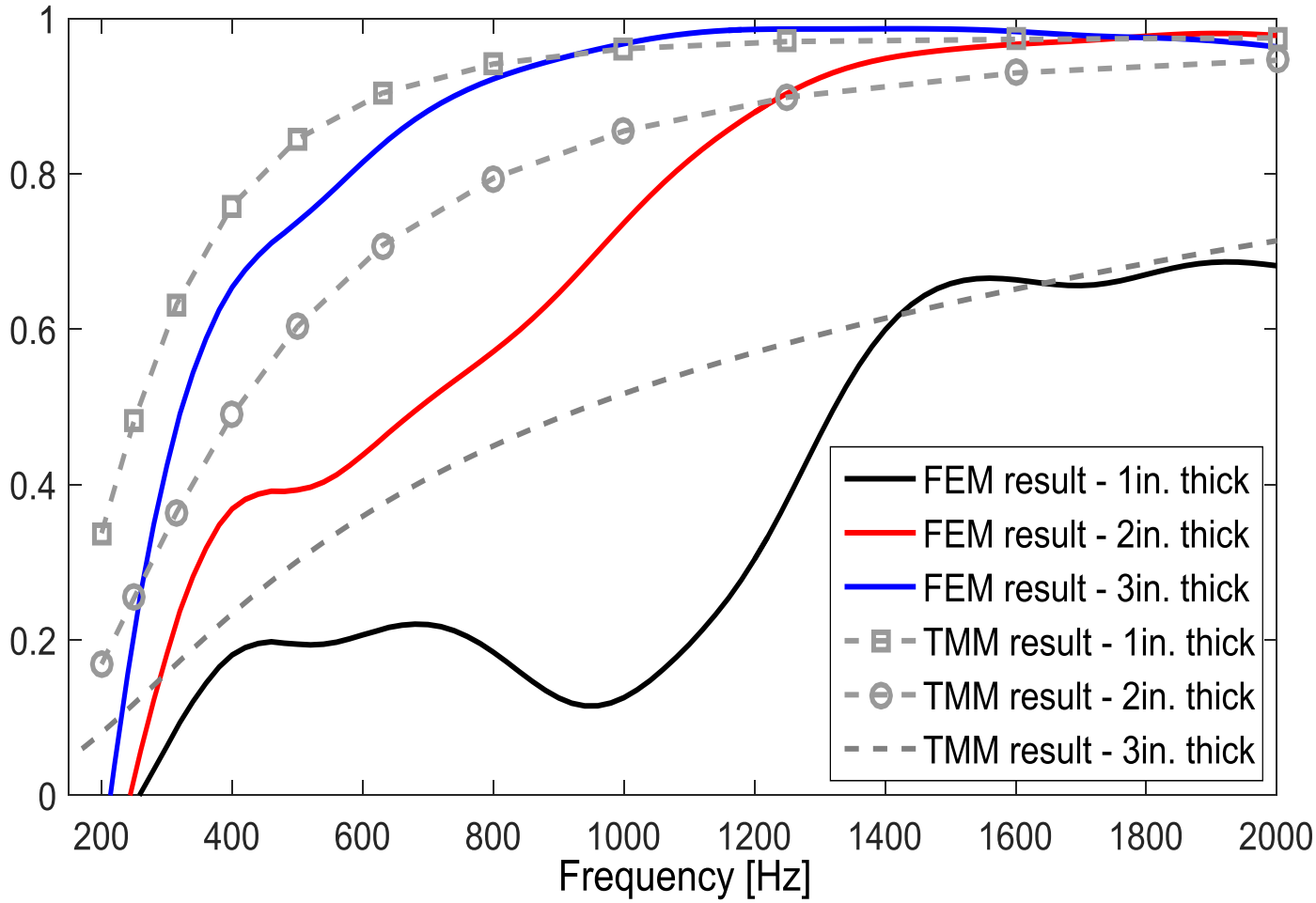
- Results are compared with TMM calculations ('∞' material) or with experimental results for different sample sizes or array sizes

Numerical simulations : sample size effect

Material of sidelength 0.22 m (**four times smaller** than the synthetic array)

FEM result ≡ numerical simulation of the method / TMM ≡ theoretical result for ∞ material

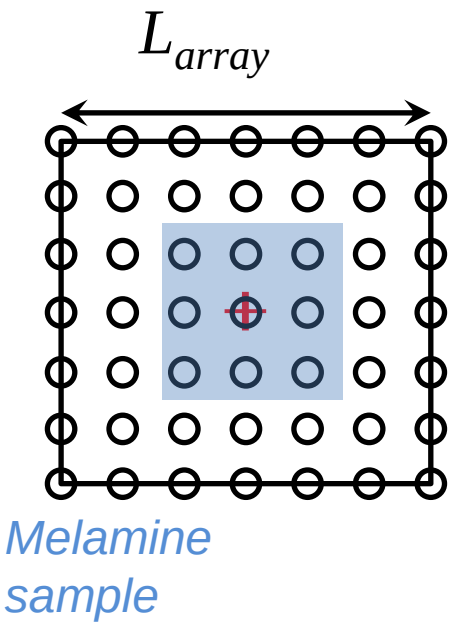


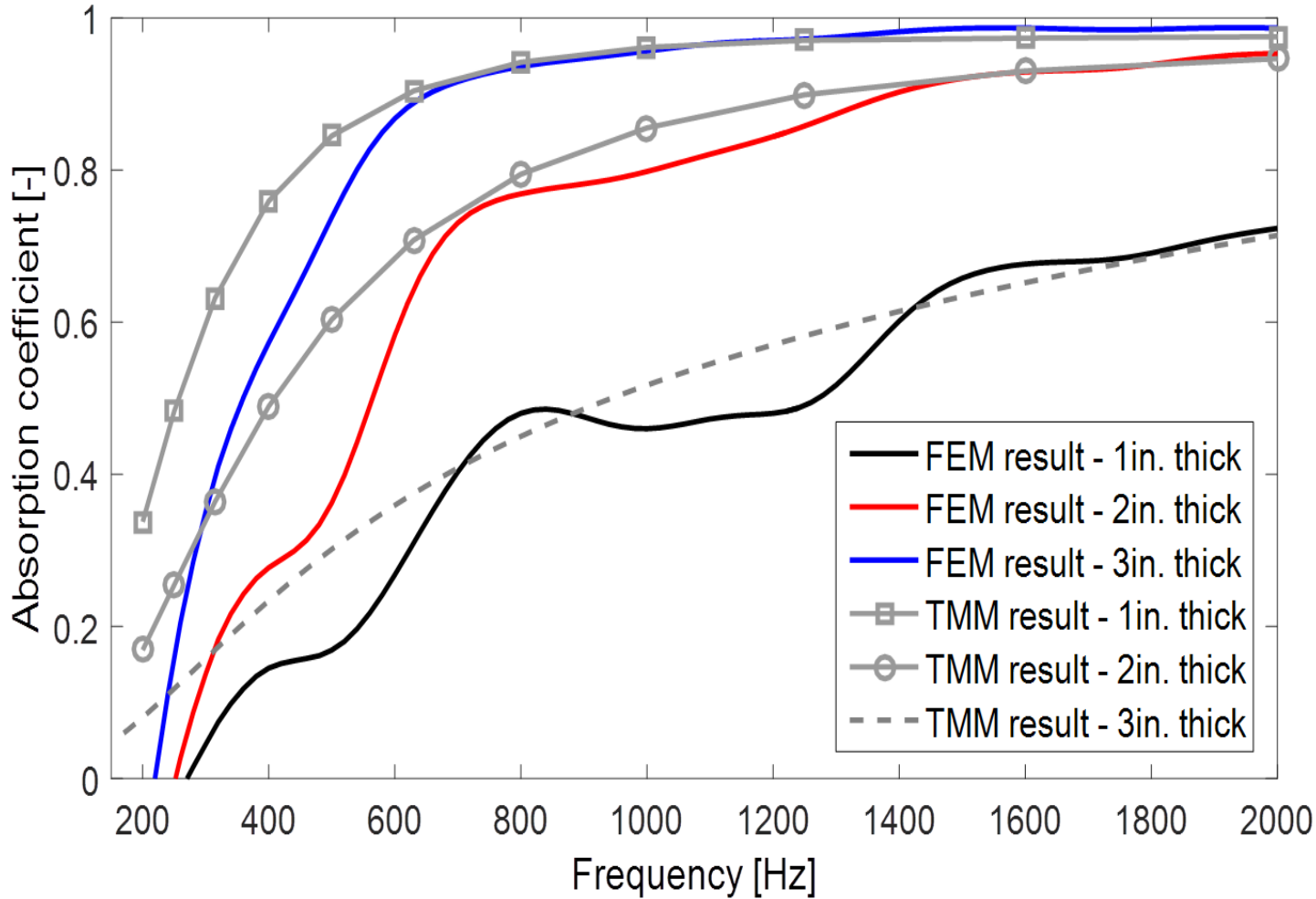


Numerical simulations : sample size effect

Material of sidelength 0.45 m (**two times** smaller than the synthetic array)

FEM result ≡ numerical simulation of the method – TMM ≡ theoretical result for ∞ material

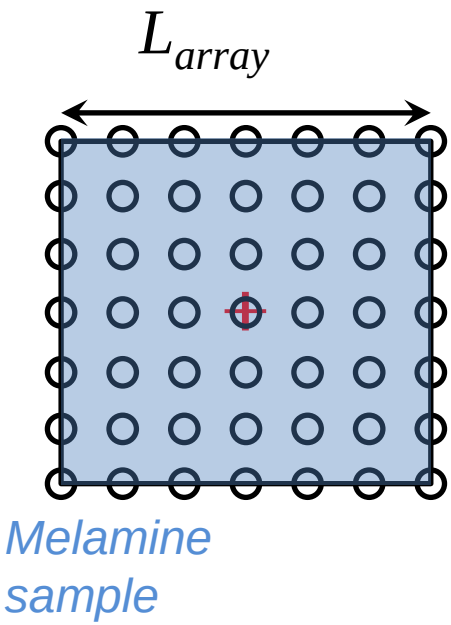


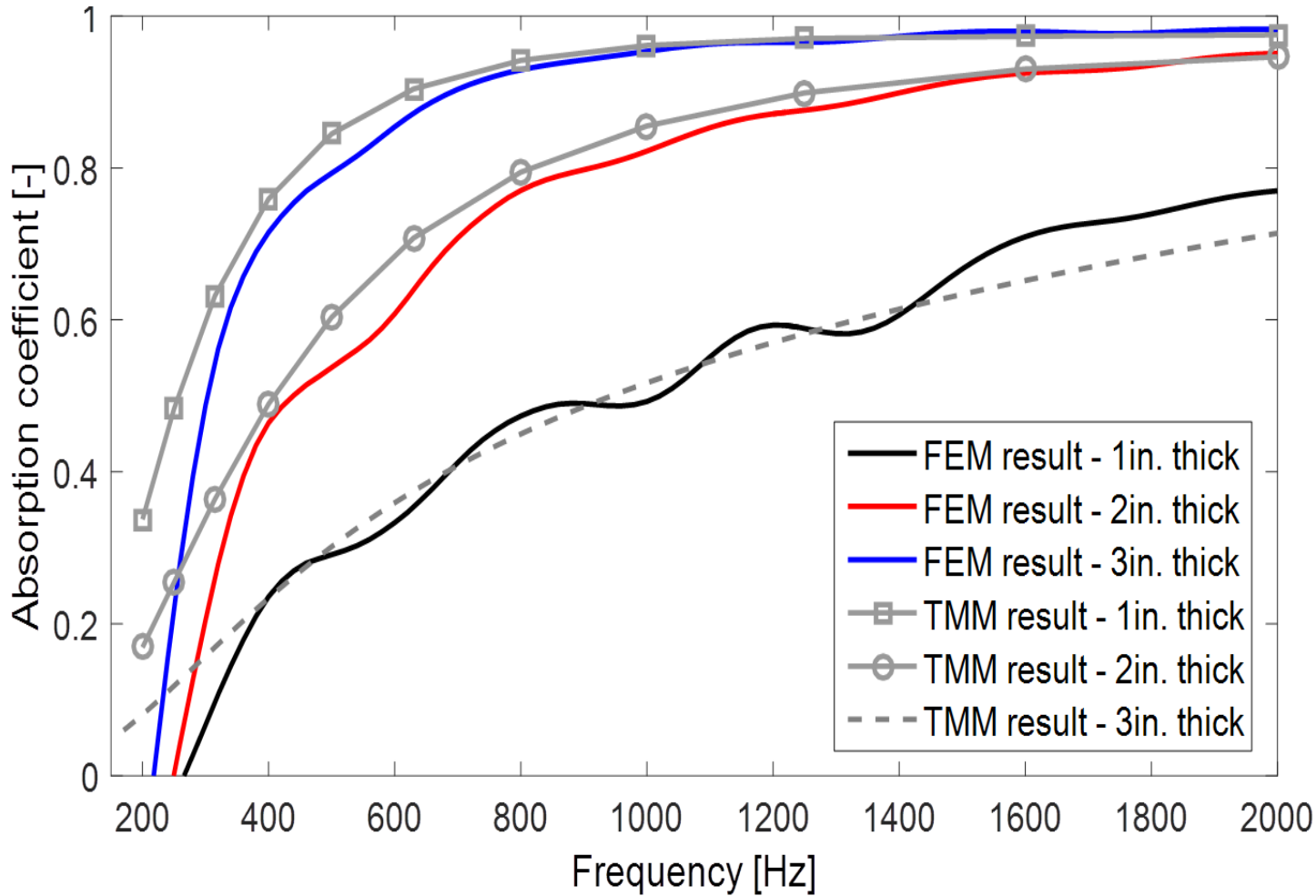


Numerical simulations : sample size effect

Material of sidelength 0.9 m (**same size** than the synthetic array)

FEM result ≡ numerical simulation of the method / TMM ≡ theoretical result for ∞ material

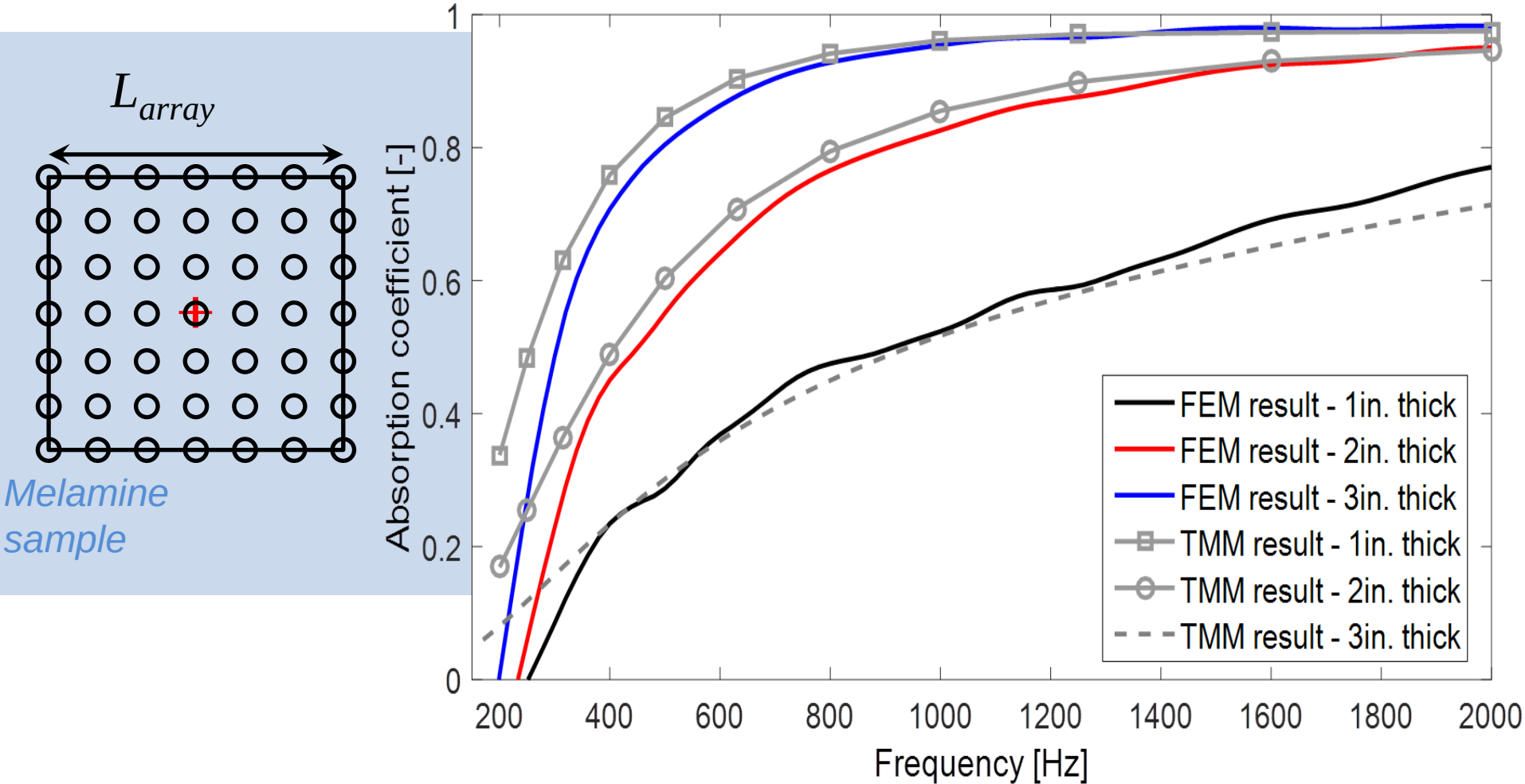




Numerical simulations : sample size effect

Material of sidelength 1.8 m (**two times larger** than the synthetic array)

