A new scattering method that combines Roughness and Diffraction effects

Claus Lynge Christensen
ODEON A/S
Jens Holger Rindel
Ørsted-DTU, Acoustic Technology

Agenda

- Scattering coefficients in current prediction programs
- Examples on scattering coefficients used in current prediction programs
- Summary, the current calculation method in Odeon
- The Reflection Based Scattering coefficient
- Oblique Lambert
- A short case study – Elmia hall 2nd Int. Round Robin on Room Acou. Simul.
- Another case – An antique Byzantine church
- Conclusions

Scattering needed for reliable results

It is commonly accepted
that scattering must be handled by room acoustic programs

1995
In 1st International Round Robin on Room Acoustical Computer Simulations:
Only programs which include scattered reflections provides reliable predictions

Today
most room acoustics programs do include scattering

Combined Scattering
coefficients applied to each surface, accounts for:

- Surface roughness at high frequencies (structure of surface)
- Diffraction at low frequencies (size of surface)
- Edge diffraction for reflections close to surface edges

Y.W.LAM 1993
0.1 for large/smooth surfaces, 0.7 for audience area (includes roughness and diffraction)

Problems with combined scattering coefficient

User must make guesswork
Surfaces with same material must be assigned different scattering properties *depending* on their area

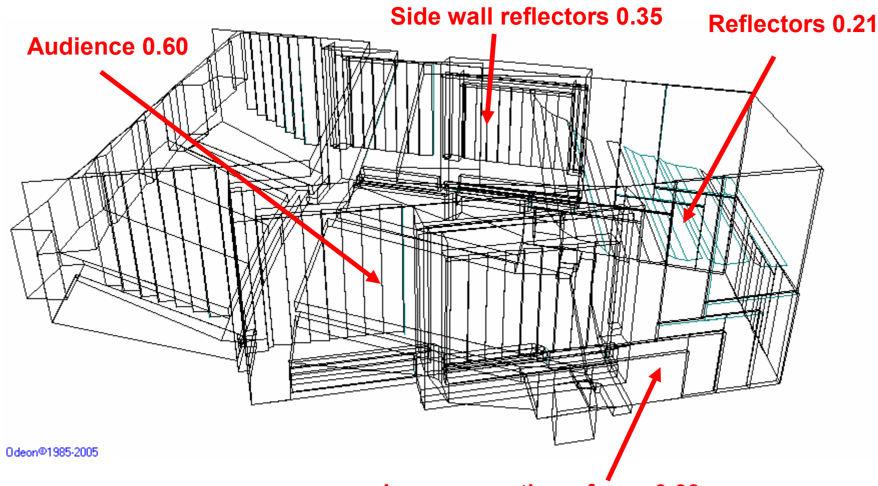
Not compatible with ISO/DIS-17497-1
The numbers provided by an ISO/DIS-17497-1 measurement describes the roughness of the surface material

Diffraction is not known before calculation, depends on

- Source and receiver position – small surface close to receiver provides no scattering
- Angles of incidence, surface hit at oblique angles give rise to higher scattering – looks small
- Etc. etc…..

Example on combined scattering coefficients at 1000 Hz

(data taken from the Elmia hall, Round Robin II)



Elmia, continued

Even so…..

Most surfaces are essentially *very* smooth, except the audience area

Scattering coefficients measured according to ISO-17497-1 might be 3, 4 or 5 % at 1000 Hz

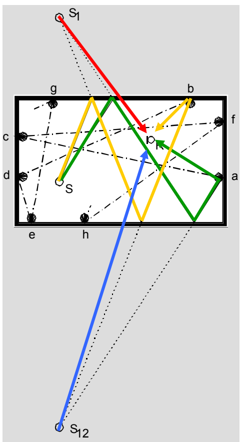
Would be nice if….