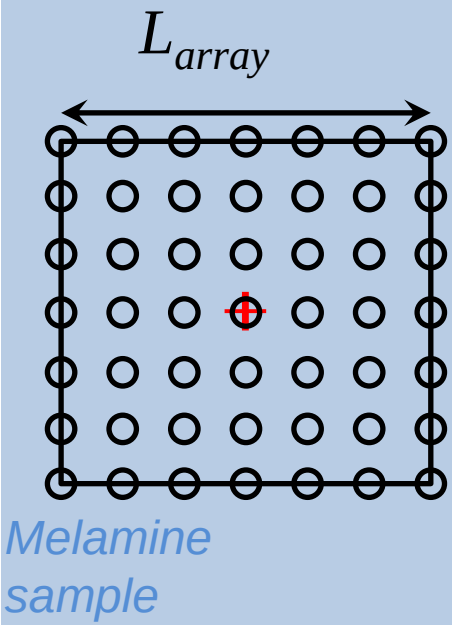
FEM result ≡ numerical simulation of the method / TMM ≡ theoretical result for ∞ material

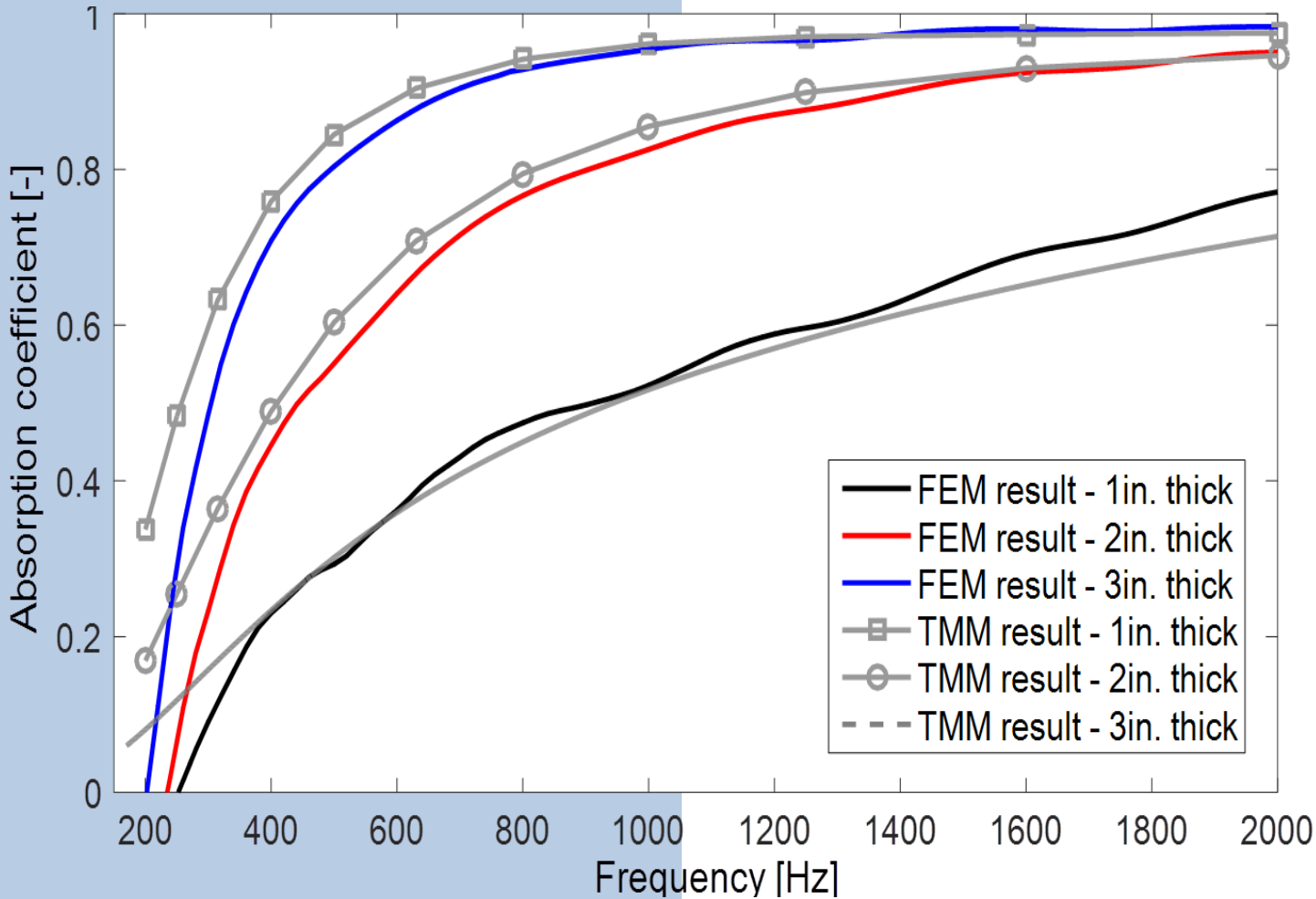


Numerical simulations : sample size effect

Material of sidelength 3.6 m (**four times larger** than the synthetic array)

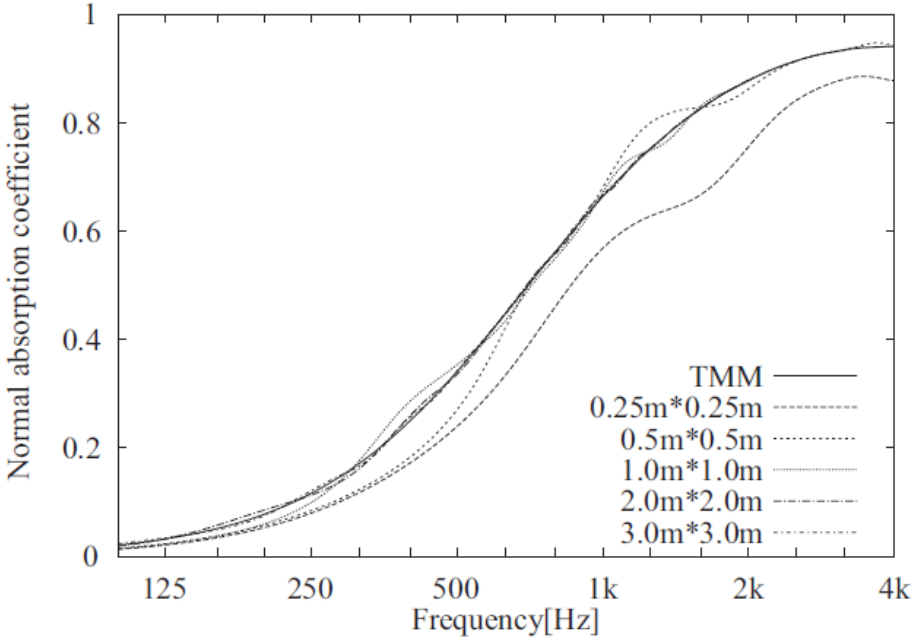
FEM result ≡ numerical simulation of the method / TMM ≡ theoretical result for ∞ material





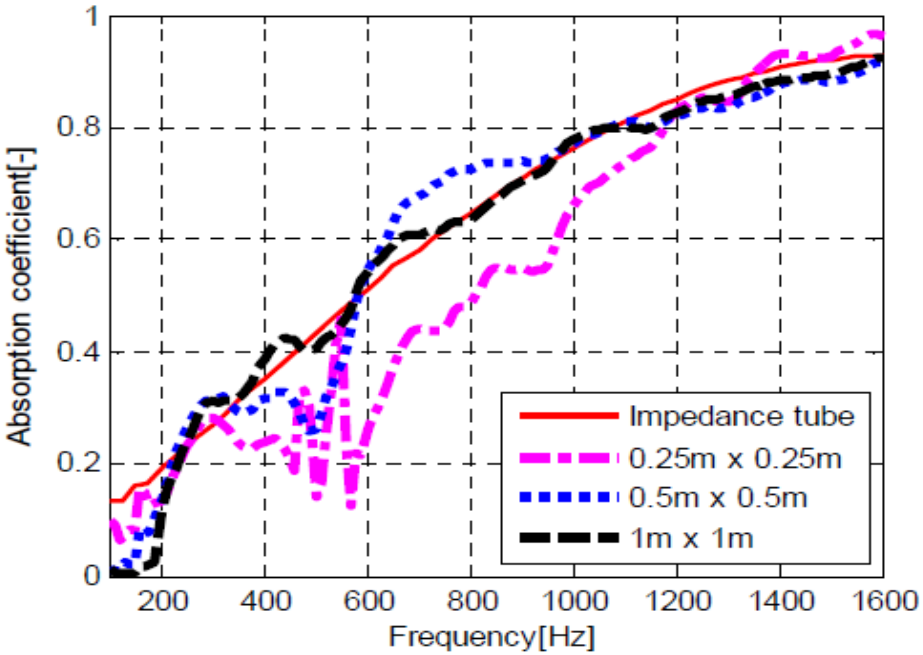
Numerical simulations : sample size effect

Consistent results with other works



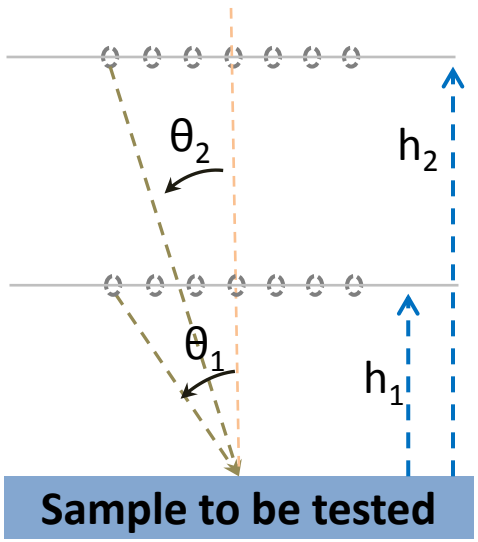
Simulation of the effect of specimen area on a glasswool (Hirosawa et al., JASA 2009)

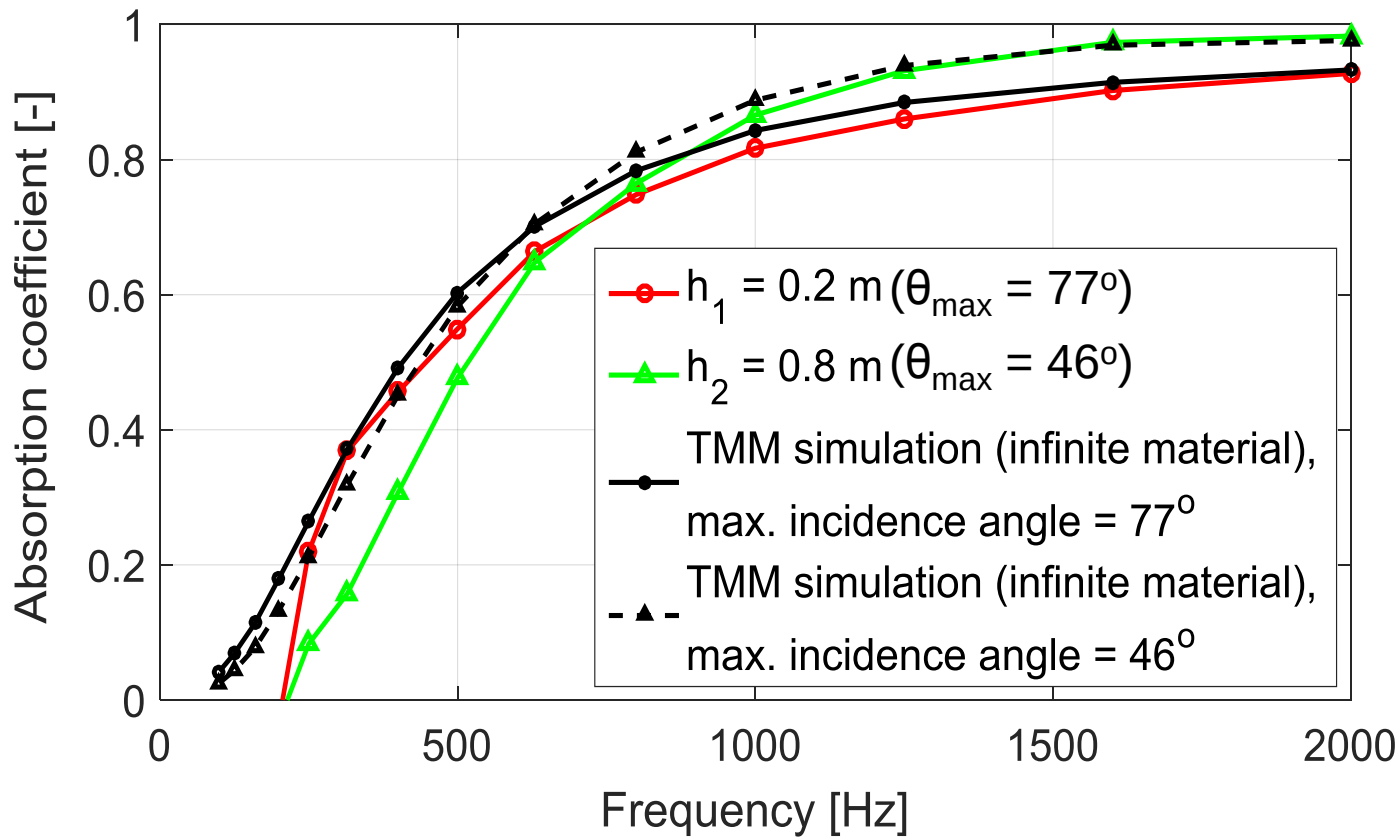
Measurement with a plane wave synthesis on a melamine foam (Yankai et al., ICSV 2016).



Numerical simulations : array height effect

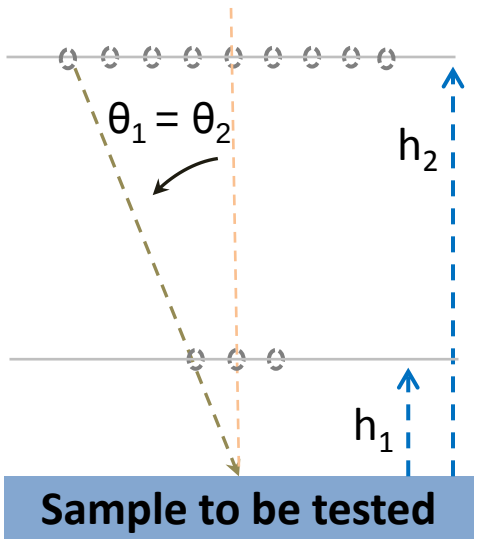
- For a fixed array size, its height is now increased
- Simulation results for a 2-inch thick melamine foam
- 9x9 source array, $h_2 > h_1$, $\theta_2 < \theta_1$

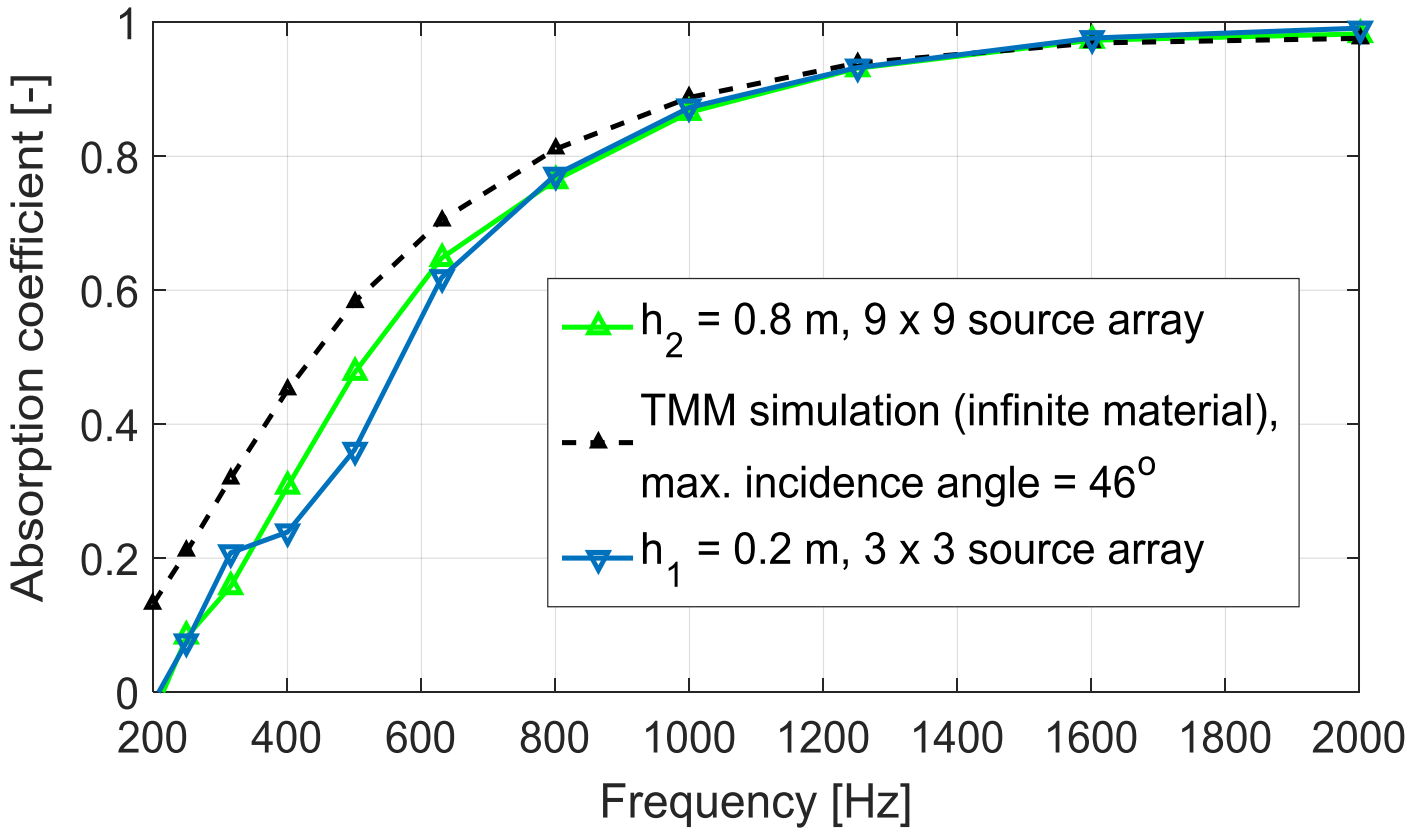




Numerical simulations : height/size effect

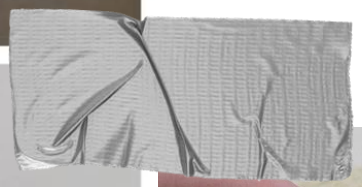
For a fixed array side length, increasing the array height has the same consequence as reducing the array side length for a fixed array height : the highest incidence angle included in the database becomes lower





Tested materials

Initially five…



But 6: Mineral wool was also tested

1: melamine foam

2: fiberglass

3: high-density fiberglass board

4: PU foam

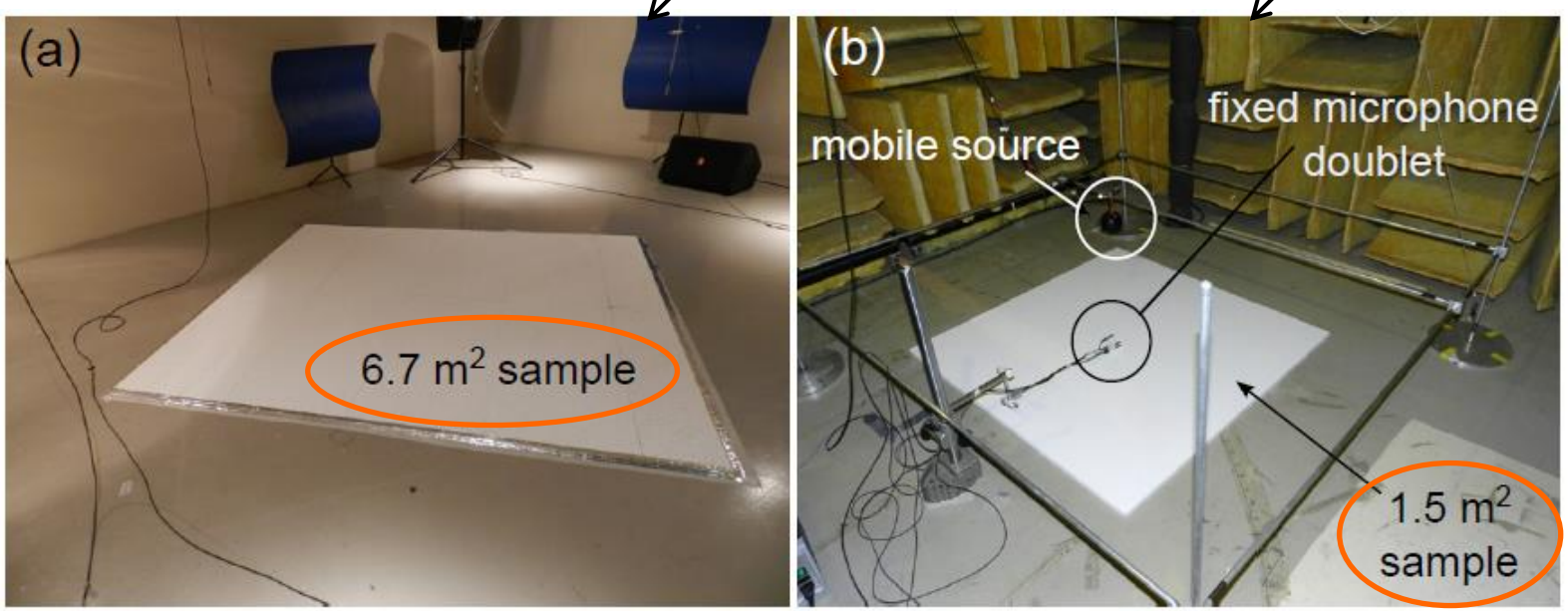
5: ceiling tiles

Tested materials

Materials were characterized at GAUS laboratory

Material	Tortuosity α_∞ [-]	Porosity ϕ [-]	Resistivity σ [$Nm^{-4}s$]	Viscous length Λ [μm]	Thermal length Λ' [μm]	Foam mass density ρ_1 [$kg.m^{-3}$]
Melamine foam	1	0.98	7920	132	149	6.1
Fiberglass	1	0.99	4860	225	388	10
HDFB	1	0.96	22200	57	115	66
PU foam	2.95	0.96	9770	123	227	29.8
Tiles	> 4	0.82	> 1e6	25	60	210

Measurements made using reverberant room and proposed method



Tested materials

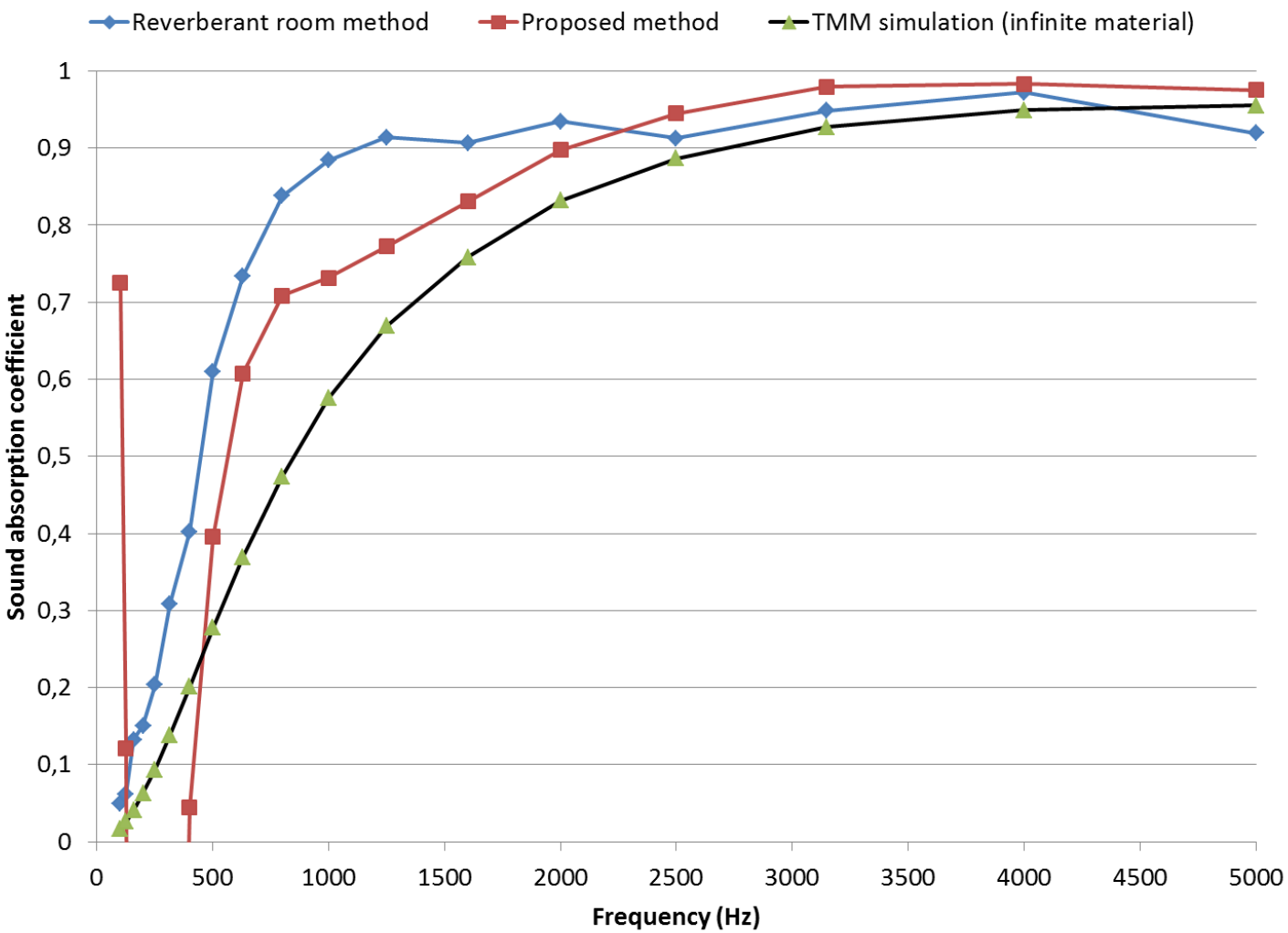
The final setup :

- A 7 x 7 virtual array, with sources spaced by 0.15 m in both directions
- A source translated at a height 0.2 m to include large incidence angles
- A microphone triplet, instead of a doublet, in order to cover the whole frequency range (a microphone spacing of 50 mm up to 3150 Hz [1 -> 3], and a microphone spacing of 25 mm above [1 -> 2])

- The microphone permutation technique is used to improve accuracy at low frequency (phase mismatch reduction)
- A swept sine signal is used to improve signal to noise ratio