We could use the same frequency depending scattering coefficient
For all surfaces which looks smooth

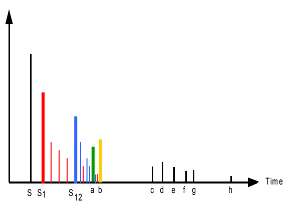
Only special cases would be

- Audience area
- Surfaces where details were not included in the model, e.g. coffered ceiling

Summary of the ODEON method

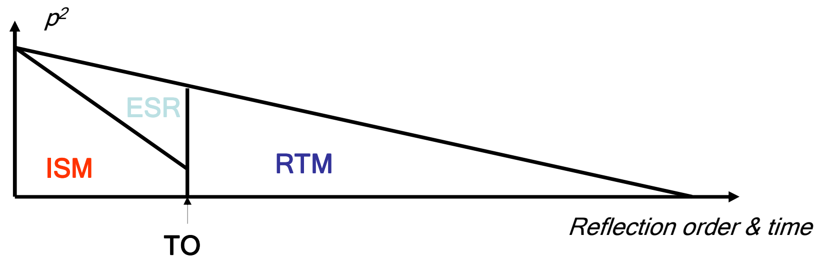


- Image sources + Area radiation /Ray-radiosity
- Ray-radiosity for late reflections



Summary of the ODEON method

Reflection algorithms



The calculation method is of type Hybrid-Hybrid allowing fast yet reliable results

TO Transition Order from early to late method

ISM Image Source Method

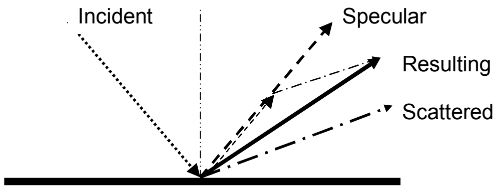
ESR Early Scattering Rays: Area radiation /Ray-radiosity

RTM Ray Tracing Method: Ray-radiosity

*Note: All methods may overlap in time

Summary of the ODEON method

Vector based scattering



Geometrical weighting of specular and a scattered direction

The scattering coefficient being the weighting factor

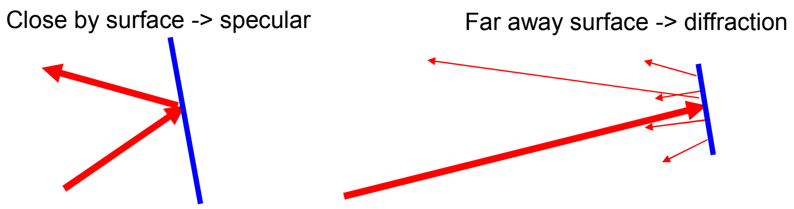
Reflection based scattering coefficient

New Concept

- Use scattering coefficient according to ISO/DIS17497-1 – can be measured
- Scattering caused by diffraction is estimated in software – per reflection

Benefits

- User need not guess coefficients
- Or need not assign different coefficients to same material on different surfaces
- Includes interaction between geometry and scattering



Reflection Based Scattering Coefficient

Names for scattering coefficients

$\mathbf{s_s}$

Surface Scattering coefficient – the **ISO/DIS-17497-1** value

$\mathbf{s_d}$

estimate of the fraction of energy scattered due to diffraction
– unique to each reflection

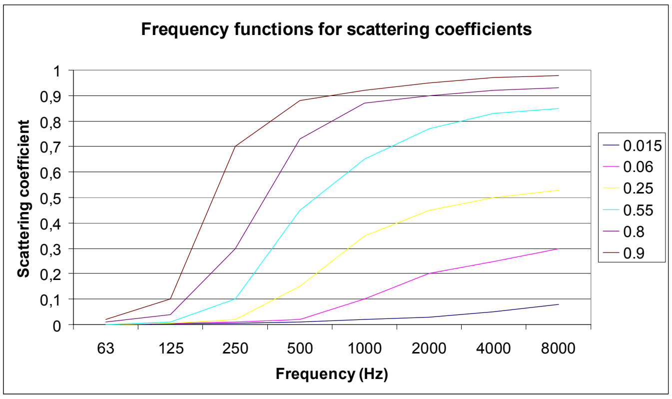
$\mathbf{s_r}$

combines diffraction and roughness into one coefficient per reflection
- the Reflection Based Scattering Coefficient

Reflection based scattering coefficient

Scattering due to surface roughness S_s

- Enter a coeffecient for middle frequency e.g. 500 – 1000 Hz
- Let Odeon expand the coefficient assuming typical frequency dependency due to surface roughness