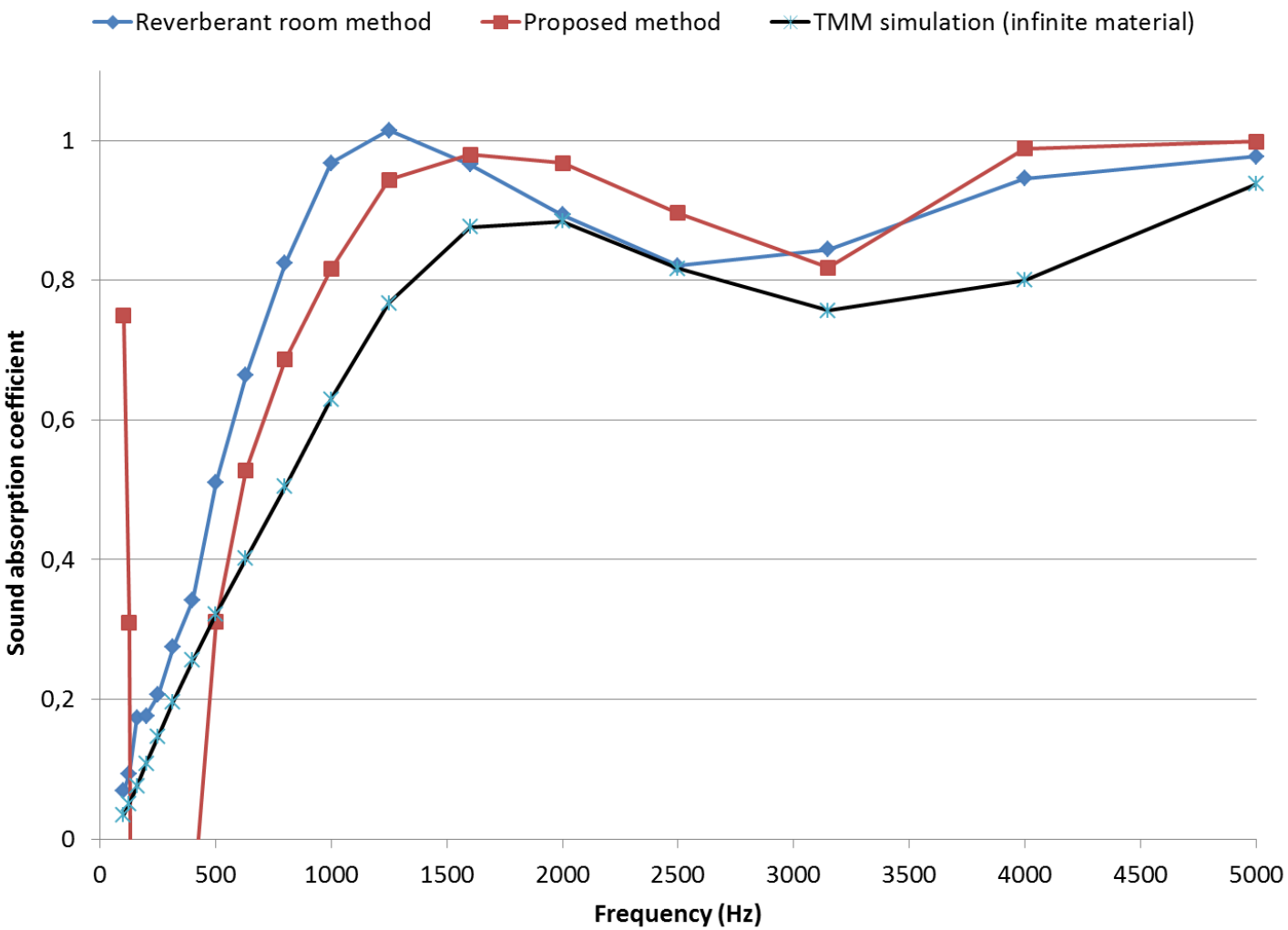
Laboratory measurements

Comparative results for the rigid fiberglass panel



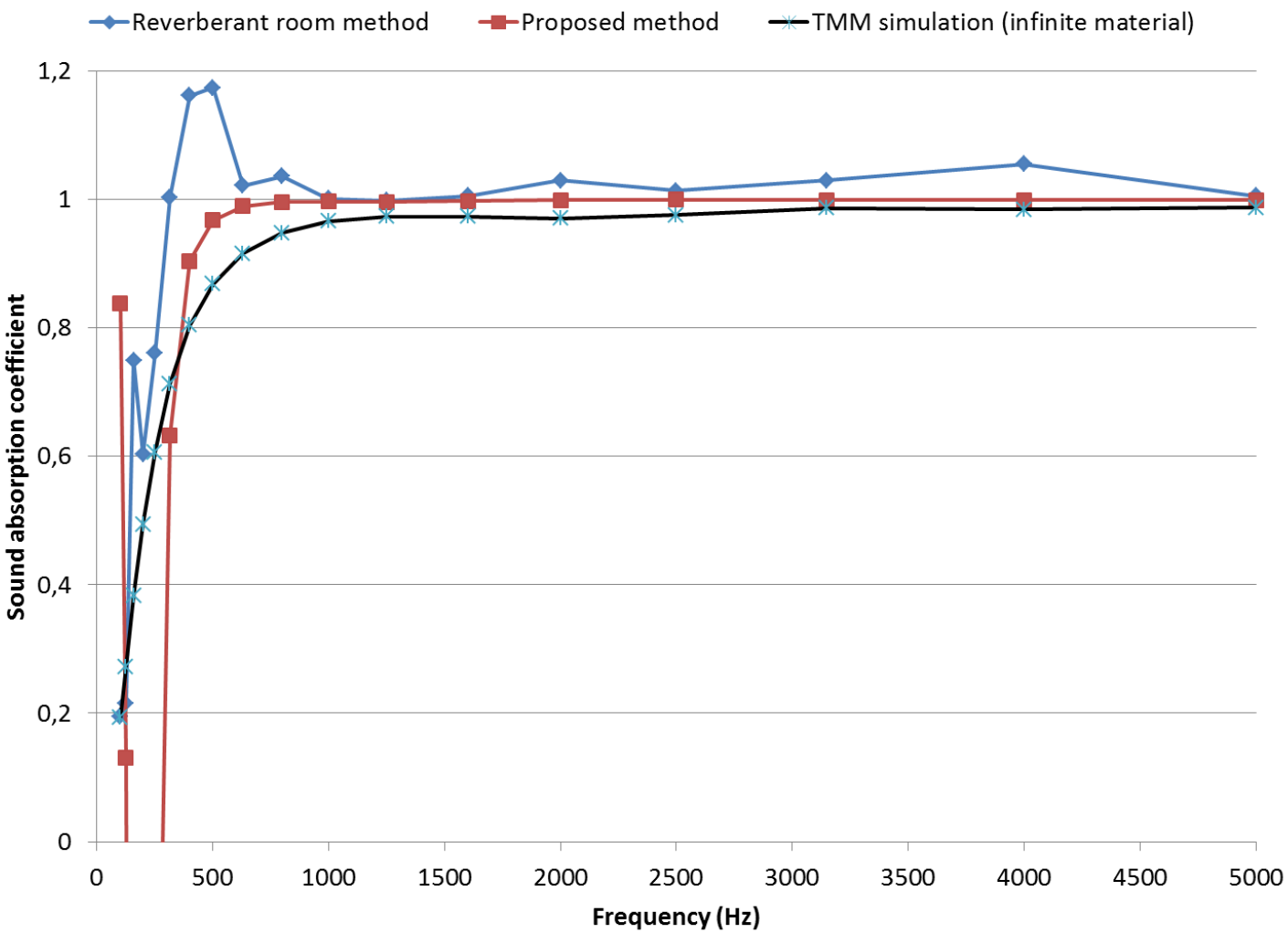
Laboratory measurements

Comparative results for the polyurethane foam



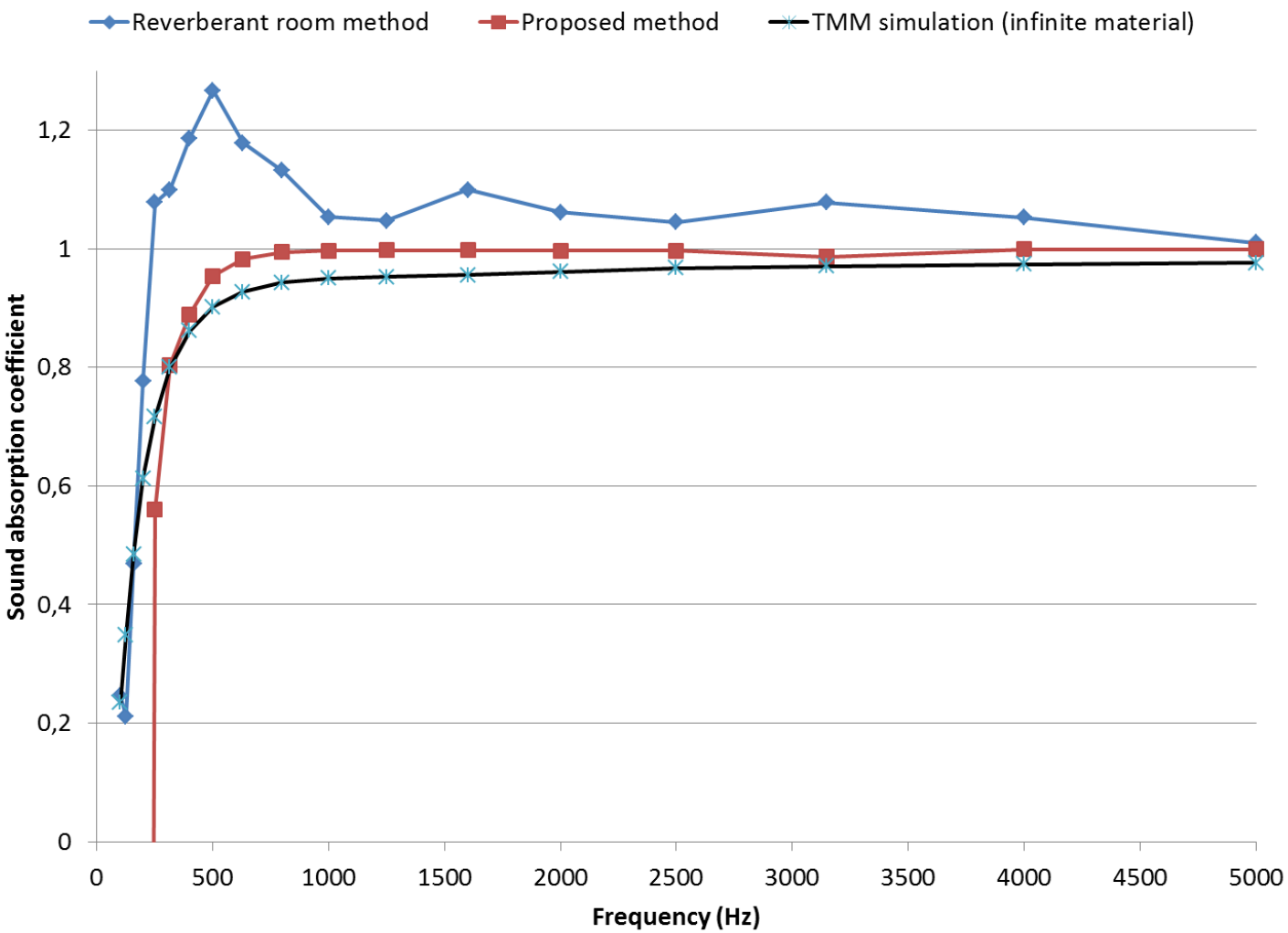
Laboratory measurements

Comparative results for the glass wool



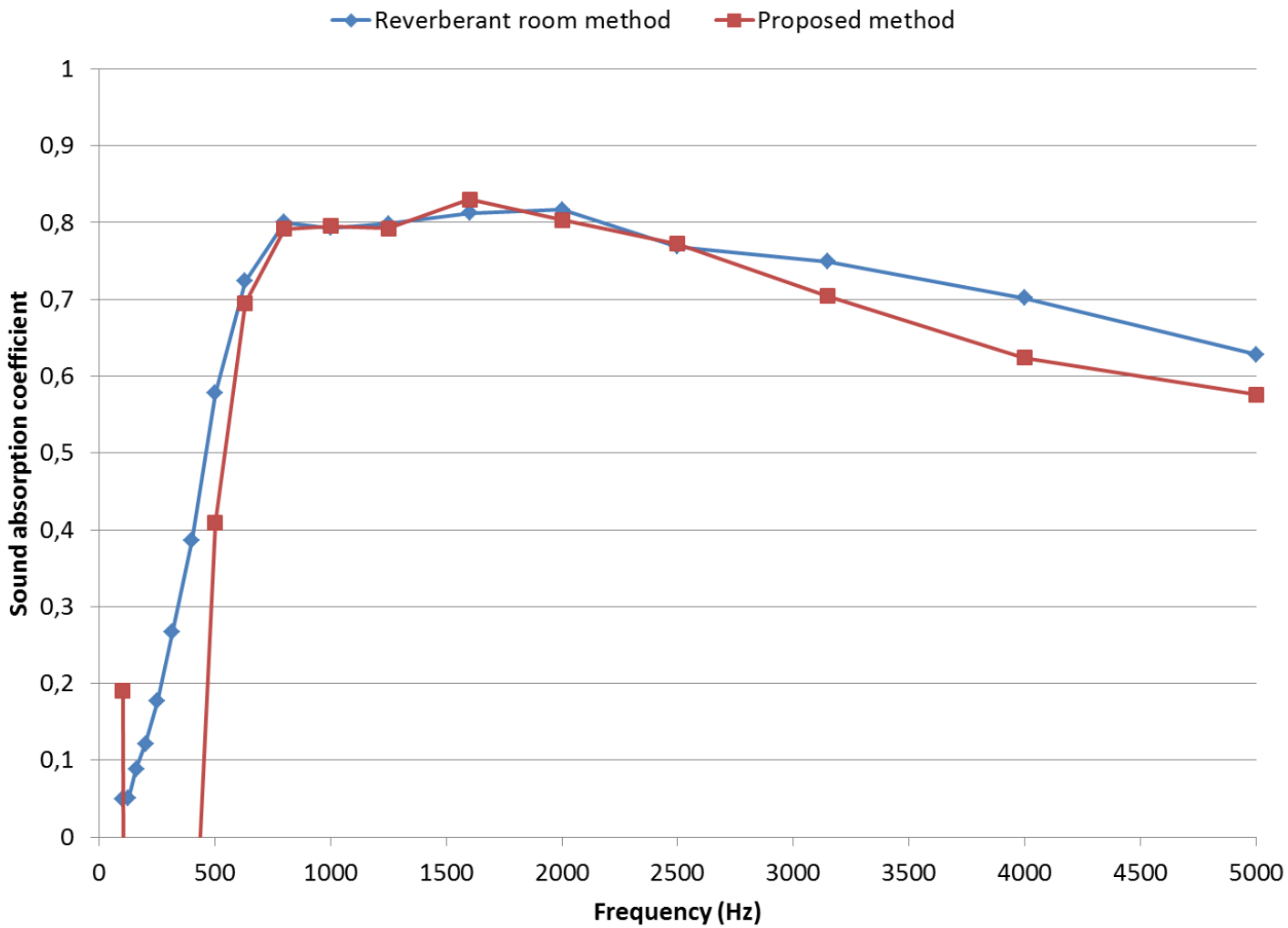
Laboratory measurements

Comparative results for the mineral wool



Laboratory measurements

Comparative results for the ceiling tiles



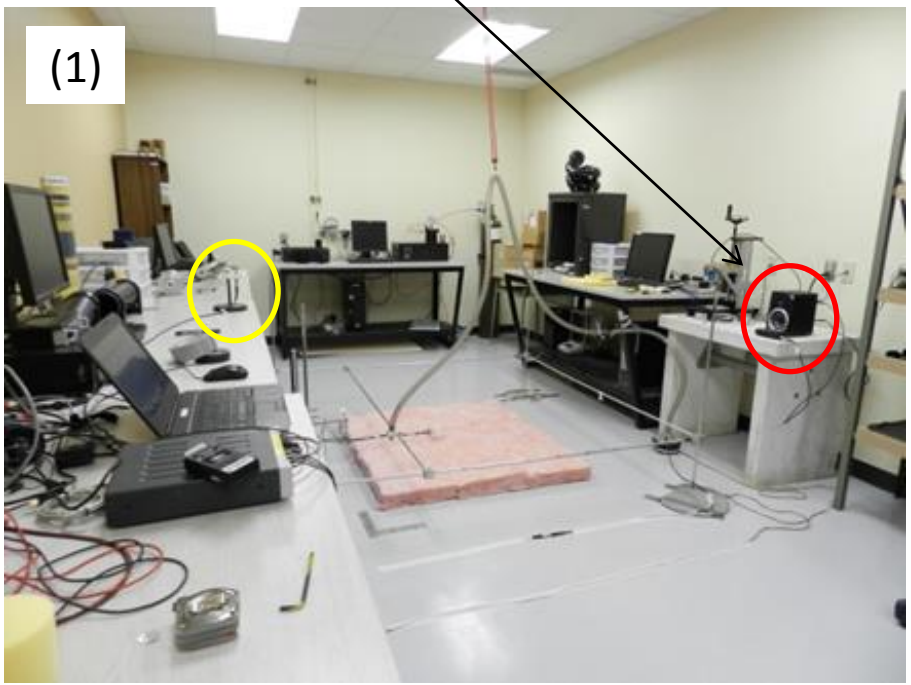
In situ measurements

Two out-of-laboratory spaces were considered (**tests were only made once**):

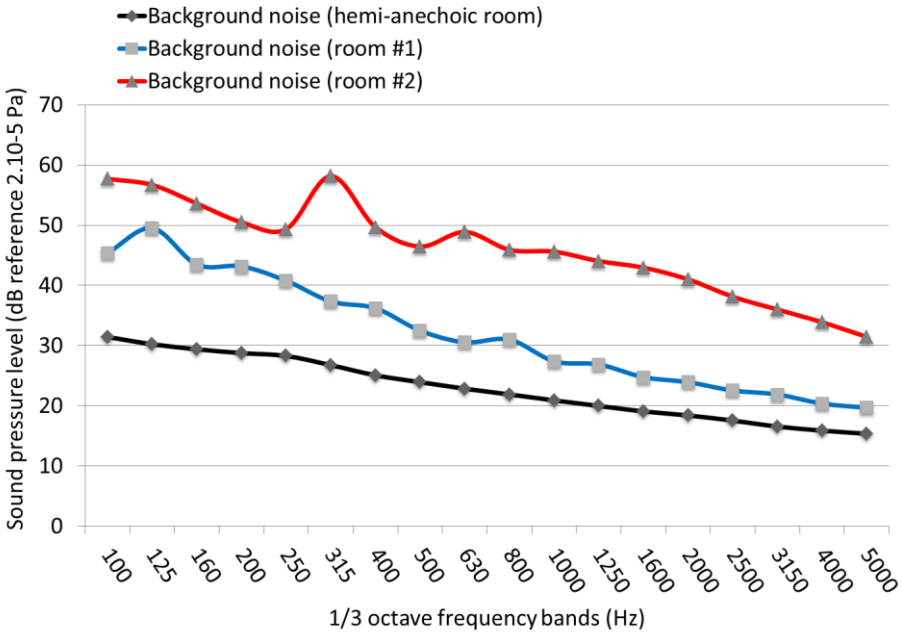
(1) a small workspace of 100 m^3 volume -> small reverberation time, many reflective surfaces close to the measurement zone

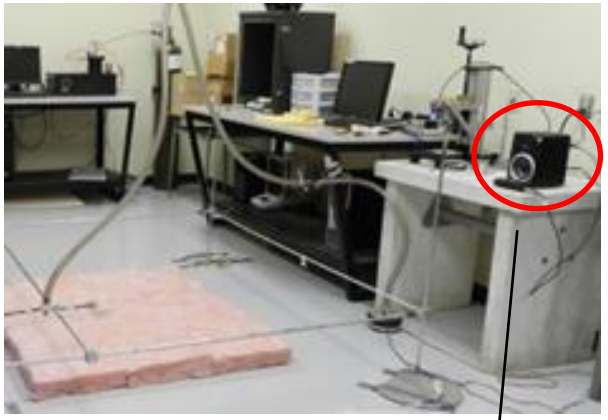
(2) a large fabrication shop of 3500 m^3 volume -> large reverberation time, reflective surfaces are away from measurement zone

Control microphone to monitor SPL, estimate reverberation time and an <u>additional perturbation sound source (for one material)</u>

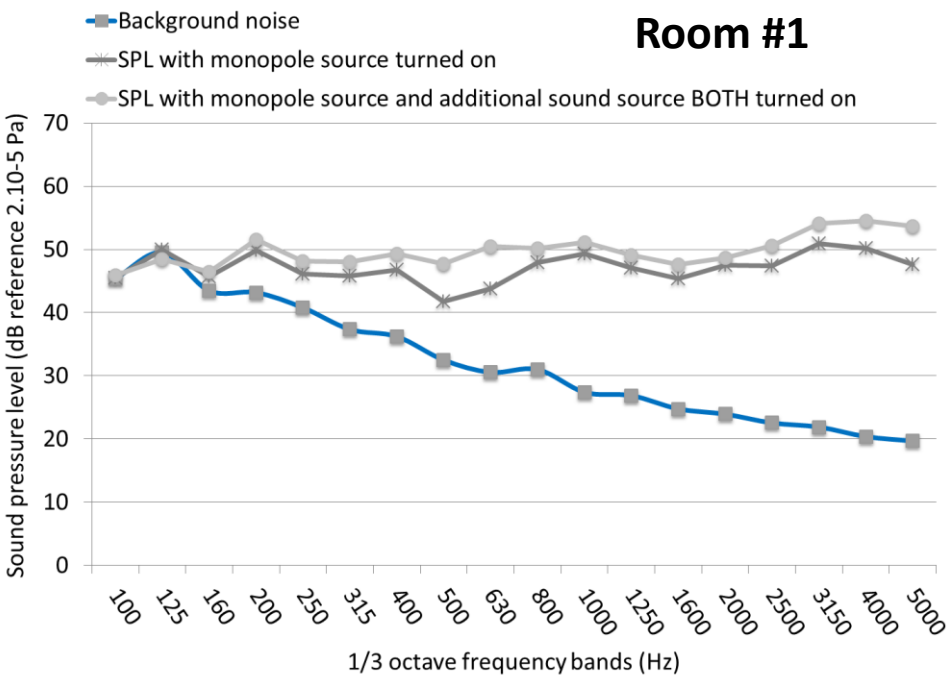


In situ measurements





Room #1

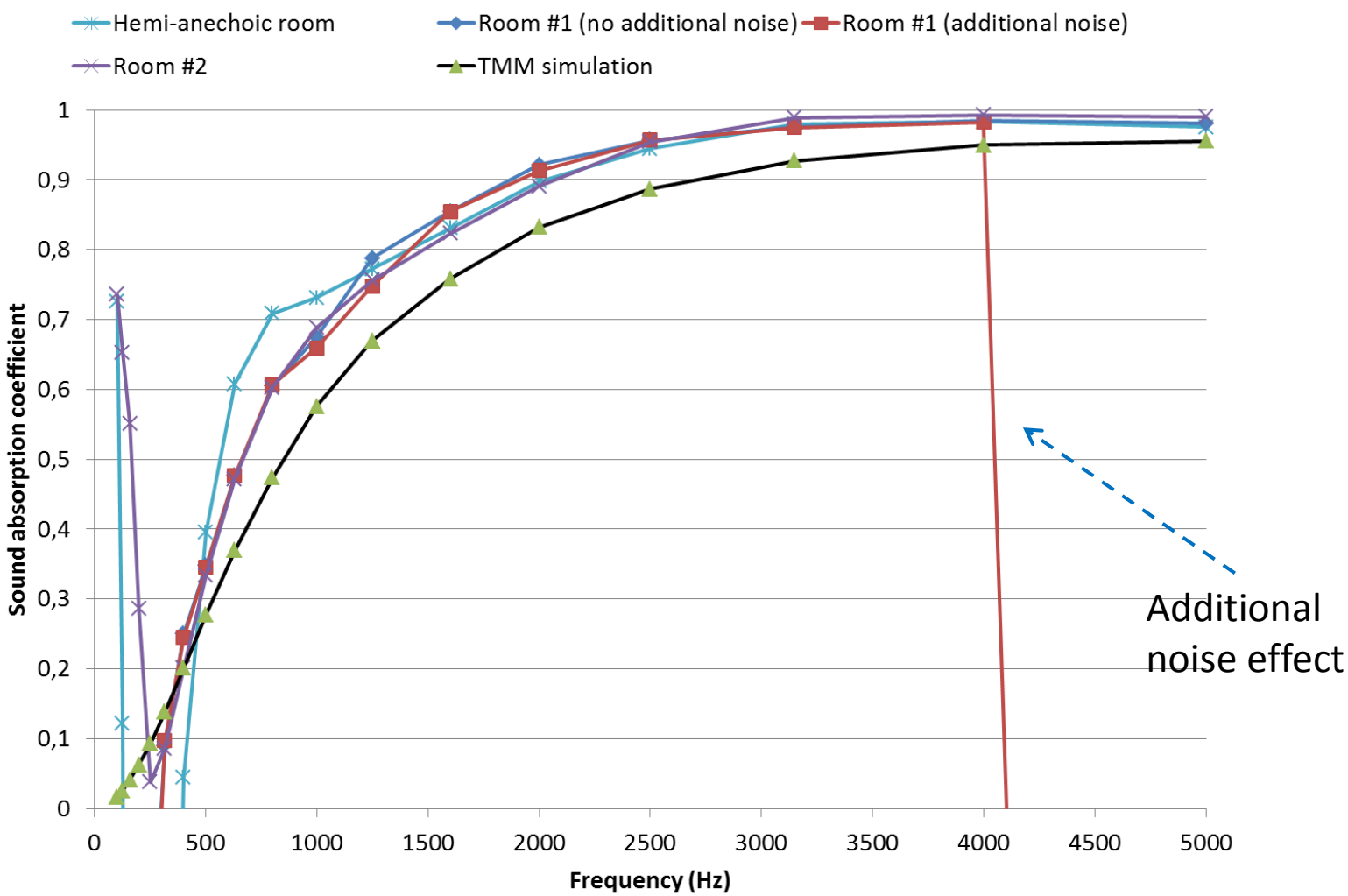


Measured reverberation times

1/3 octave band	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
Room #1	0,47 s	0,37 s	0,47 s	0,32 s	0,46 s	0,39 s
Room #2	-		1,1 s	1,29 s	0,83 s	0,66 s