Reflection Based Scattering Coefficient

Combining roughness and diffraction

Energy which is not scattered due to diffraction

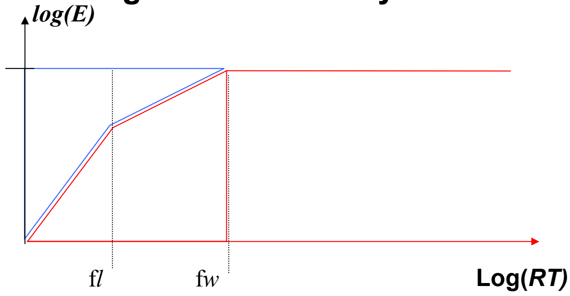
Energy which is not scattered due to roughness

$$S_r = 1 - (1 - S_d) \cdot (1 - S_s)$$

Resulting specular fraction i.e. not diffracted and not scattered due to surface roughness

Reflection Based Scattering Coefficient

Using Reflector theory to obtain S_d



RED

At high frequencies the surface reflects energy specularly

BLUE

at low frequencies the rest of the energy is scattered

Two cutoff frequencies defined from length and width of panel

Reflection Based Scattering Coefficient

S_d – the equations

$$K_w = \begin{cases} 1 & for \quad f > f_w \\ \dfrac{f}{f_w} & for \quad f <= f_w \end{cases} \qquad K_l = \begin{cases} 1 & for \quad f > f_l \\ \dfrac{f}{f_l} & for \quad f <= f_l \end{cases}$$

$$f_w = \frac{c \cdot a^*}{2(w \cdot \cos\theta)^2} \quad , \quad f_l = \frac{c \cdot a^*}{2 \cdot l^2} \quad where \quad a^* = \frac{d_{inc} \cdot d_{refl}}{2(d_{inc} + d_{refl})}$$

$$S_d = 1 - K_w K_l \times (1 - S_e)$$

Edge scattering from a free edge

Specular fraction is decreased due to edge scattering

- When reflections happens close to a free edge in terms of wave lengths
- A reflection is close to the edge if distance is less than one wave length
- The edge scattering coefficient ranges from 0 to 50%

$$S_e = \begin{cases} 0 & for \quad d_{edge} \times Cos\ \theta \geq \dfrac{c}{f} \\ 0.5\left(1 - \dfrac{d_{edge} \times Cos\ \theta \times f}{c}\right) & for \quad d_{edge} \times Cos\ \theta < \dfrac{c}{f} \end{cases}$$

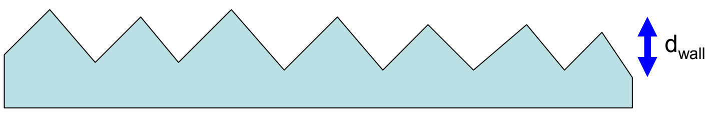
Adapting reflector theory to boundary walls

Freely suspended reflectors

- area assumed to be an average of room dim and surface dim

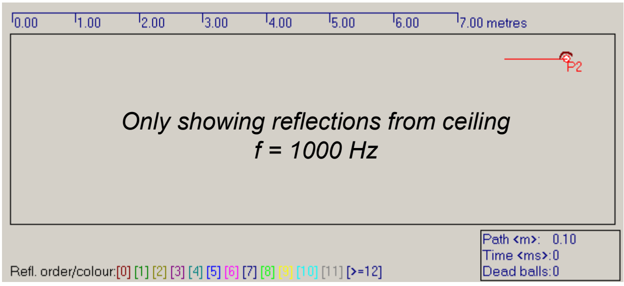
Boundary surfaces, compare wavelength with characteristic wall depth

- *High frequencies*, assume that reflector theory is valid when i.e. $\lambda/2<d_{wall}$
- *Low frequencies*, use *l,w* of rooms cross section instead of dimensions of individual surfaces when $\lambda/8>d_{wall}$
- Mid-frequencies: Interpolate between two above.