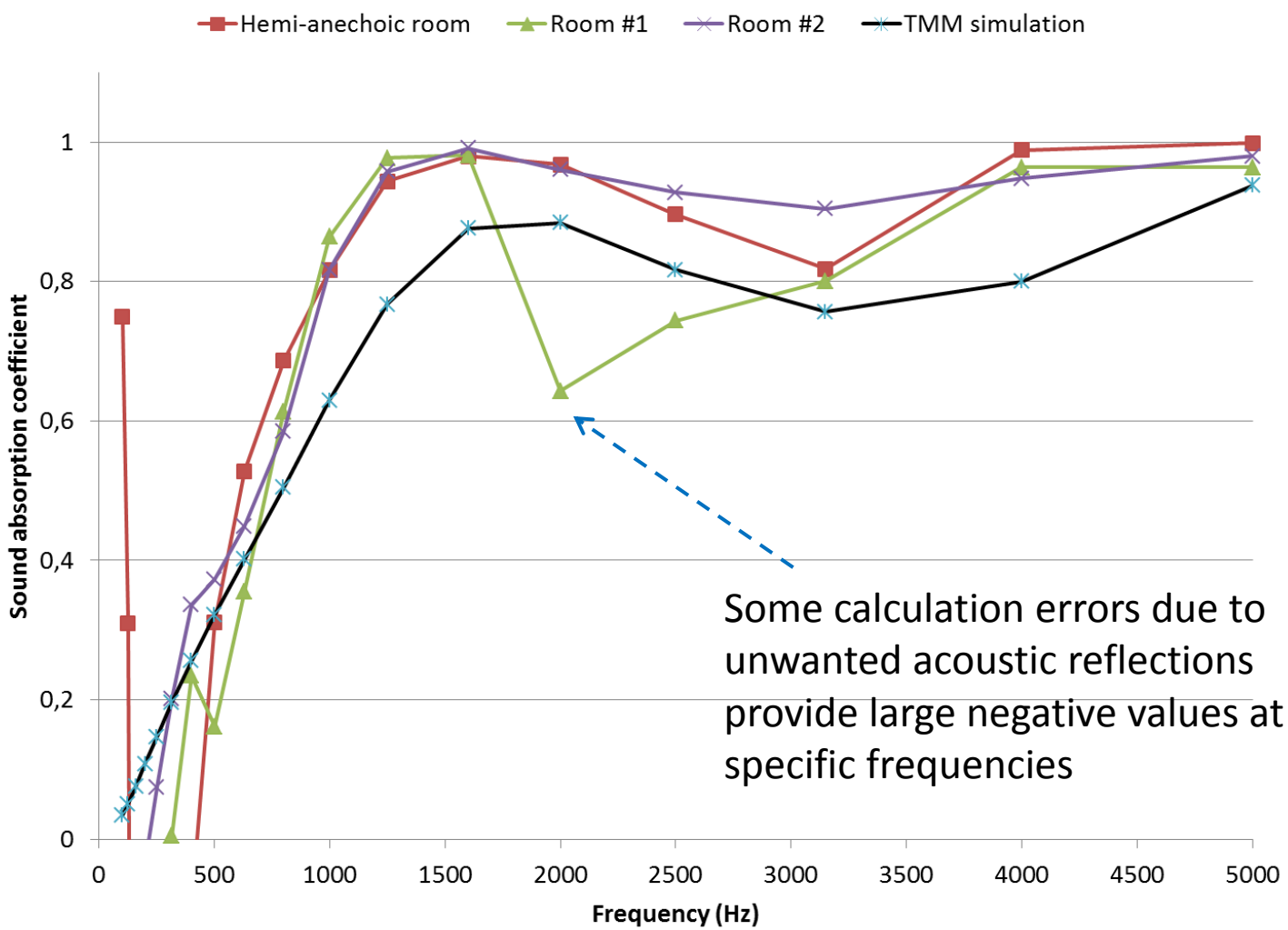
In situ measurements

Comparative results for the rigid fiberglass panel



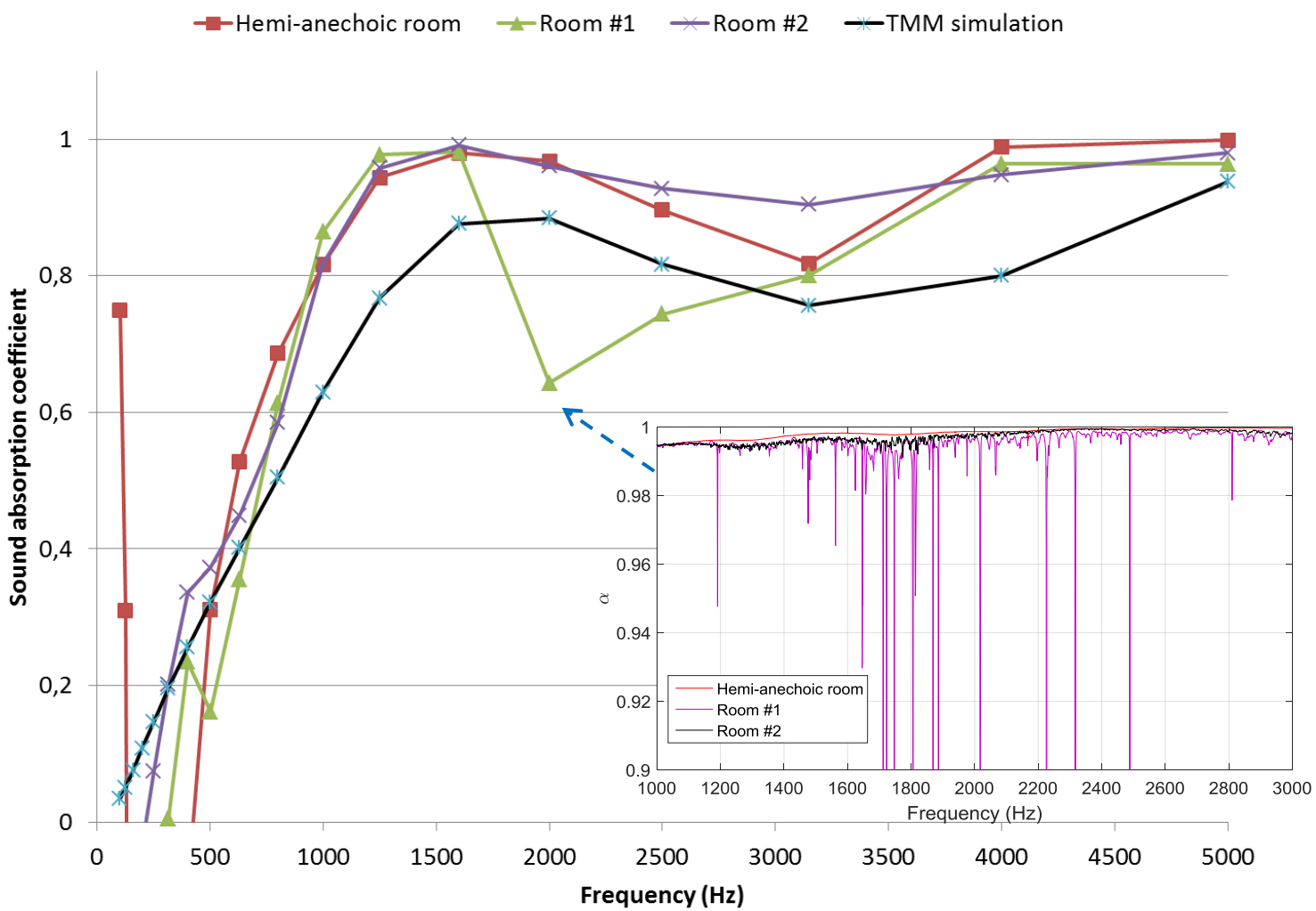
In situ measurements

Comparative results for the polyurethane foam



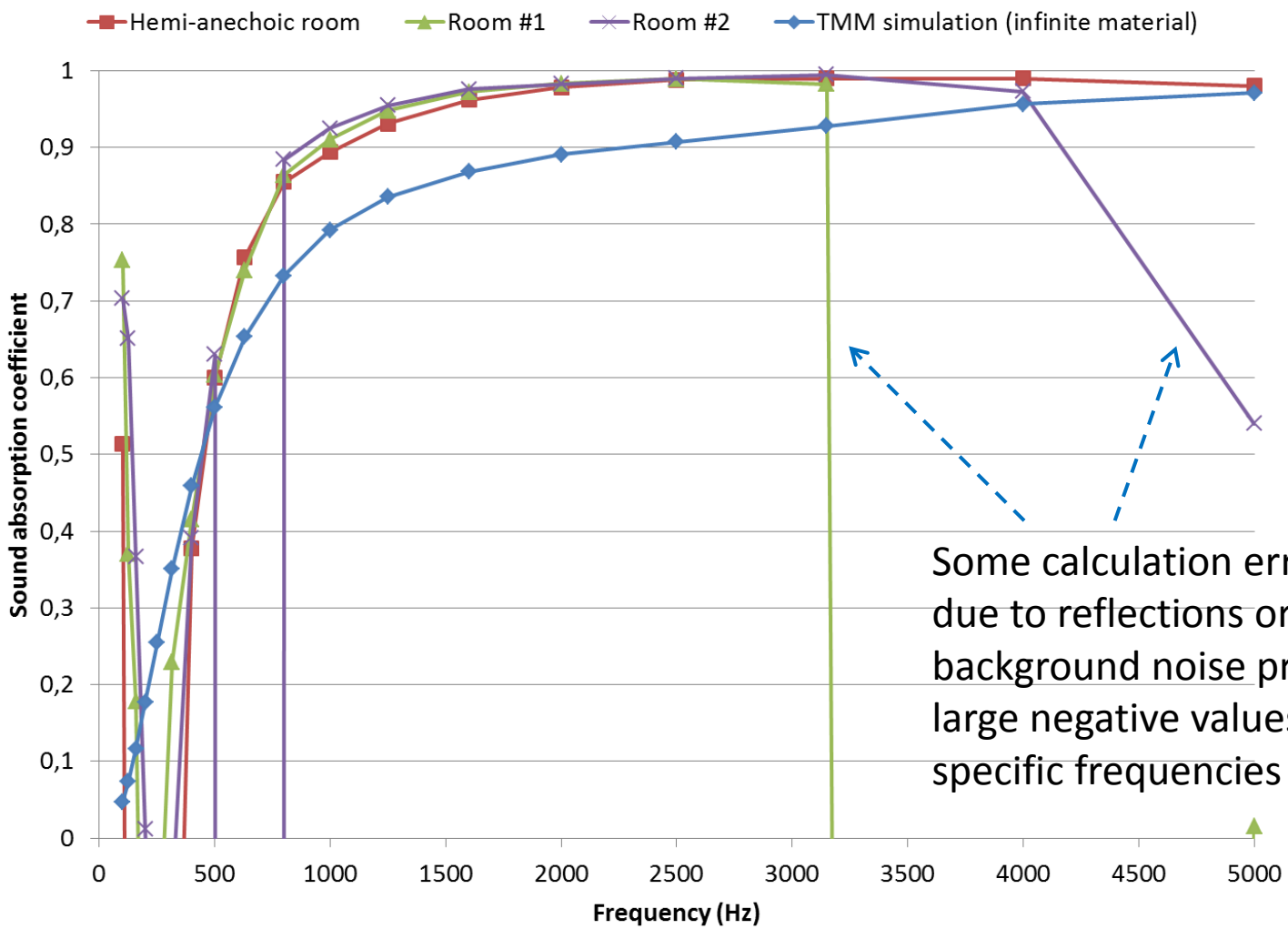
In situ measurements

Comparative results for the polyurethane foam



In situ measurements

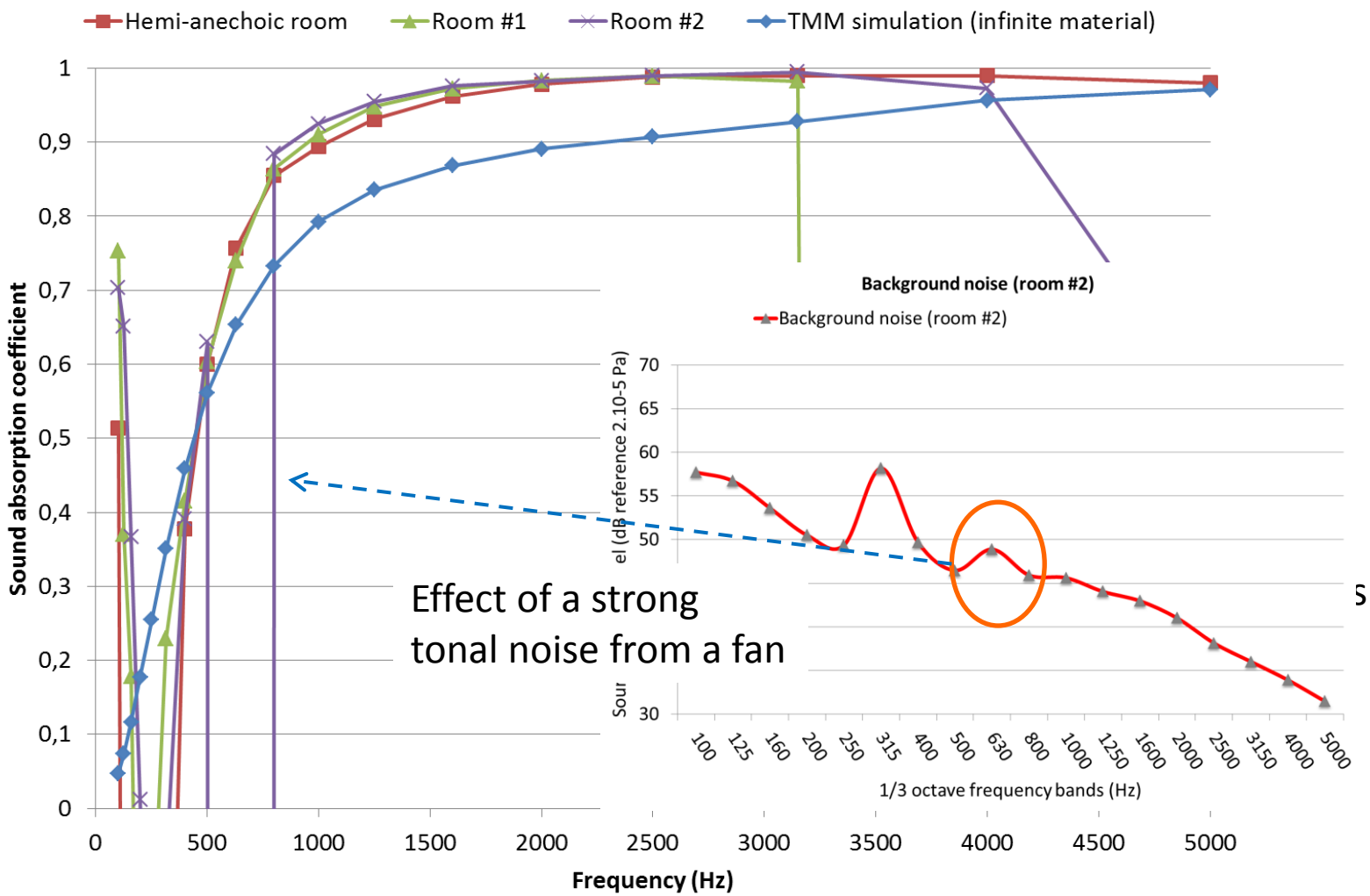
Comparative results for the melamine foam



Some calculation errors due to reflections or large background noise provide large negative values at specific frequencies

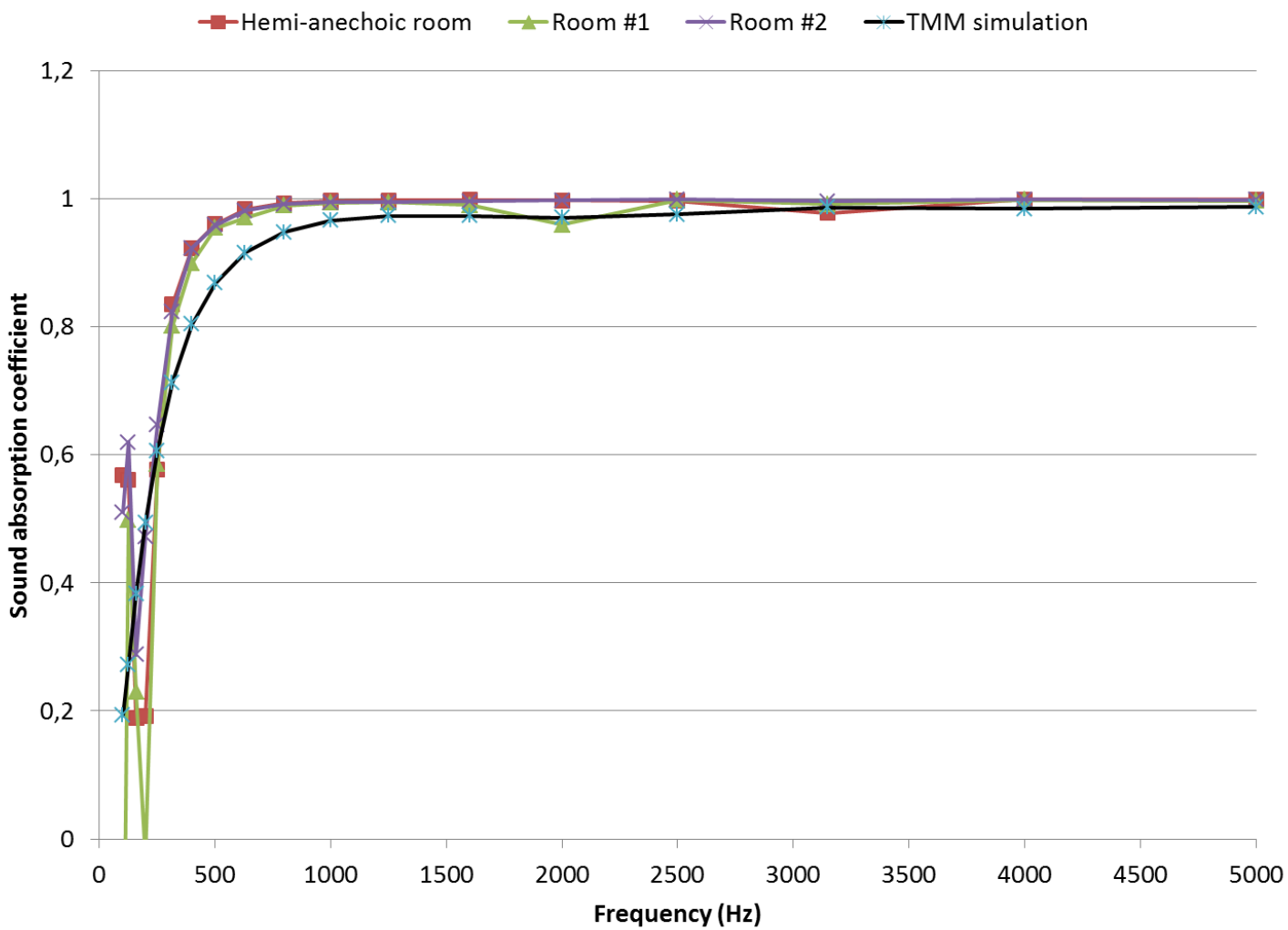
In situ measurements

Comparative results for the melamine foam



In situ measurements

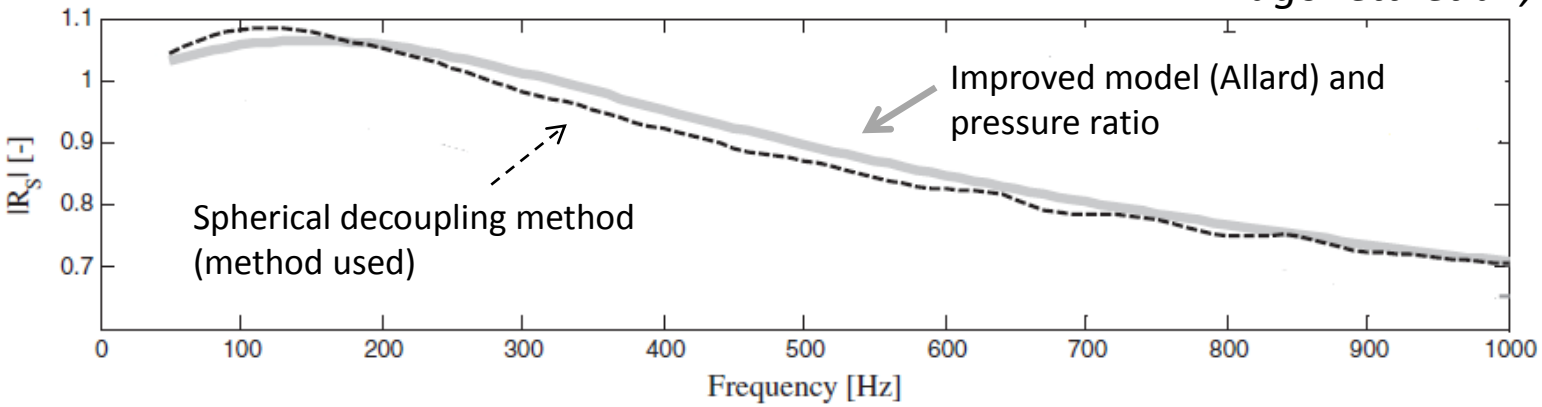
Comparative results for the glass wool



Improvement of the method ?

The simplified sound propagation model is the main source of discrepancies at low frequency, at low frequency and for small source heights -> provide values of |R| > 1 then $\alpha < 0$

Dragonetti et al., Applied Ac. 2015

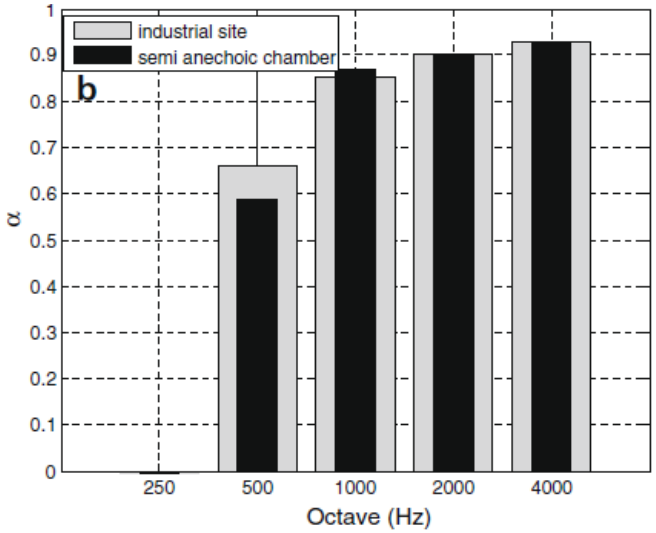


h = 0.75 m
θ = 40°

Such a low frequency limitis also met in other in situ works

Ducourneau et al., Applied Ac. 2009

Directional 13 microphone array

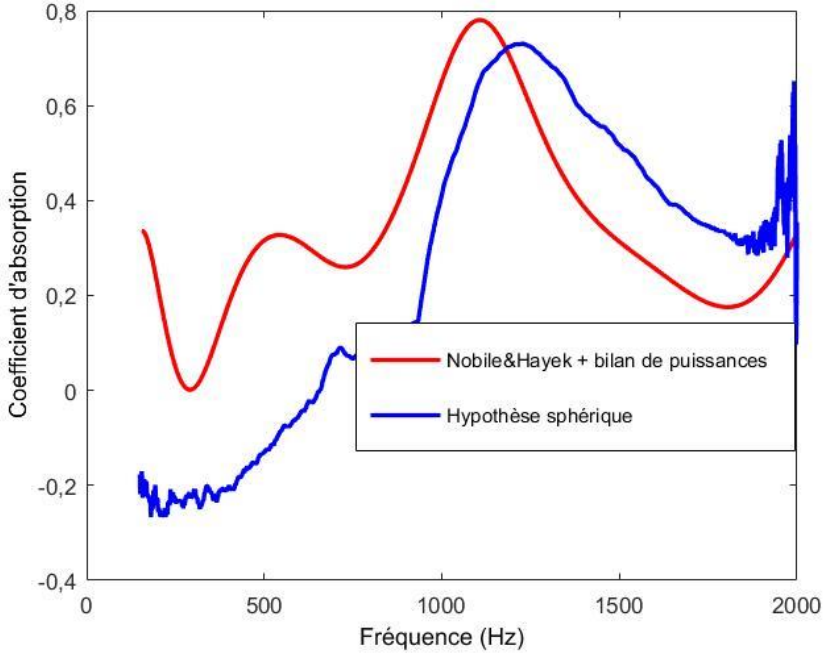


Improvement of the method ?