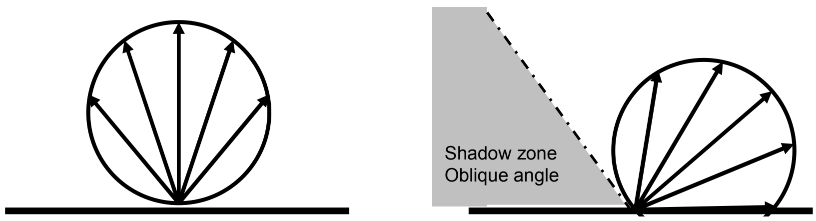
Reflection Based Scattering Coefficient

Scattering due to oblique angle of incidence



Reflection Based Scattering Coefficient

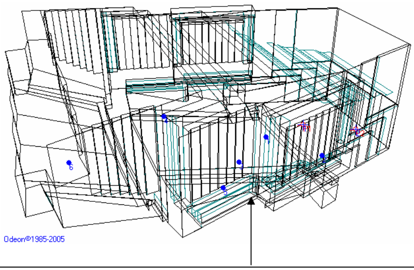
Oblique Lambert



Oblique Lambert for inclusion of frequency depending scattering
-Orientation according *Vector Based Scattering*.
-Area radiation tilted towards specular direction

Compensation factor to avoid energy loss
-depends on oblique angle
1 for 0 degrees
2 for 90 degrees

Case studies

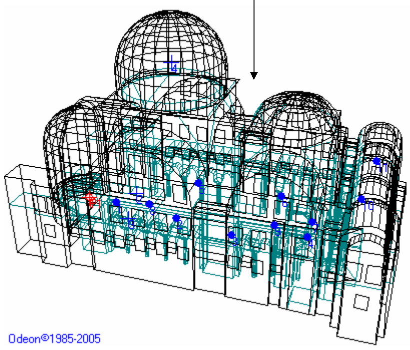


The Elmia hall
2nd Int. Round Robin on Room Acoustic Computer Simulations
470 Surfaces

2 scattering coefficients used
•65% for Audience
•5 % for all other surfaces

The St Irene Church in Istanbul
An antique Byzantine church
1766 surfaces, coupled rooms

Only one scattering coefficient applied
•5 % for all surfaces



Reflection Based Scattering Coefficient

Performance measure

To find number of rays needed

$$Error = \frac{\sum_{n=1}^{AP}\sum_{n=1}^{Freq}\sum_{n=1}^{Pos}\frac{|AP_{measured} - AP_{simulated}|}{SL}}{N_{AP}\cdot N_{Freq}\cdot N_{Pos}}$$

$AP_{Measured}$ = *Measured value of the current acoustic parameter*

$AP_{simulated}$ = *Simulated value of the current acoustic parameter*

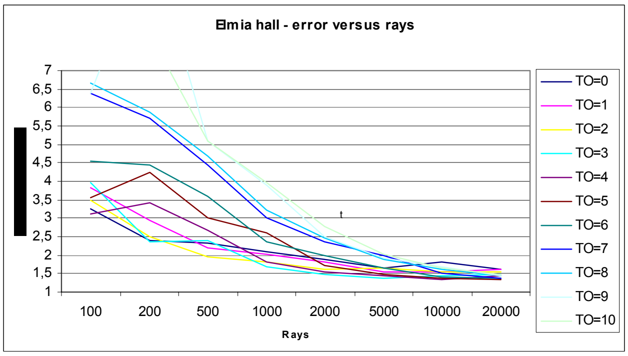
SL = *The subjective limen for the current acoustic parameter*

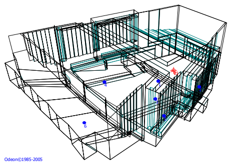
N_{AP} = *Number of Acoustic parameters*

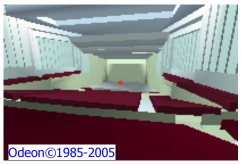
N_{Freq} = *Number of frequency bands (500-2000 Hz in this case)*