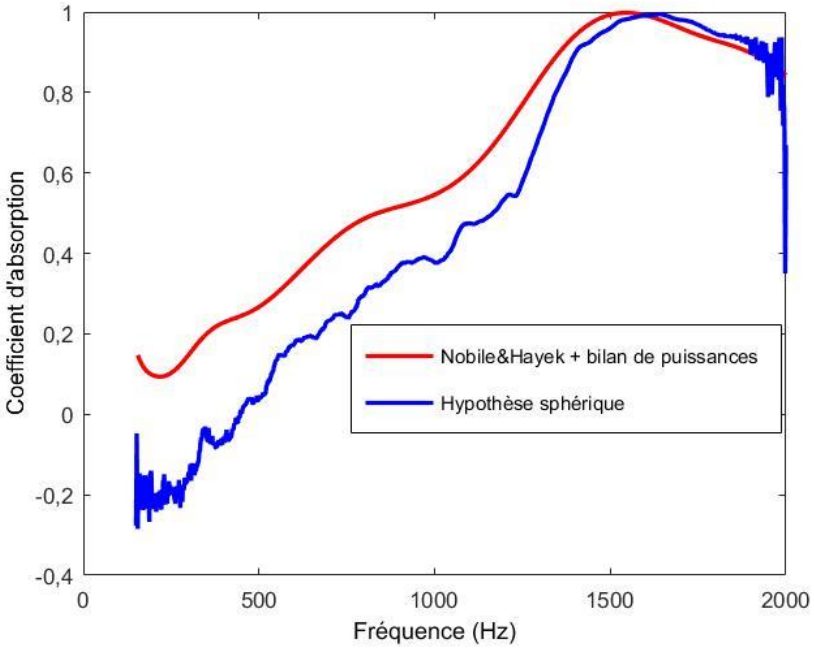
- The **Nobile-Hayek model** is used with an estimation of the reflection coefficient following **an acoustic power balance**, and compared with the classical spherical wave hypothesis and a sound pressure ratio
- Measurements were post-processed for two point source positions :

  1 = (0 cm, 0 cm); 2 = (15 cm, 15 cm)

Rigid fiberglass panel



Position 1

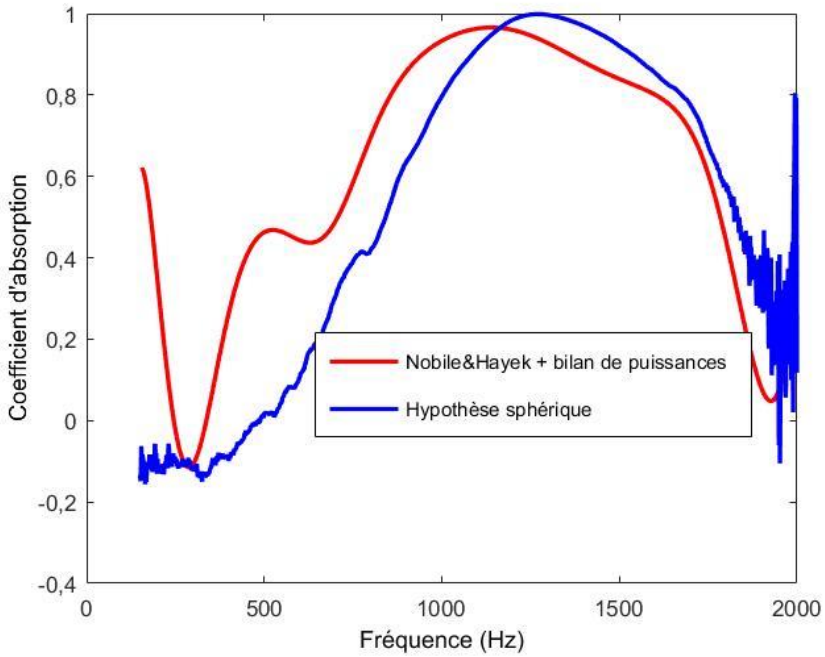


Position 2

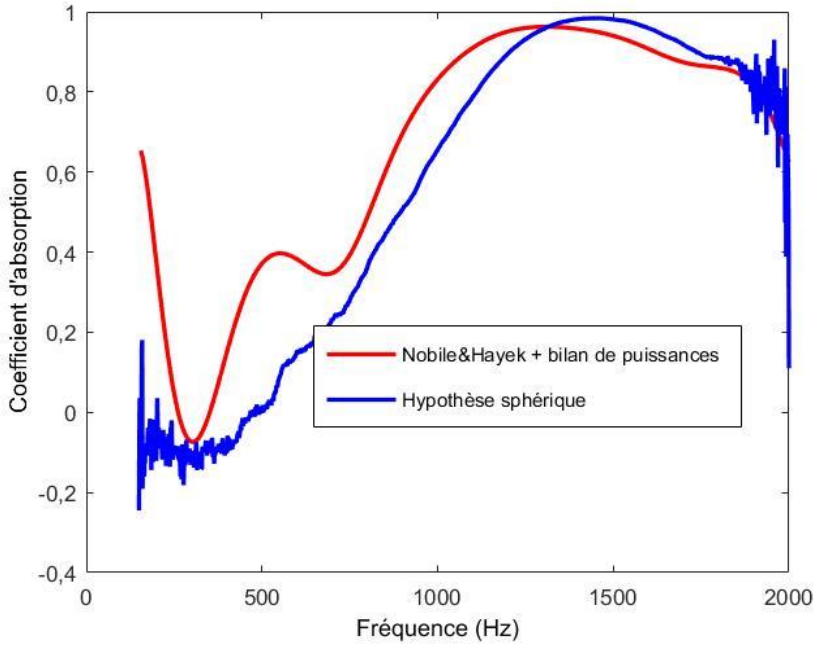
Improvement of the method ?

- The Nobile-Hayek model is used with an estimation of the reflection coefficient following an acoustic power balance, and compared with the classical spherical wave hypothesis and a sound pressure ratio
- Measurements were post-processed for two point source positions : 1 = (0 cm, 0 cm); 2 = (15 cm, 15 cm)

Polyurethane foam



Position 1



Position 2

Conclusion

- A method for the estimation of the absorption coefficient of an absorbing material under a synthesized DAF excitation in free-field conditions was presented

- Concerning laboratory measurements : the method allows testing smaller samples than with the standard method, and always provides physical values ($\alpha \leq 1$) – no specific preparation of samples is needed

- Concerning *in situ* measurements : the great majority of the obtained results are in line with those measured in lab conditions – the presence of close reflective surfaces is more crucial than an important background noise level

- Perspectives :
  1. Improving the post-processing step to solve the low-frequency issue
  2. Adding automatic source and microphone translation systems to improve accuracy, repeatability and reduce measurement time

- Thank you for your attention
- Questions ?
- Funding from IRSST is greatly acknowledged
- Enjoy SAPEM 2017

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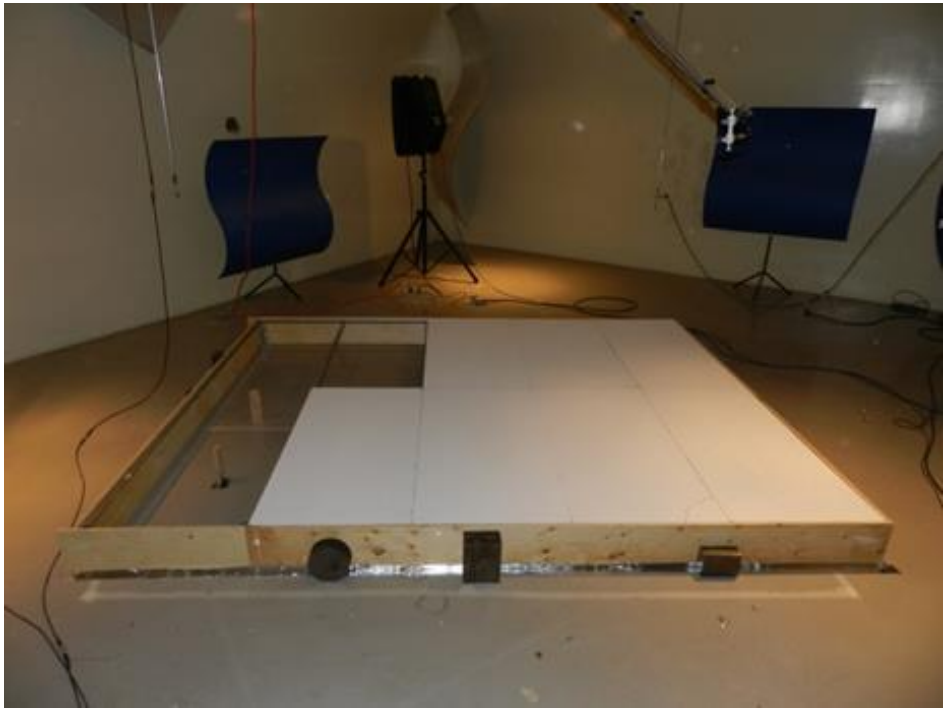
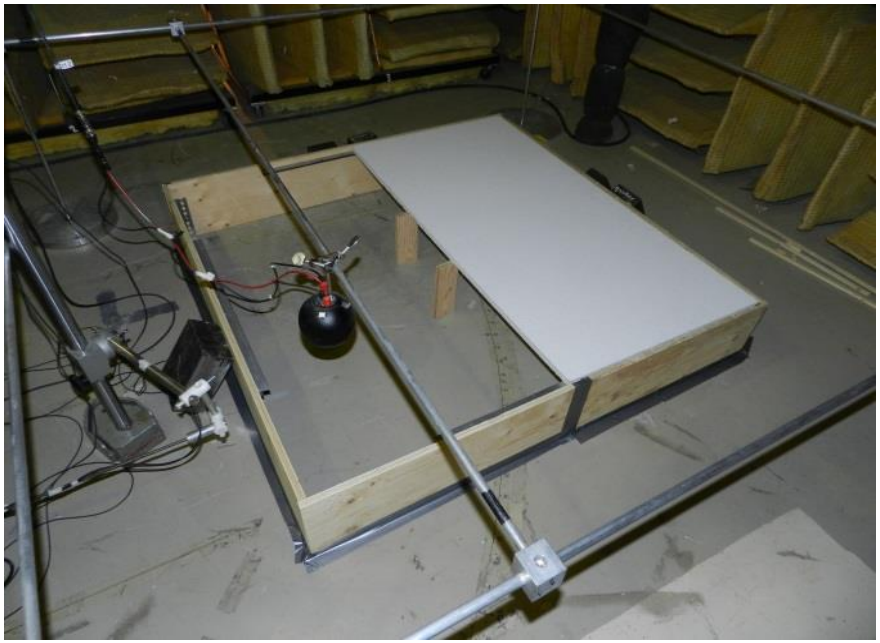
Laboratory measurements

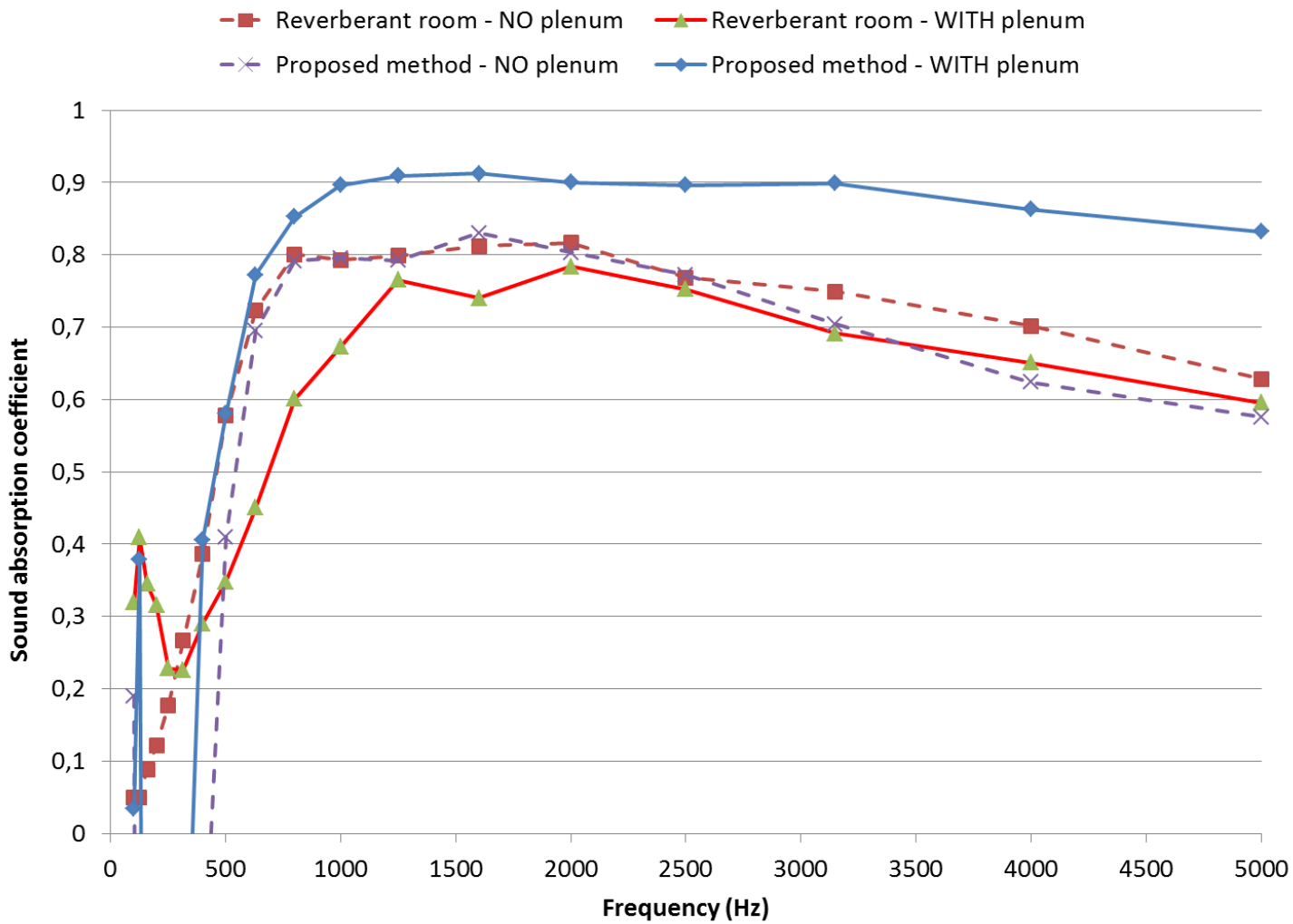
Case of ceiling tiles with and without plenum





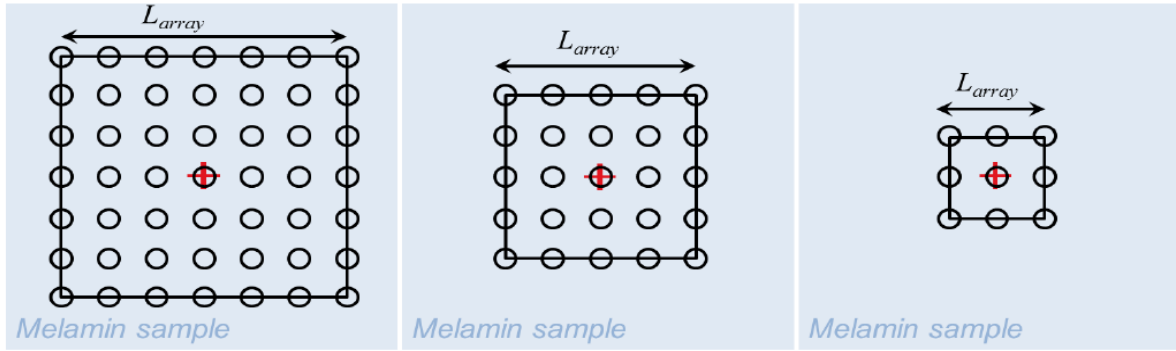
Laboratory measurements

Comparative results for the ceiling tiles with and without plenum



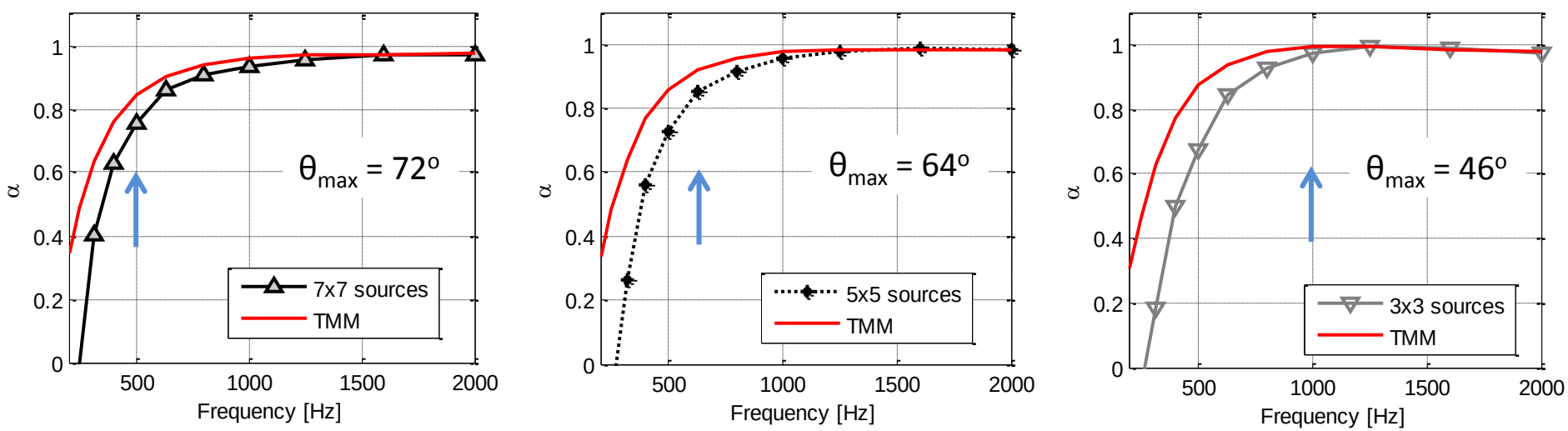
Numerical simulations : array size effect

- Array size is reduced at post-processing with fixed height, which reduces the highest incidence angle θ_{max}



(a) Original 7x7 mesh (b) 5x5 mesh (c) 3x3 mesh

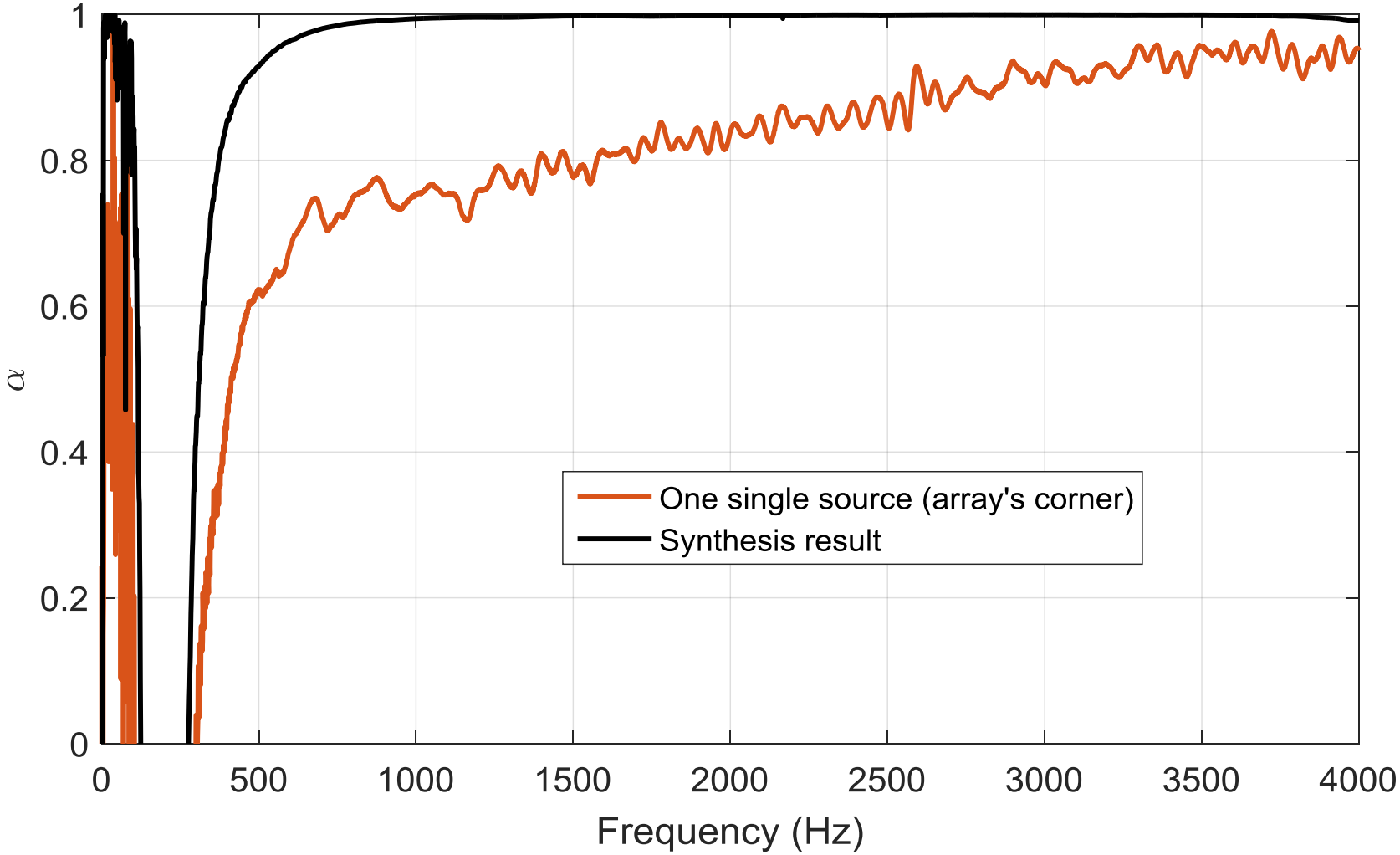
- Satisfactory agreement between results and simulations above the 1/3 octave band that nearly corresponds to the lowest frequency that could be reproduced (≈ c_0/L_{array}, see ↑)



Using a database including the highest incidence angle, the absorption coefficient under a DAF excitation with other incidence angles can be then computed

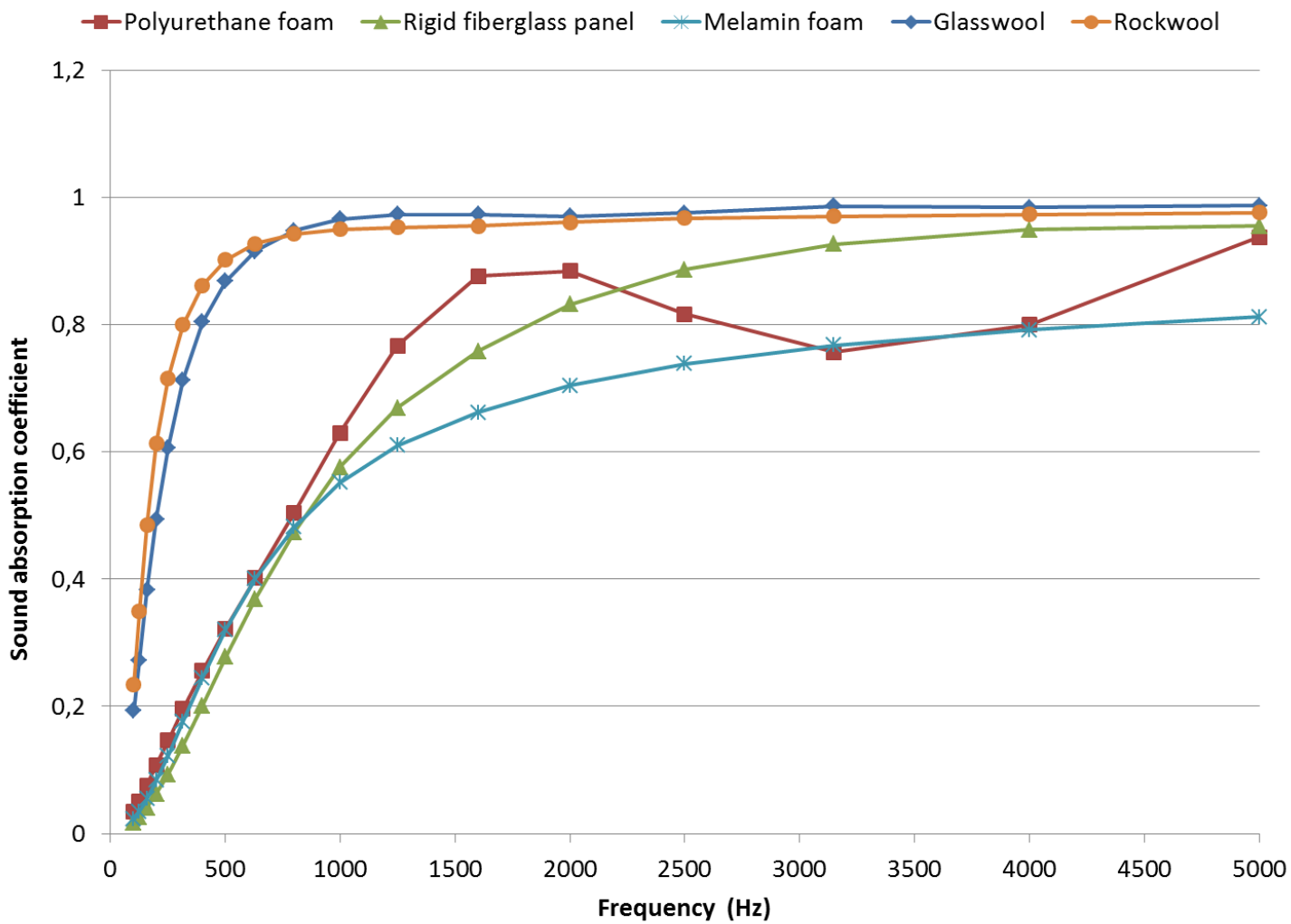
Au cas où....

- Is the synthesis effective ?



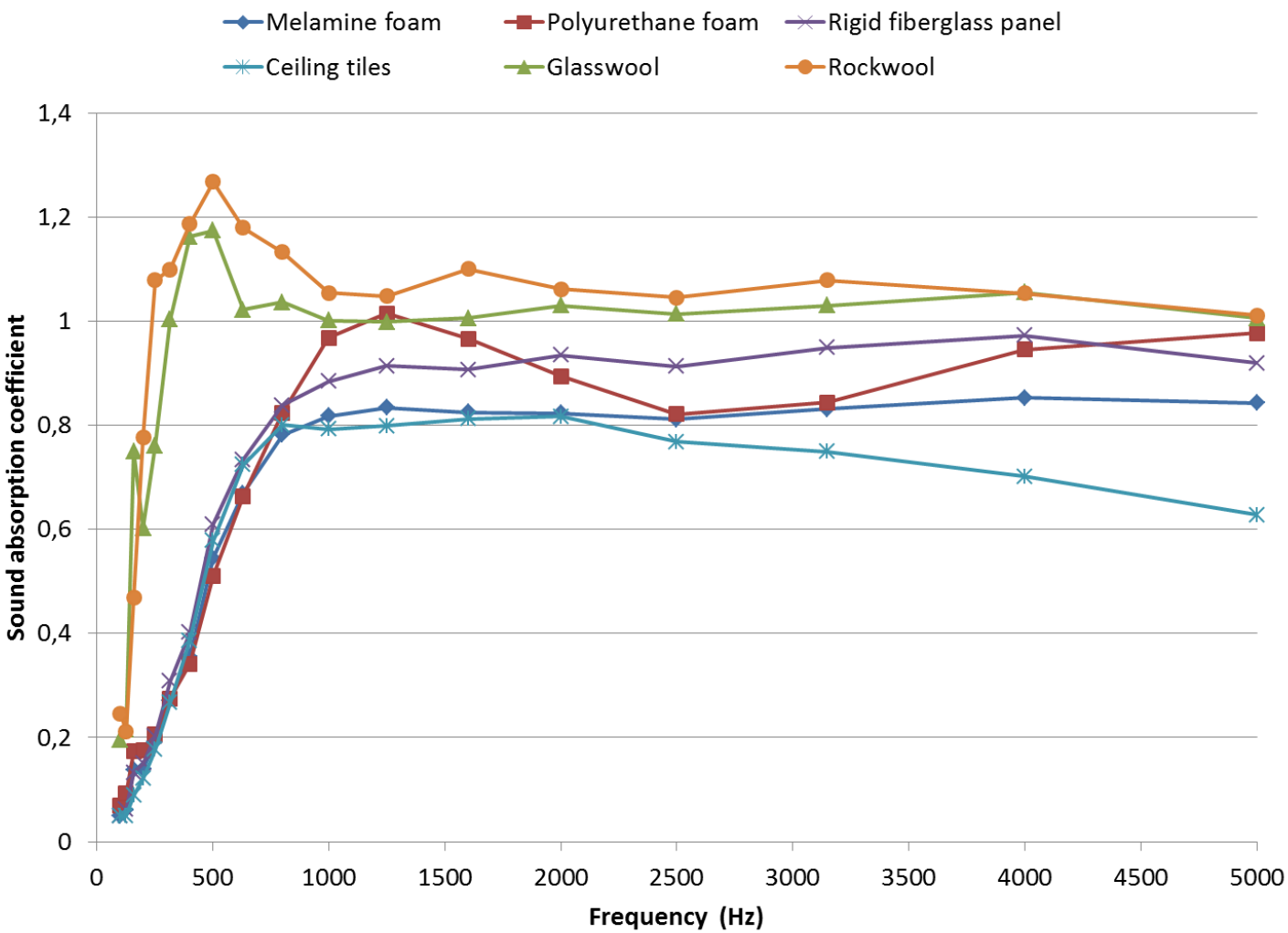
Tested materials

Simulation results following Transfer Matrix Method (infinite material)



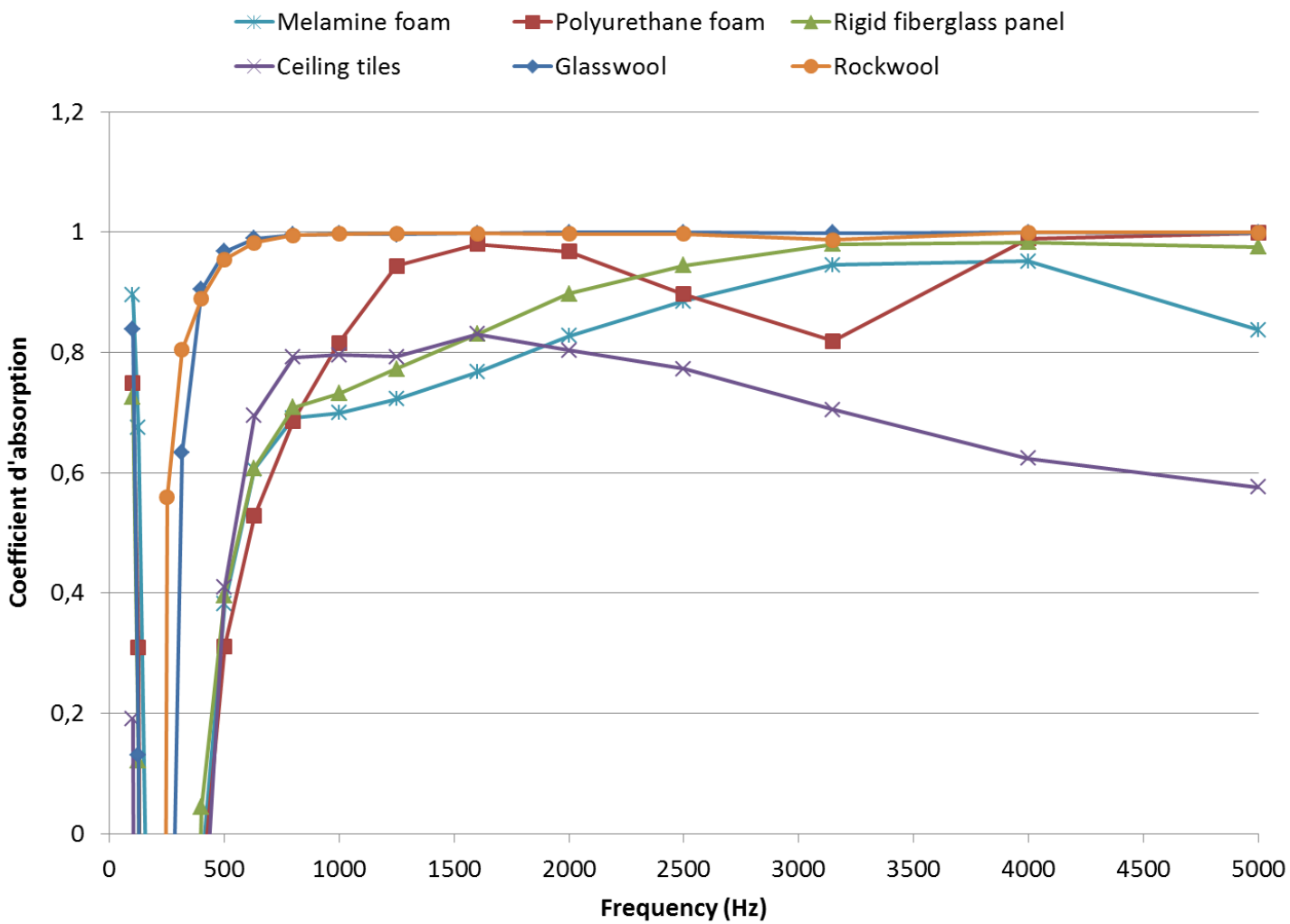
Laboratory measurements

Measurements in reverberant room results (following ASTM C423), samples of minimum 6.7 m² area (72 sq ft)



Laboratory measurements

Measurements in anechoic room following the proposed method, using samples of 1.4 – 1.7 m²



Numerical simulations : height/size effect

- **For a fixed array side length, increasing the array height has the same consequence as reducing the array side length for a fixed array height : the highest incidence angle included in the database becomes lower**