N_{Pos} = *Number of measuring positions*

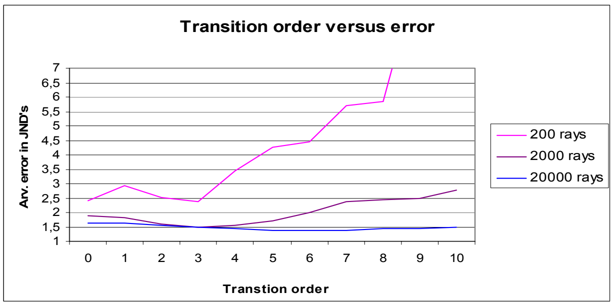
Reflection Based Scattering Coefficient

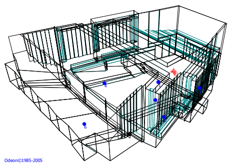


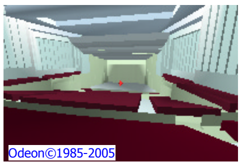




Reflection Based Scattering Coefficient

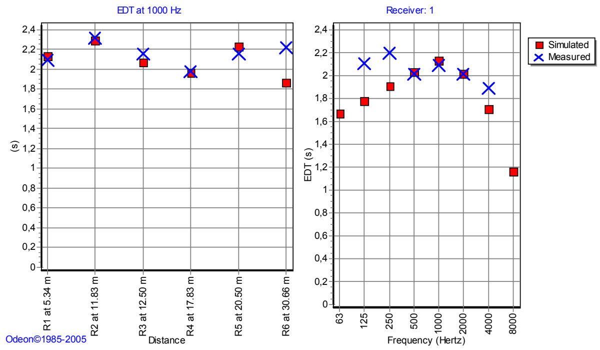


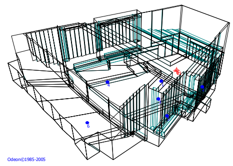


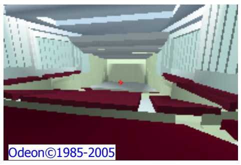


- Error decreases at higher TO – when sufficient rays are used
- TO= 6 and 20000 rays yields an average error of 1.35
- On the other hand for fast estimates with few rays a lower TO should be used (3?)

Elmia Source 1, EDT

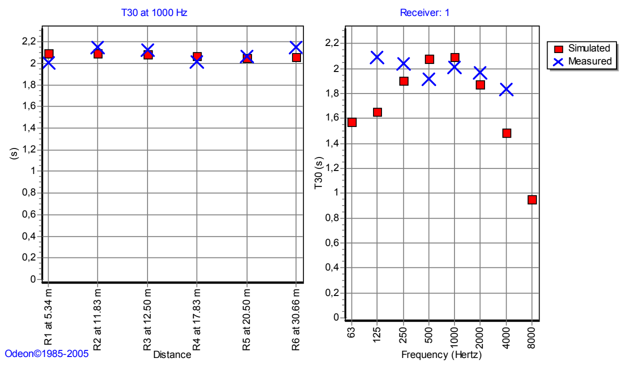


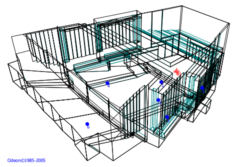


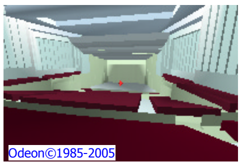


Average measured at 1000 Hz 2.15 seconds
Average deviation at 1000 Hz:-0.06 seconds (2.7%)
Max. deviation at 1000 Hz:-0.35 seconds (16%)

Elmia Source 1, T30

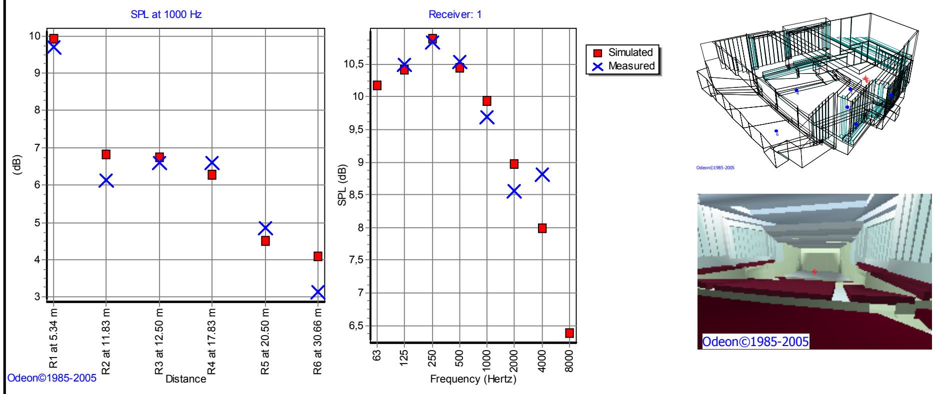






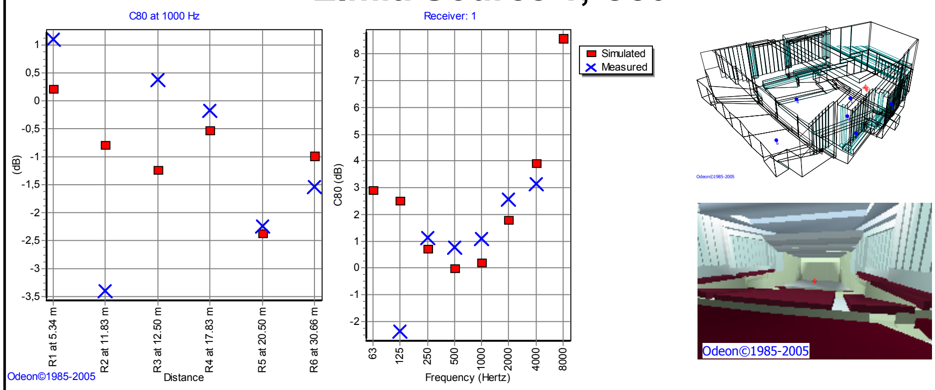
Average measured at 1000 Hz 2.09 seconds
Average deviation at 1000 Hz: +0.01 seconds (0.5%)
Max deviation at 1000 Hz -0.09 seconds (4.3%)

Elmia Source 1, SPL



Average measured at 1000 Hz 6.2 dB
Average deviation at 1000 Hz: 0.2 dB
Max. deviation at 1000 Hz: 1 dB

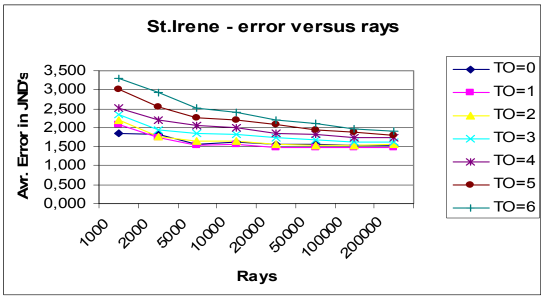
Elmia Source 1, C80

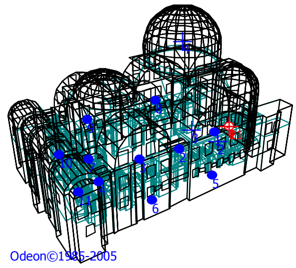


Average measured at 1000 Hz 1 dB
Average deviation at 1000 Hz: 0 dB,
Max deviation at 1000 Hz: 2.6 dB

Reflection Based Scattering Coefficient

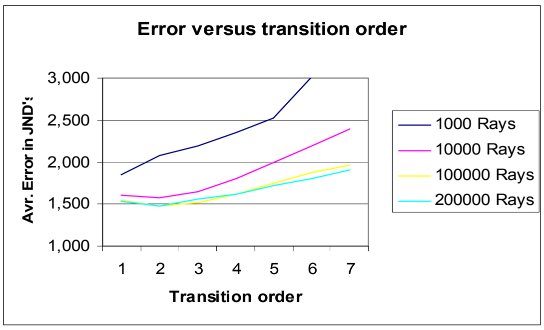
St. Irene Church

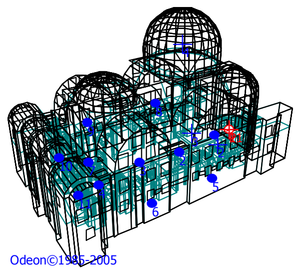




Reflection Based Scattering Coefficient

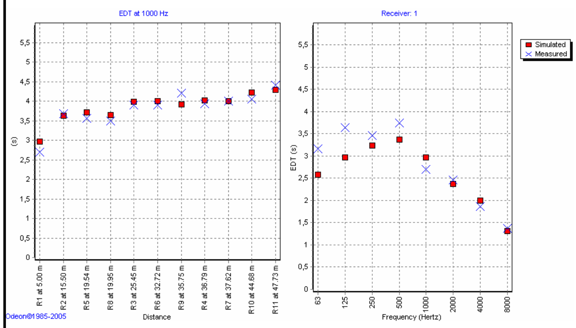
St. Irene Church

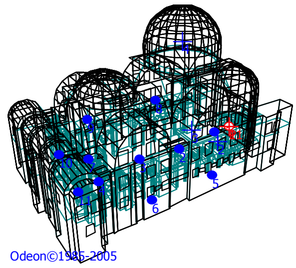




Reflection Based Scattering Coefficient

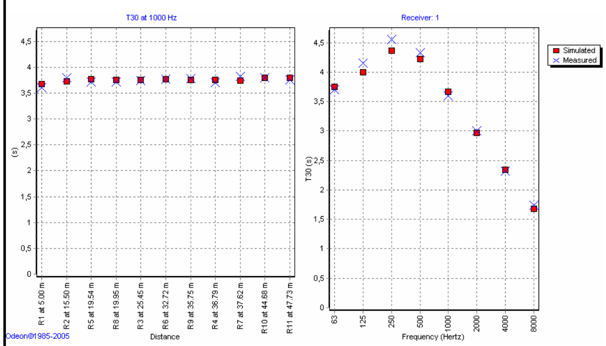
The Church, EDT

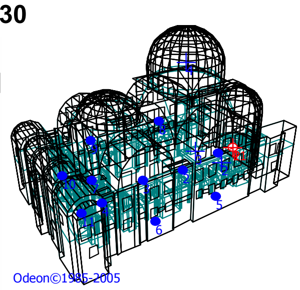




Average measured at 1000 Hz 3.82 seconds
Average deviation at 1000 Hz: 0.01 seconds (0.3%)
Max deviation at 1000 Hz: -0.29 seconds (7.5%)

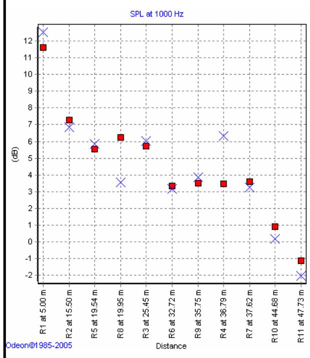
The Church, T_{30}

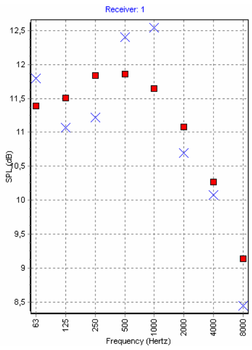


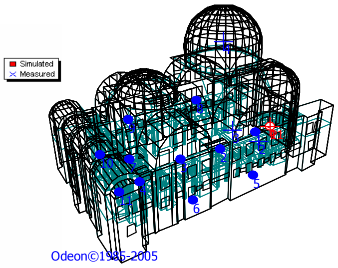


Average measured at 1000 Hz 3.74 seconds
Average deviation at 1000 Hz: 0.03 seconds (0.7%)
Max. deviation at 1000 Hz: 0.13 seconds (3.4%)

The Church, SPL

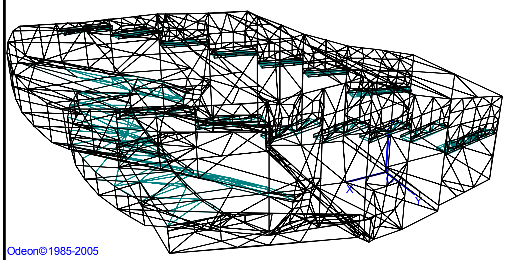






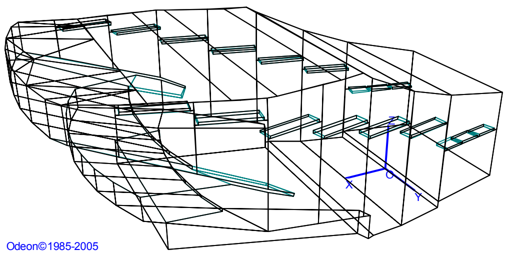
Average measured at 1000 Hz 4.5 dB
Average deviation at 1000 Hz: 2.5 dB,
Max. deviation at 1000 Hz: 0.1 dB

Using geometries from AutoCAD



Conflict with diffraction handling
AutoCAD and similar programs generates numerous irrelevant small surfaces (1362 surfaces)

Solution
Odeon DXF Import glues or stitches surfaces to make geometries more suitable (209 surfaces)



Conclusions

A new method for scattering

- which is compatible with the scattering coefficients obtained by ISO/DIS-17497-1 was developed

Initial evaluations

- indicate that same scattering coefficients (ISO/DIS 17497-1) can indeed be used for surfaces with different size or in different geometries

Benefits

- Less guesswork, less work….
- Improved prediction – not investigated in depth
- Less sensitivity to small surfaces, e.g. better compatibility with architects CAD models